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Comparing the performance of active and passive reflectance sensors to assess the normalized relative canopy temperature and grain yield of drought-stressed barley cultivars

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ABSTRACT

High-throughput precision phenotyping, using spectral reflectance measurements, has the potential to provide more information for making better-informed management decisions at the canopy scale in real time. Active and passive spectral reflectance sensors are available for ground-based remote sensing; however, they have not been compared in their performance for assessing the normalized relative canopy temperature (NRCT) and the grain yield of drought-stressed plants. In this study, five spectral passive and active reflectance sensors, including a hyperspectral passive sensor (HPS), a hyperspectral active sensor (HAS), an active flash sensor (AFS), the Crop Circle (CC) and the GreenSeeker (GS), were tested to assess the NRCT and grain yield of barley cultivars under mild and severe drought stress in 2012 and 2013. Simple linear regression and partial least squares regression models were used for analysing the spectral data. The results showed that the spectral indices of all sensors were more closely related to NRCT and grain yield under mild drought stress (R^2 up to 0.70, significant correlation at $p \leq 0.001$) than under severe drought stress (R^2 up to 0.53, significant correlation at $p \leq 0.001$). Closer relationships between three normalized water indices (NWI-1, NWI-3 and NWI-4) and NRCT and grain yield were obtained for the hyperspectral passive sensor compared to the same indices of the hyperspectral active sensor and the active flash sensor under both mild and severe drought stress. Multivariate analysis using partial least square regression improved the relationship (R^2 up to 0.77, significant correlation at $p \leq 0.001$) compared to the individual spectral indices and the single reflectance bands for each sensor. In conclusion, both the selection of adapted measurement devices and advanced statistical methods can improve assessments of NRCT and grain yield.

1. Introduction

Spectral and thermal high-throughput technologies have the potential to provide quick and precise measurements of important physiological and agronomic traits for crop phenotyping in breeding nurseries (Hatfield et al., 2008; Mistele and Schmidhalter, 2010; Gutierrez et al., 2010; Elsayed et al., 2011). Proximal remote sensing systems for phenotyping on the field scale can be based on passive and active reflectance sensing. Passive sensor systems depend on sunlight as a source of light in contrast to active sensors, which are equipped with light-emitting components that provide radiation in specific waveband regions. Therefore, active sensors are more independent of changing irradiation conditions (Kipp et al., 2014). Whereas passive sensors allow hyperspectral information to be obtained in the visible and near-infrared range currently, commercially available active sensors such as the GreenSeeker (NTech Industries Inc., Ukiah, California), the Crop Circle ACS-470® (Holland Scientific Inc., Lincoln, Nebraska) and an active flash sensor (AFS) (tec5 AG, Oberursel, Germany) are limited to comparatively few wavelengths according to the number and type of light sources and possible user-selectable filters (Erdle et al., 2011; Kipp et al., 2014). Active hyperspectral sensing allows for the evaluation and testing of the relationship of not yet identified wavelength combinations to relevant crop traits, which are nearly independent of the ambient environmental conditions (Erdle et al., 2011; Rischbeck et al., 2014), and has, therefore, been further tested in this study to investigate the relationship to the normalized relative canopy temperature and grain yield of drought stressed barley cultivars.

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Passive reflectance sensors have widely been used in the past to measure several canopy variables such as plant water status, biomass, leaf area index, nitrogen status or grain yield. Recently, active sensors have been used to estimate parameters such as the nitrogen status of wheat cultivars and maize hybrids (Tremblay et al., 2009; Shaver et al., 2010; Erdle et al., 2011; Winterhalter et al., 2013), the grain yield of wheat and maize (Inman et al., 2007; Marti et al., 2007), green biomass, the leaf area index and plant coverage in cereals (Trotter et al., 2008; Fitzgerald, 2010; Kipp et al., 2014).

Use of these sensors for identifying promising genotypes in a breeding program will be facilitated, if grain yield can be predicted before harvest (Royo et al., 2003). Early prediction of grain yield by spectral reflectance measurements prior to harvest could reduce phenotyping time and expenses compared to destructive measurements (Marti et al., 2007; Prasad et al., 2007).

In previous studies, several researchers suggested that the grain yield could be estimated using spectral reflectance during different growth stages (Peñuelas et al., 1997; Schmidhalter et al., 2001; Aparicio et al., 2002; Osborne et al., 2002; Babar et al., 2006; Marti et al., 2007; Prasad et al., 2007; Gutierrez et al., 2010); for example, the NDVI at the milk-grain stage was well correlated to the final wheat grain yield at two levels of nitrogen fertiliser application under rainfed and irrigated conditions. However, it was also observed that the NDVI $(R_{774}-R_{656})/(R_{774}+R_{656})$ was also reasonably correlated to the grain yield at the onset of stem elongation (Marti et al., 2007). The normalized water index 1 (NWI-1; $(R_{970}-R_{900})/(R_{970}+R_{900})$) and the normalized water index 2 (NWI-2; $(R_{970}-R_{850})/(R_{970}+R_{850})$), as well as the normalized water index 3 (NWI-3; $(R_{970}-R_{920})/(R_{970}+R_{920})$) and the normalized water index 4 (NWI-4; $(R_{970}-R_{880})/(R_{970}+R_{880})$) from passive reflectance sensor measurements demonstrated great potential at differentiating high- and low-yielding genotypes in advanced lines of spring wheat under well-irrigated, water-stressed and high-temperature conditions in diverse trials (Gutierrez et al., 2010). Lobos et al. (2014) found that the normalized NWI-3 and the normalized difference vegetation index NDVI $(R_{830}-R_{660})/(R_{830}+R_{660})$ were most closely related to the grain yield of wheat genotypes subjected to drought stress.

Prasad et al. (2007) found that the relationships of the grain yield of wheat cultivars with the water index (WI; (R_{970}/R_{900})) and the normalized water indices (NWI-1, NWI-2, NWI-3 and NWI-4) were stronger than with the red normalized difference vegetation index (RNDVI; $(R_{780}-R_{670})/(R_{780}+R_{670})$) and the simple ratio (SR; (R_{970}/R_{680})). They performed better at identifying superior genotypes, either at any individual growth stage or in a combination of growth stages under rainfed conditions. Babar et al. (2006) found that under reduced irrigation, near infrared radiation (NIR)-based indices (WI, NWI-1, and NWI-2) resulted in the highest levels of association with grain yield.

The crop water stress index (CWSI) or the normalized relative canopy temperature (NRCT) is an important method to assess the drought stress based on leaf or canopy temperature. The use of leaf or canopy temperature to detect the drought stress is based on the principle that a plant's stomatal closure takes place during drought stress, which results in a decrease of energy dissipation and an increase in plant temperature (Idso et al., 1981; Patel et al., 2001). The CWSI quantifies the combined effects of soil water, atmospheric, and crop conditions on the crop water status, which ultimately affects the grain yield of cultivars. Nielsen and Anderson (1989) found that the CWSI was well related to the stomatal conductance, leaf water potential, leaf transpiration rate, available soil water, and leaf CO_2 exchange rate in sunflower. Several studies reported that there was a good relationship between the CWSI and grain yield (Irmak et al., 2000; Kashefipour et al., 2006; Zia et al., 2012).

Few studies have tried to relate spectral indices with the CWSI and canopy temperature. Zarco-Tejada et al. (2013) found that the CWSI was well related to a normalized Photochemical Reflectance Index PRI_{norm} $((R_{570}-R_{531})/(R_{570}+R_{531})/(R_{800}-R_{670})/(R_{800}+R_{670})^{0.5}*(R_{700}/R_{670}))$ and weaker relationships were obtained with the vegetation index NDVI $(R_{800}-R_{670})/(R_{800}+R_{670})$ for vineyards at different measurement times.

Winterhalter et al. (2011) reported good relationships between the spectral index (R_{760}/R_{730}) and the canopy temperature (CT) for maize under irrigated and drought stress treatment. Observed associations between the NWI-3 and canopy temperature were consistent with the idea that genotypes with a better hydration status have a larger water flux and transpirative cooling (Gutierrez et al., 2010).

To the best of our knowledge, there is very little information available about the comparative assessments of the performance of passive and active sensing systems for assessing the grain yield and CWSI. Since the NRCT is similar to the CWSI, we preferred to the index "NRCT" in this study.

Therefore, the purpose of this work was to evaluate the performance of passive and active sensors to: i.e. (i) assess whether spectral indices can reflect changes in the NRCT of barley cultivars under drought stress conditions, (ii) assess the grain yield of barley cultivars under drought stress conditions, and (iii) compare the performance of spectral reflectance indices respective of the reflectance bands and the partial least square regression for retrieving such information from five spectral sensing systems by assessing the NRCT and grain yield of drought stressed barley cultivars.

2. Materials and methods

2.1. Field experiments and design

The field experiments were conducted at the Dürnast research station of the Technische Universität München in southwestern Germany (11°41′60″ E, 48°23′60″ N). Dürnast is characterized by a sub-oceanic climate, with mild cloudy winters and warm summers. The average yearly precipitation was 844 mm, and the average temperature was 8.3 °C. At the research station, two rain-out shelter facilities were used for conducting field trials under controlled drought stress. A rain-out shelter is a moving greenhouse mounted on tracks. Crops were grown under open sky, and only in case of rain does the shelter close to keep plants and the soil dry. There is a sensor that allows the rain-out shelter to move and cover the crops in case of light rain. The sensor is similar to a leaf wetness senor. The rain-out shelter was kept closed during the autumn and winter to keep the soil dry. Spring barley was sown on 17 April 2012 and 18 April 2013. According to the residual mineral nitrogen contents in the soil measured after winter, additional mineral fertiliser was applied up to a level of 130 kg N ha^{-1} before sowing in all trials. To reduce the lodging risk, especially of the historic cultivars, the growth regulator "Trinexapac" was applied at the initiation of the shooting (BBCH 31) in all trials.

Two types of experiments were conducted:

Mild drought stressed field trials were established in a randomized block design with five replicates in a rain-out shelter facility during the 2012 and 2013 seasons. The soil is a calcaric Cambisol consisting of silty loam. It has a field capacity of 42%$_v$, and the permanent wilting point is at 20%$_v$. The rooting depth of spring barley in this soil was assessed to be at 150 cm based on former soil sampling (Rischbeck et al., 2014). The rain-out shelter was kept closed during autumn and winter to keep the soil dry. Gravimetric soil samples were taken until a depth of 150 cm at the start and the