# Smart fLAIr: a Smartphone Application for Fast LAI Retrieval using Ambient Light Sensors


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***Abstract*—The efficiency of precision agriculture fundamentally depends on the exploration of bio-physical and bio-chemical plant parameters and the assessment of current crop conditions. The leaf area index (LAI) represents one of the most important crop parameters and is defined as the ratio of foliage area to ground area. It is widely-used in agriculture and agronomy as it indicates yield-limiting processes. In this paper, we present Smart fLAIr (fast LAI retrieval), a novel smartphone application for a low-cost in-situ LAI estimation. This estimation is based on the gap fraction analysis, a widespread indirect and non-destructive methodology. For that purpose, Smart fLAIr leverages the smartphone's internal Ambient Light Sensor (ALS). However, in order to improve the gap fraction accuracy, we enhance the ALS by a diffuser cap combined with an optical band-pass filter. Our prototype is implemented on the Android platform with a focus on usability aspects and its practicability. Conducting a comparative analyses with a commercial instrument, we successfully evaluated this prototype for maize canopies. The convincing performance of our approach in terms of accuracy and stability highlights the potential of Smart fLAIr as a valuable alternative for in-situ LAI assessment.**


## I. Introduction

In agronomic research and environmental studies, the exploration of bio-physical plant characteristics demands for adequate parameters such as fractional cover, biomass, fraction of absorbed photosynthetically active radiation (fPAR), and leaf area index (LAI) providing valuable information on the current plant conditions and agricultural fields. The LAI is a key parameter which is defined as the ratio of foliage area to ground surface area ($m^2$ foliage / $m^2$ ground). As it estimates the amount of solar radiation transmitted by the canopy, it characterizes the photosynthetic performance of vegetation [10] and serves as an indicator for yield-limiting processes [3]. Moreover, the LAI is essential for models in climatology, meteorology, ecology, and agronomy [1].

There is a variety of different methods for LAI determination. Traditionally, the LAI is assessed manually by ground-based methods [4], [10], either in a destructive or in a non-destructive manner (also referred to as indirect). Although providing most accurate results, destructive measurements are often limited to small areas since they require extensive time and labor costs. In contrast, non-destructive in-field methods mitigate these costs by avoiding the laborious harvesting. Various commercial instruments, e.g., LAI-2200 [11] (LI-COR, USA), and digital hemispherical photography (DHP) technology [8], [10], [15], estimate the solar transmittance of plant canopy (known as *gap fraction analysis*).

However, manual LAI assessments remains costly and, thus, often are sparsely conducted. In order to improve the spatial and temporal resolution of LAI information, there are two complementary approaches. (1) Remote sensing – a key technology that enables the identification of in-field variability and agricultural decision-making – allows an LAI assessment derived by satellite or airborne images [3], [9]. (2) Wireless Sensor Network (WSN) technology establishes the basis for agricultural monitoring systems which present a novel approach for in-situ LAI assessment [2], [13], [17]. These networks are based on a plurality of interconnected low-cost and low-power devices disposing of similar sensors as used by the above mentioned non-destructive instruments. Tailored to a long-term, large-scale, and mostly unattended deployment in agricultural fields, these networks will eventually enable a fine-grained in-situ LAI assessment. Nevertheless, traditional in-situ LAI estimation is still a prerequisite for the occasional calibration and validation of both automated methods, remote sensing and WSNs.

Even widely used in agronomic research due to its reliable results, commercial instruments for LAI assessment, such as the mentioned LAI-2200 or AccuPAR (Decagon, USA) and SunScan (Delta-T, USA) devices, are generally quite expensive and limited in their level of portability [5].

The continuous technical progress in the area of mobile phones and mobile computing devices has enabled advanced and affordable smartphones. As these phones have increasing processing power, are GPS-capable, and are enriched with more and more additional sensors, smartphones have recently been proven to be suitable as an economical alternative for the in-situ LAI assessment [5], [7].

This paper introduces Smart fLAIr (fast LAI retrieval), a novel smartphone application for a low-cost in-situ LAI estimation based on gap fraction analysis that leverages the smartphone's internal Ambient Light Sensor (ALS). After a discussion on existing approaches and related work (Sec. II), we present the design concept of Smart fLAIr, its implementation details, as well as a brief theoretical background

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of its measurement methodology in Section III. Moreover, we propose an external ALS modification to improve the accuracy of LAI estimation (Sec. III-B2) and evaluate the application's performance for maize canopies in extensive measurement campaigns by comparative analyses against the LAI-2200 (Sec. IV). Finally, evaluation results and the potential of Smart fLAIr as a valuable alternative are discussed (Sec. V). In Section VI, we conclude the paper and outline future work.

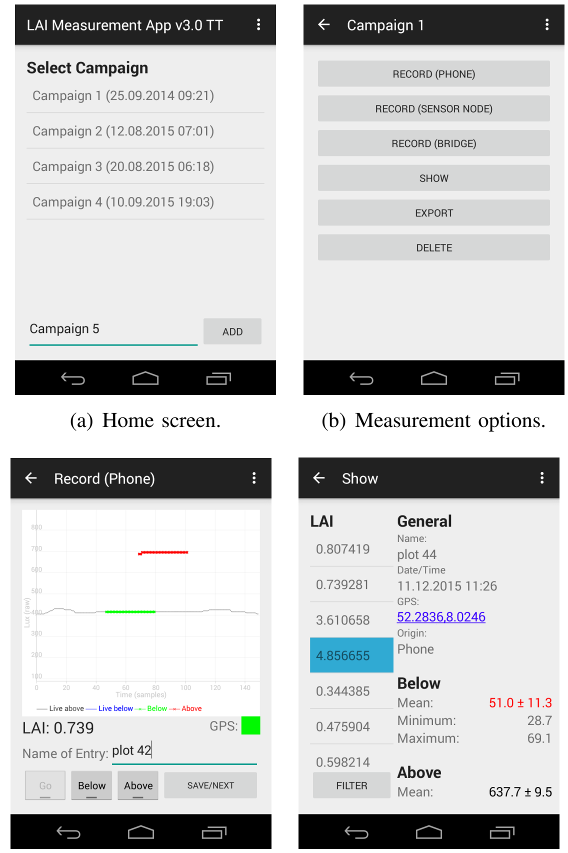
## II. Related Work

Previous work which is closely related to the approach presented in this paper can be classified in two categories corresponding to their indirect LAI assessment methodology and its complexity.

Digital image processing based LAI assessment enabled by in-situ digital cameras and DHP devices [5], [10], [15] represents the first category. The approaches published in this category have been proved to achieve good performance compared to conventional LAI instruments [5], [7], [12], [15]. The advantages of the approaches in this category is that they need only a single measurement location, usually an upward-pointing position below canopy. However, the image processing is quite complex and, thus, typically requires a few minutes of processing time [12]. Furthermore, the accuracy of the results strongly depend on the quality of the camera's optical lens.

Confaloniere et. al [5] introduced the first approach which successfully leveraged the increasing capabilities of smartphones. This approach might seem to be the most directly related work at a first sight. Indeed, the authors use smartphones and the same platform, namely Android. Moreover, they clearly point out the advantages of using relatively cost-effective smartphones instead of expensive commercial measurement instruments. However, they exploit the digital camera as sensor and apply image processing algorithms for LAI estimation, although a method based on above and below canopy luminance acquisition (App-L) was also tested. Because the smartphone's camera is used and specific EXIF metadata is required (i.e., f-number, exposure time, and ISO sensitivity), the later approach is stated as not fully compatible with Android [6].

The second category interconnects a large number sensing devices within agricultural monitoring systems based on WSN technology [2], [13], [17]. The strength of these systems lies in the high spatiotemporal resolution achieved by the large number of devices and in its holistic accuracy rather than in the accuracy of individual sensors. Such agricultural WSNs typically estimate the LAI by sensing solar radiation above and below canopy. For that purpose, photosynthetically active radiation (PAR) sensors are used which are similar to the ALSs our approach is based on. Moreover, special modifications are usually applied to PAR sensors in order to increase the sensors capability for LAI estimation. In [2], we propose the view pipe modification, for instance, whereas Qu et al. [13] deploy sensors with optical diffusers and band-pass filters.



(a) Home screen.
(b) Measurement options.
(c) Measurement view.
(d) Measurement table with LAI readings and metadata.

Fig. 1. The graphical user interface of Smart fLAIr.

## III. Concept and Android App Development

Smart fLAIr aims to serve as a convenient, applicable, and low-priced alternative to commercial plant canopy analyzers. The overarching objective is to provide reliable results with sufficient accuracy for the validation of remote sensing or WSN data.

### A. Basic Functionalities

The application is developed for the Android platform and offers the basic functionalities for its objective. Figure 1 shows the main views of its Graphical User Interface (GUI). In the home screen (Fig. 1(a)), a user can create a new collection of measurement data (represented by a separated data base) or select an existing one. These clearly arranged collections are suggested to be used for different measurement campaigns and/or sites. After choosing the intended collection, various options are available (Fig. 1(b)). The user can either decide to (1) record new (or additional) measurements (details in Sec. III-B) and gets the corresponding measurement view (Fig. 1(c)). Alternatively, the user can decide to (2) get a summary of all data base entries in the chosen collection (Fig. 1(d)) or has the possibility to (3) export and (4) delete these entries.

The summary view (Fig. 1(d)) allows the user to switch between all acquired LAI entries and to access their metadata. Beside the name or number of each LAI entry, its timestamp and (if available) its GPS position are given. Statistical data is listed and emphasized in case of unusual variances. Moreover, there is the possibility to review recorded samples belonging to a corresponding LAI entry as graphical time series and to selectively delete specific entries.

All collections can be exported as CSV files to the smartphone's storage or by using the *share* button provided by Android. Using the later option, CSV files can be directly forwarded via Bluetooth, email, or even cloud uploads.

## B. Measurement Methodology

*1) Theoretical Background and Reference Instrument:* Our approach of indirect LAI estimation is based on the gap fraction analysis. This analysis derives the LAI from the amount of solar radiation transmitted by the vegetation, i.e., the residual luminance below the canopy. Thus, generally two measurements are required, one above the canopy gathering non-intercepted luminance and the other one below [4], [10].

As we have already gained practical experiences [2] with the LAI-2200 instrument, we select it as reference device for the comparative evaluation. The LAI-2200 instrument consists of a measurement wand attached to a handheld control unit. At the end of the measurement wand, there is a fish-eye optical sensor. The sensor's field of view is divided into five rings with different center angles: 7, 23, 38, 53, and 68 ° [8], [11].

Moreover, encouraged by [2], we adopt LI-COR's LAI determination. The determination is based on *Miller's* formula which is closely related to the formula of *Waren-Wilson* used in [5]. Applying the formula to the five rings of the LAI-2200, it results in [11]:

$$LAI = 2\sum_{i=1}^{5}\overline{K_i}W_i\,,\ \text{with}\ \overline{K_i} = \frac{1}{N_{obs}}\sum_{j=1}^{N_{obs}}\frac{-ln\left(\frac{B_{ij}}{A_{ij}}\right)}{S_i}\,. \quad (1)$$

For each ring $i$, the LAI-2200 measures the gap fraction simultaneously. Each measurement consists of a number ($N_{obs}$) of above ($A_{ij}$) and below ($B_{ij}$) canopy readings. The factors $W_i$ and $S_i$ (also adopted) are specific weightings for the individual rings, both increasing from the first (7 °) to the last ring (68 °). More details and the simplified assumptions behind Equation 1 can be found in [8], [11].

*2) Implementation:* In our approach, the gap fraction measurement is realized by a direct luminance sensing using the smartphone's internal ALS. Thus, we do not rely on gathering EXIF information of the camera device as in [6].

Smart fLAIr provides two measurement modi for LAI measurements: a *single-angle* and a *multi-angle* mode. In both modi, a fixed number of ambient light samples per angle were acquired, which can be defined as multiples of 17 in the options menu. This value originally stems from packet size restrictions in the WSN domain, cf. [2]. By default, we use 51 samples in order to cope with potential small-scale

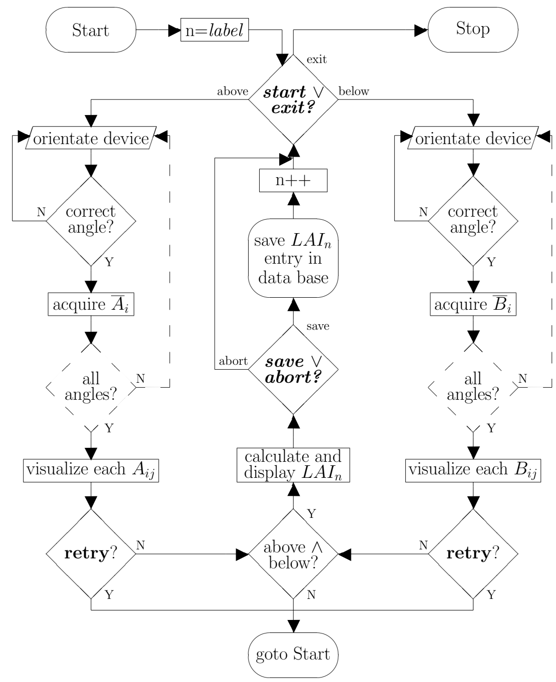



Fig. 2. Flowchart visualizing the measurement process of Smart fLAIr. The dashed elements represent the additional acquisitions required in the multi-angle mode.

environmental noise and calculate their means ($\overline{A}$ and $\overline{B}$). In the single-angle mode, ALS readings are acquired in a single orientation only, namely an upward-pointing position, i.e., the surface normal of the display is oriented towards the zenith angle (ALSs are generally mounted on the front side). For each $A_{ij}$ and $B_{ij}$ in Equation 1, we then reuse these means. The multi-angle mode is inspired by the five rings of the LAI-2200. Hence, the luminance is not only sensed in the zenith angle but also in 23, 38, 53, and 68 ° angles. Thus, the original $A_{ij}$ and $B_{ij}$ can be used.

Once the user initiates a new measurement, currently sensed luminance is visualized as live-preview in the measurement view (Fig. 1(c)). Therefore, we use *AChartEngine*, a framework that allows such a dynamic visualization. Now, the above canopy measurement can be startet using the *Above* button, and subsequently, the below measurement using the corresponding *Below* button, or vise versa. Moreover, the user can assign a label to the new entry or use the automatic label incrementation.

The measurement process (outlined in Figure 2) depends on the chosen mode. In the single-angle mode, only one acquisition per position is required whereas the multi-angle mode necessitates five acquisitions per position which are obtained successively by rotating the smartphone. For that purpose, the inertial sensor is used to ensure that the user orientates the smartphone correctly.

*3) External ALS Enhancement:* Commercial LAI instruments often take advantage of using optical filters. The higher reflectance and transmittance of green vegetation in the green range within the spectrum of visible light (so-called green peak) mitigates the differentiation between sky and vegetation.

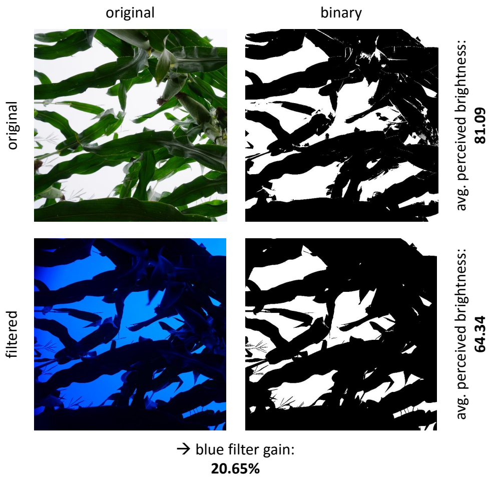



Fig. 3. Simplified visualization of the impact of blue band-pass filters for the LAI assessment.

(a) Samsung i9250 with ALS modification.

(b) Practical use of the smartphone prototype during the maize measurement campaign.

Fig. 4. Measurement setup for the smartphone-based indirect LAI assessment.

This effect can be countered with an adequate filter, i.e., by fading out the green range. The LAI-2200, for instance, increases the contrast with a blue band-pass filter [11] and, thus, improves its accuracy. Figure 3 demonstrates the advantage of such a filter. Applying a filter significantly improves the contrast between sky and vegetation as more plant details are perceived by the (camera) sensor.

In the domain of WSN, there also exist approaches that use such band-pass filters, e.g., [13]. Moreover, due to the lower complexity of WSN sensors, devices are often enhanced by optical diffusers [13], [17]. As the WSN sensor's characteristics are similar to these of ALSs, we adopt the WSN approach and optionally enhance the smartphone with a low-cost blue band-pass filter (Baader Planetarium, Germany) and a diffusing hemispherical plastic cover as shown in Figure 4(a). In Section IV, we will investigate the impact of this enhancement.

### C. Usability

Smart fLAIr is designed with a special attention on its usability and does not require root privileges. Our goal is a user-friendly and easy-to-use application. Thus, we considered ergonomic aspects and the typical Android user experience which are only briefly described here. For instance, measurement intervals are acoustically signaled and vibration feedbacks are used to inform the user about the correct ALS orientation during a measurement. If the orientation differs more than a specific threshold ($\pm 4\,°$) from the required angle, incoming sensor readings are discarded until the original orientation is reached again. Another mentionable issue is the labeling of LAI entries. Smart fLAIr recognizes numerals in an entered label and provides an automatic incrementation for following measurement labels. Due to operational errors and also by reasons of unstable weather conditions during field campaigns, variances of individual sample sequences might be extraordinary which is emphasized in the summary view. In that case, repeating measurements may be necessary. Then, the user can choose if the automatic numeration is normally continued after the repeated measurement or the numeration is reset for the case that all subsequent measurements are invalid. Furthermore, for the practical use, it is possible to mount the smartphone onto a commercial off-the-shelf selfie-stick as shown in Figure 4(b). If connected to the headphone jack of the smartphone, the shutter button starts the LAI measurement in a convenient way. Besides, using such a monopod reduces a possible influence (e.g., shadowing) of the operator.

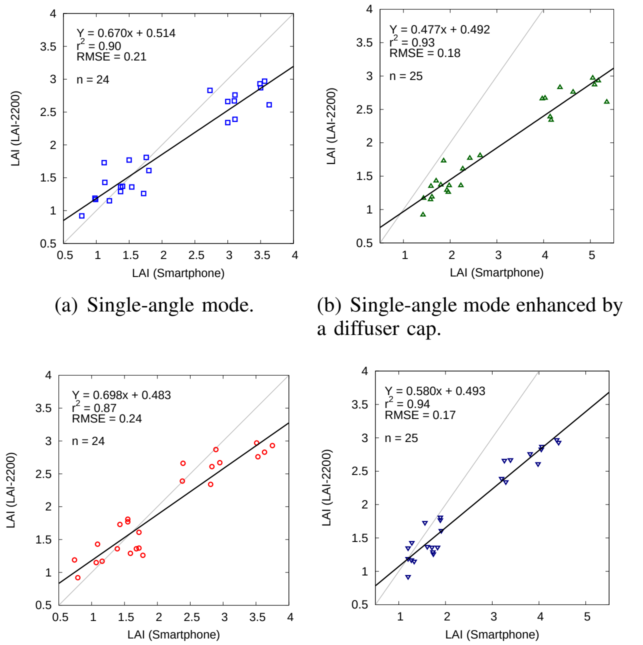
## IV. Evaluation

The overall goal of the evaluation is an investigation of Smart fLAIr's potential as an alternative for in-situ LAI assessment. Therefore, four measurement campaigns in a maize field (*Zea mays L.*) were carried out and comparative analyses with results obtained by the LAI-2200 as reference device are conducted. The first campaign compares both measurement modi and investigates the impact of the sensor enhancement. Campaign 2 and 3 provide an additional validation of the enhanced setup and, finally, Campaign 4 evaluates the stability of our approach.

### A. Study Area & Measurement Details

The maize field used for our evaluation campaigns is located near the University of Osnabrück in the north-western part of Germany and has a size of around 3.5 ha. The mean annual precipitation of the area is about 700 mm and the mean annual temperature between 8 and 9 °C. Four campaigns were conducted in the growing seasons 2014 and 2015 (Sept. $25^{th}$ in 2014 and Aug. $12^{th}$, Aug. $20^{th}$, and Sept. $10^{th}$ in 2015) In the first three campaigns, the LAIs of roughly 30 plots with seasonal variations and different growth characteristics were acquired in order to cover a wide range of LAI values. On the contrary, in the last campaign, the stability was investigated and, thus, we chose a fixed plot. Moreover, we took care of stable cloud cover guaranteeing diffuse light which is a basic requirement of the LAI-2200 instrument.

The Smart fLAIr application is installed on a Samsung Galaxy Nexus (GT-i9250) with Android 4.4.4. That device includes a GP2A ALS manufactured by Sharp with a resolution of 1.0 lx and a comparable high range (up to 55000 lx) in which the measurement accuracy is ensured by the manufacturer [16]. The ALS offers an effective sampling rate of roughly 43 Hz. Hence, around 1,19 s per position (and angle)




(a) Single-angle mode.

(b) Single-angle mode enhanced by a diffuser cap.

(c) Multi-angle mode.

(d) Multi-angle mode enhanced by a diffuser cap.

Fig. 5. Correlation between LAI-2200 estimates and LAIs assessed by Smart fLAIr using different methods (Campaign 1).

are needed to gather 51 samples (default setting) enabling the fast LAI retrieval of Smart fLAIr.

## B. Results

*1) Impact of Measurement Mode & Sensor Enhancement:* In the first campaign, we compared the single- and the multi-angle measurement mode as well as the sensor modification with a diffuser cap. The results of a comparative analysis between these setups and the LAI-2200 is visualized in Figure 5. Each scatter plot shows LAI estimates and the degree of linear correlation. Moreover, considering the linear regression, the corresponding coefficient of determination ($r^2$), and the root-mean-square error (RMSE) as correlation metrics (representing the accuracy), one can observe a general strong linear correlation and conclude that (1) the multi-angle mode which implies additional effort does not necessarily improve the accuracy and (2) it might be worth to use the diffuser enhancement. Hence, from now on, we focused on the single-angle mode and, furthermore, extend the diffuser with the optical filter as mentioned in Section III-B3.

*2) Impact of the Optical Filter:* In the two following campaigns, we evaluated the impact of our proposed sensor enhancement consisting of an optical filter and a diffuser cap. It can be seen from Figure 6 that this enhancement further improves the strong linear correlation ($r^2 = 0.95$) and balances the LAI ranges of both devices as the regression line runs closer to the 1:1 line.

*3) Stability Considerations:* In the last campaign, we finally investigated the stability of our approach. As stability, we consider the repeatability of a certain LAI estimation. Thus,

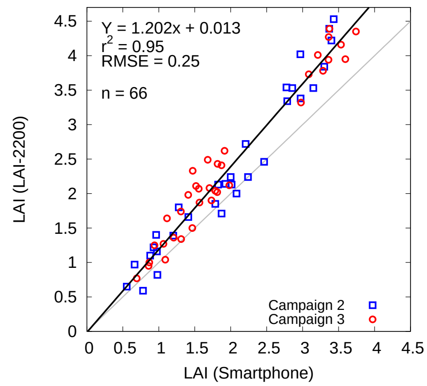



Fig. 6. Correlation between LAI-2200 estimates and LAIs assessed by Smart fLAIr in single-angle mode using a diffuser combined with a blue band-pass filter (Campaign 2 and 3).

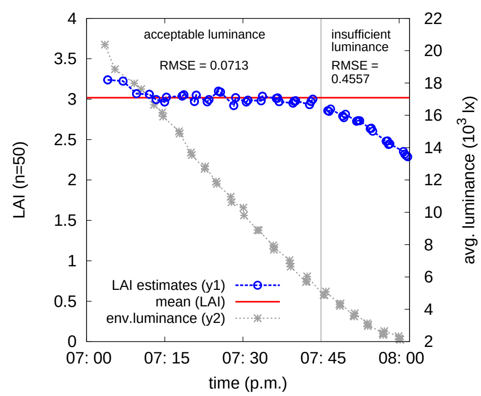



Fig. 7. Stability of Smart fLAIr (single-angle mode using diffuser and filter). LAI was accessed at a fixed location in the maize field but environmental light conditions changed during the measurements (Campaign 4).

we chose a fixed position in the field as well as a stable and diffuse luminance condition as recommended in [11]. For that purpose, we start the campaign immediately after sunset (6:56 p.m. (UTC+1)). Assuming a robust approach, nearly the same estimates in all successive measurements are expected. However, if the environmental luminance condition changes during the campaign, it might have a negative impact on the LAI estimation. This instability or sensitivity to illumination conditions is a known weakness of both commercial devices, LAI-2200 and AccuPAR, as reported in [8].

Figure 7 reveals that on the one hand our approach enables a very good stability during a phase with ideal conditions and acceptable luminance (until circa 7:45 p.m.). This is emphasized by the proximity of LAI estimates to their mean value (RMSE = 0,07 (≈ 0,236 %)). On the other hand, when the environmental luminance decreases to an insufficient intensity during dusk (after 7:45 p.m.), one can observe that the actual mean LAI is the more underestimated, the less residual luminance is perceivable. Thus, Smart fLAIr should be used under sufficient luminance conditions to guarantee stable and precise results.

TABLE I
PERFORMANCE OF RELATED APPROACHES

| Category | Approach | Species | Result ($r^2$) | Reference |
|---|---|---|---|---|
| DHP | [15] | trees | 0.94 | LAI-2000 |
| PocketLAI | [5] | rice | 0.97 (App-L) | destructive |
| PocketLAI | [7] | grass | 0.86 | AccuPAR |
| | | maize | 0.92 | AccuPAR |
| | | giant reed | 0.88 | AccuPAR |
| PocketLAI | [12] | shrubs | 0.78 | DHP |
| | | conifers | 0.16 | DHP |
| WSN | [14] | maize | 0.27–0.97 | LAI-2000 |
| WSN | [2] | shrubs | 0.85–0.90 | LAI-2200 |

## V. DISCUSSION AND OUTLOOK

The evaluation results presented in the previous section have successfully shown the strong linear relation ($r^2 = 0.95$) with the reference measurements. Although, our approach is comparatively simple as it uses simple sensor technology and a light-weight computation, it is effective and can compete with more complex approaches surveyed in Table I.

The presented approach offers a convenient opportunity for in-field LAI estimation as long as the user can easily handle the above measurement. However, if the vegetation cover becomes too height, e.g., in grown maize or even in forests, DHP techniques are preferable as above data acquisition is not required. A solution, already prepared in the Smart fLAIr application, is represented by secondary sensing devices. This can either be achieved by a second adequately placed smartphone connected via Bluetooth (or GRPS infrastructure) or by a suitable WSN device, cf. recording options in Fig. 1(b). The later can be tethered using a USB receiver or a WSN-to-Bluetooth gateway.

## VI. CONCLUSION AND FUTURE WORK

In this paper, a novel ALS based smartphone application for the non-destructive in-field LAI assessment was presented. Using an external sensor enhancement, this approach was evaluated to achieve a very good performance (correlation coefficient $r^2 = 0.95$ to LAI-2200 in maize crops) that can compete with more complex methods. Furthermore, it guarantees adequate stability under daylight conditions. Thus, it provides a reasonable and low-cost alternative to commercial instruments.

As future work, we plan to continue the promising approach by conducting additional measurement campaigns in other crop types and to consider various ambient light sensors, i.e., different smartphones and manufacturers. Moreover, a direct comparison with PocketLAI [6] would be interesting.

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