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Evaluation of active and passive sensor systems in the field to phenotype maize hybrids with high-throughput

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ABSTRACT

New technologies, such as high-throughput precision phenotyping could offer an effective method of increasing genetic gains in breeding, as the screening of maize characteristics in the field remains a major bottleneck, whereas progress has been made in genomics technology. The architecture of tall maize plants presents a particular challenge to obtaining information about where reflectance-based information within the plant is collected to disentangle the contributions of the upper and lower leaves, as well as the stem and cob. High-throughput non-invasive assessments of a dedicated panel of seventeen diverse maize hybrids were conducted to assess the potential of two active sensors and one passive sensor to discriminate the biomass and nitrogen uptake. The passive sensor detected the nitrogen uptake of the entire maize foliage, whereas the sensing depth of the two active sensors was confined to the upper canopy layer. Although almost half of the nitrogen was stored in the stems, the reflectance values were primarily influenced by the foliage, with reflectance values from the remaining stems and cobs barely differing from that of bare soil. The results indicate that the sensing depth of various sensors needs to be taken in account, particularly when phenotyping tall plants, such as maize.

1. Introduction

To satisfy the needs of a human population predicted to reach 9 billion by 2050, connecting genotypes to phenotypes is required to achieve the fast and efficient selection of high-yielding, stress-tolerant plants (White et al., 2012). Given that agriculture is also facing major challenges due to the expected impacts of global climate change on temperature, as well as rainfall distribution, technical advances in plant phenomics have the potential to improve our understanding of gene function and environmental responses, leading to improvements in plant breeding (Furbank and Tester, 2011). In-field high-throughput phenotyping has been recognised as one of the major bottlenecks in this area (Berger et al., 2010; Montes et al., 2011); therefore, well-focussed high-throughput phenotyping will be essential for the estimation of new and effective plant traits. However, the use of high-throughput phenotyping to improve crop performance and hence accelerate the breeding progress is still in its infancy and far from being routinely used (Passioura, 2012; Walter et al., 2012). Field-based phenotyping is the most promising approach for delivering the required throughput in terms of numbers of plants as well as populations for a precise description of plant traits in cropping systems (Nicotra and Davidson, 2010; Thoren et al., 2010; White et al., 2012). Therefore, high-throughput methods for phenotyping are crucial for investigating the connection between phenotype and genotype (Gao et al., 2012).

Proximal sensing systems designed for precision agriculture are increasingly used for phenotyping as well. They are based on passive or active multispectral measurements conducted manually or from air- or tractor-borne systems. Passive spectral sensors use sunlight as the light source, in contrast to active sensors, which possess their own light-emitting units. Consequently, active sensors are independent of varying irradiation conditions but are limited to fewer wavelengths according to the number of light sources and type (Erdle et al., 2011). The reflectance of a plant canopy is a function of the leaf morphological properties, the absorption of light by pigments as well as plant architecture, with varying arrangements of leaves, branches, and stems (Hatfield et al., 2008). The potential of active and passive sensing systems in assessing relevant agronomic and physiological traits is well documented but requires further understanding. Active sensing has been used to assess biomass (Freeman et al., 2007) as well as the nitrogen status of maize (Guo et al., 2008; Hong et al., 2007). The variable nitrogen application rate in maize could best be directed between the V11 to V15 (15 collars, 10–12 days before silking) growth stages (Solari et al., 2008). The combination of remote sensing with crop modelling could offer a robust method with a steady calibration across seasons, to estimate biomass and therefore estimating canopy nitrogen remotely, but needing future

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research exploring the use of active and passive sensor technologies for the use in precision farming for targeted nitrogen management (Fitzgerald et al., 2010). Indices derived from passive spectrometer measurements showed the potential to determine the aerial biomass and nitrogen uptake of maize hybrids (Mistele and Schmidhalter, 2010; Winterhalter et al., 2011a) and to measure the canopy water mass of several maize hybrids grown under different drought stress conditions (Winterhalter et al., 2011b).

In contrast, active and passive sensing principles have seldom been compared, and only spurious information is available regarding where within a canopy the reflectance information originates and how this origin is affected by the sensing principle. This information is of particular relevance for tall and structured crop stands, such as maize, particularly in later growth stages. Such information is required to optimise management actions in precision farming and is also of high relevance for precision phenotyping. Plants vary in canopy architecture and height, which requires understanding how such factors influence spectral readings.

During the growing period, the local light irradiation influences the nitrogen distribution and remobilisation in maize leaves in addition to the development under changing nitrogen supplies throughout growth while leaf appearance remains constant, leading to a heterogeneous nitrogen distribution (Drouet and Bonhomme, 1999; Gastal and Lemaire, 2002). The quality and informativeness of canopy information gained from sensor measurements could be improved by identifying the contributions of vertical leaf layers from plant canopies to spectral reflectance (Wang et al., 2005). A vertical bell shape distribution of leaf biomass and nitrogen uptake in maize canopies grown under different nitrogen fertilisation treatments was found, and a footprint of a passive reflectance sensor was established, demonstrating that a passive reflectance sensor was able to detect the leaf biomass and leaf nitrogen uptake of the lowest leaf levels as well (Winterhalter et al., 2012).

The light emitted from active sensors follows the inverse square law, which means that the light intensity decreases by a factor of four when the measuring distance doubles. Optimised sensor-target distances were recently determined for two of the investigated actives sensors used in this study: 70–110 cm and 30–160 cm for the Greenseeker RT 100 (NTech Industries Inc., Ukiah, CA) and the Crop Circle ACS-470® (Holland Scientific, Inc., Lincoln, NE), respectively. This information differs slightly from the manufacturers' specifications of 81–122 cm and 25–213 cm, respectively (Kipp et al., 2012). Consequently, the measured targets should not be too close or too distant. Although the proximity of a sensor to an object can theoretically be well defined, its definition is confronted with substantial difficulties in three-dimensional canopies that may differ in their vertical biomass distribution under heterogeneous field conditions within the same cultivar, but likely even more among different maize cultivars. With regard to tall maize plants, the distances suggest, that only part of the canopy can be assessed. Because no such information is available hitherto, this study aimed to elucidate the extent to which active and passive sensors can sense tall maize plants that differ in height and presumably also in their vertical biomass and nitrogen distributions.

The objectives were therefore to estimate the biomass and nitrogen uptake of different maize hybrids with field- and carrier-based, non-destructive, high-throughput measurements by comparing two active and one passive bidirectional reflectance sensors. Whereas active sensing is daylight independent, passive sensing is daylight dependent. Therefore, a new technique for the accompanying destructive assessments had to be developed to match the destructive information to the non-destructive observations.

2. Materials and methods

Experimental field trials were conducted in the year 2011 at the Dürnast research station (11° 70′ E, 48° 40′ N, and 450 m asl) of the Technische Universität München in Germany. This region has an annual precipitation of 800 mm, with an average temperature of 7.5 °C. The soil is characterised as homogeneous Cambisol with silty clay loam. The cultivation methods followed local technical recommendations, with a seeding density of 12 plants m^{-2}, the use of Thomaskali 10/15 (24 kg P ha^{-1} and 77 kg K ha^{-1}) and Alzon 46 (162 kg N ha^{-1}) fertilisers, as well as a herbicide treatment of 2.5 l of Artett and 0.7 l of Kelvin. Seventeen different maize hybrids (*Zea mays* L.) used for corn, silage, or energy production, received from KWS (KWS Saat AG, Einbeck, Germany), were planted in three replications. A detailed description is given in Table 1. The plant heights in 2011 varied from 260 to 330 cm.

High-throughput sensor measurements were conducted on August 2, 2012 on a sunny day under clear sky conditions at the BBCH 67 growth stage (male: flowering completed; female: stigmata drying). Sensor measurements were conducted with intact plant stands, plant stands with the bottom half of the leaves removed, plant stands where all leaves had been removed (leaving only the stem and cob standing), and a treatment with only bare soil remaining. Because time is a critical factor for the radiation distribution in maize canopies, all spectral measurements were performed within one hour, from 12:00 to 13:00. The leaves

Table 1
Description of the maize hybrids with corresponding plant heights in 2011.

Nr.	Name	Height (cm)	Description of hybrids				Type of use		
			Maturity group	FAO number	Plant height	Type/form	Corn	Silage	Energy
1	LAPRIORA	263	Early	190	Very short	Slim	X		
2	LAURINIO	297	Early	210	Long	Slim	X		
3	AMAGRANO	287	Early	210	Average	Slim	X		
4	FABREGAS	282	Early	210	Long	Bulky		X	
5	COLISEE	285	Early	220	Average	Balanced	X	X	
6	AMADEO	277	Early	220	Average	Balanced	X	X	X
7	RICARDINIO	278	Intermediate	230	Long	Balanced	X	X	
8	TORRES	282	Intermediate	250	Average	Balanced	X	X	
9	GROSSO	301	Intermediate	250	Long	Balanced	X	X	
10	BARROS	279	Intermediate	250	Long	Bulky		X	X
11	SEVERO	288	Intermediate	260	Long	Bulky		X	X
12	KXA0152	325	Intermediate	240	Very long	Massive			X
13	ATLETICO	324	Late	280	Very long	Slim			X
14	ATLETAS	314	Late	280	Very long	Bulky			X
15	KXA0172	308	Late	270	Very long	Balanced			X
16	CANNAVARRO	303	Late	310	Long	Bulky			X
17	KWS 9361	299	Late	290	Long	Balanced	X	X	X