ACTIVE SENSOR PERFORMANCE – DEPENDENCE ON MEASURING HEIGHT, DEVICE TEMPERATURE AND LIGHT INTENSITY

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ABSTRACT

Spectral remote sensing is widely used for land-use management, agriculture, and crop management. Spectral sensors are most frequently adopted for site-specific fertiliser applications and, more recently, are also being used for precision phenotyping. With the use of active sensors in the field, it is inevitable that they will be used under varying ambient conditions and with varying crop distances, but it remains unclear how these factors affect the performance of these sensors. This study was conducted to determine whether changes in light intensity, ambient temperature, and measuring distance influence the accuracy of the spectral reading from three different active sensors (Ntech GreenSeeker RT100, Holland Scientific CropCircle ACS 470, YARA N-Sensor ALS). We found that the readings were influenced by the distance to the crop target and optimised measuring distances to crop canopies that enable stable sensor outputs were determined. In addition, the device temperature was shown to influence the sensors' readings as well. In contrast, varying light conditions, including nocturnal usage, did not affect the performance of the sensors in agreement with the manufacturers' claims that sensor performance is independent of ambient light conditions. Given the preliminary nature of these investigations, we conclude that further research into optimising the performance of the active sensors with respect to the sensor-target distance and the device's temperature are needed to improve the application of this technology under field conditions.

Keywords: precision farming, nitrogen application, nitrogen fertilization, phenotyping

INTRODUCTION

Generally, little is known regarding the effects of external and internal factors that influence the performance of active sensors, and very few efforts have been made to investigate these effects, such as the study of Kim et al. (2010), who studied the effect of varying temperature or light intensity on the performance of the active sensor GreenSeeker. Such knowledge is indispensable, however, and is particularly important when only small differences in plant canopies or between cultivars are to be detected.

The factors to be known include the effects of sensor-target distances and the resulting field of view depending on the sensors' positioning height (footprint size). Differences in plant height in the field lead to changes in sensor-target distances at fixed sensor positions, which may particularly affect handheld operating systems, where constant distances are not easy to maintain. Still, it is unclear whether and to what degree varying sensor-target distances affect the sensors' performances. Although the manufacturers of active sensors provide recommendations for optimum measuring heights, it has not been demonstrated how the sensors' output values vary when the distance to the target changes during measurement, even within the recommended distances. Varying sensor-target distances have been adopted in different studies, and some of them have been outside the manufacturers' recommended distances. For example, the active sensors GreenSeeker and CropCircle were used at measuring heights from 25 to 100 cm and at distances of 150 cm to 250 cm (Scharf et al., 2007; Roberts et al., 2009; Fitzgerald, 2010). Another study recommended that the GreenSeeker sensor be used at distances of 60 to 110 cm and that the CropCircle be used at distances from 80 to 110 cm (Solari, 2006). The N-Sensor ALS can be used at a distance of 140 cm (Portz et al., 2011) or more.

When evaluating sensor-target distances, it must be considered that emitted and reflected light by plant leaves follows the inverse square law, which means the light intensity decreases four times when the measuring distance doubles. This relation illustrates that spectral readings of a single waveband change with varying distances to the target. If it is assumed that each waveband changes in the same dimension, the effect could be excluded by building spectral indices of two wavelengths. This assumption has not been substantiated by previous studies or suppliers' recommendations and has to be reviewed.

Other ambient factors that could affect the sensor performance are temperature and solar radiation/illumination. Solar radiation and air temperature may affect the temperature of the sensor itself. On measurement days with changing cloudy or sunny conditions, the device temperatures may vary widely. For the application of active sensors in the field for precision-farming purposes, it is essential to determine whether and to what degree diurnal variations in temperature and light intensity might affect spectral readings. Information regarding the effect of temperature or light intensity is rarely reported by sensor suppliers, and there are currently no associated relevant studies. In contrast, the dependency of laser-induced chlorophyll fluorescence on ambient light and temperature conditions was reported by Thoren et al. (2010). It is conceivable that such effects may also occur within other active sensor systems.

MATERIAL AND METHODS

Active Sensors and experimental design

Three different active sensors were used in this study: a GreenSeeker RT100 (Ntech Industries, Ukiah, CA), a CropCircle ACS 470 (Holland Scientific, Lincoln, NE), and an Active Flash Sensor (AFS) similar to the N-Sensor ALS (Yara International ASA, Oslo, Norway), but limited to a single sensor and USB interface (Mistele and Schmidhalter, 2010).

All measurements were performed in a temperature- and light-controlled climate chamber using metal halide lamps as a light source (MT 400DL, Osram, Munich, Germany). The airflow passed uniformly upward through the entire walk-in area to preclude the lamp heat. A green light-proof velvet tissue (2.5 m^2) mounted on a wooden board was used as a reference surface for the reflectance measurements. To enable a uniform measuring area and to avoid creases, the tissue was tightly stretched over the board. Thus, identical spectral readings at each point of the tissue could be measured. The sensors were installed on a mobile platform that allowed varying the measuring distances. Spectral indices were selected to observe the influence of modified external conditions such as distance, temperature, and light intensity. NDVI was chosen for the GreenSeeker and R_{760}/R_{730} for the CropCircle and AFS because they are regularly used to construe the spectral readings of these sensors.

Reflectance Measurements

Sensor readings were recorded at incrementally increasing/decreasing heights of 10 cm, starting at 10 cm and ending at 200 cm in the nadir position to detect effects of varying measuring distances. The readings were averaged over 10 seconds and directly stored to a notebook via USB.

To evaluate the effect of changing device temperature, the climate chamber was programmed to heat up from 5°C to 35°C during another measurement. Continuous sensor readings of the measuring target were recorded while the climate chamber heated up. The device temperature inside each sensor was measured with thermal detectors, which are standard components in the GreenSeeker and in the AFS. A thermal detector was also installed for the CropCircle. The entire measurement required approximately 60 minutes. Meanwhile, the course of the device temperature and recorded sensor reflectance values were recorded via USB to the notebook.

To illustrate the effect of external conditions, the measured values were compared to spectral information obtained from a field experiment in which different nitrogen application rates of 10, 100, 160, and 220 kg N/ha were applied to winter wheat (*Triticum aestivum L.*). Within this experiment, the winter wheat variety “Tommi” was scanned with all active sensors (Erdle et al., 2011), and the respective index values were calculated. By comparing such data with calculated sensor deviations obtained from, e.g., varying device temperatures, the degree to which deviations from recommended nitrogen fertilisation rates might occur when the device temperature shifts could be illustrated.

The sensor dependence to varying light conditions was investigated by adjusting five different light intensity levels in the climate chamber at 0, 100, 270, 410, and 580 μmol m^2*s^{-1}. At each illumination level, the sensor readings were recorded before the light intensity was increased to the next level.

RESULTS AND DISCUSSION

Sensor-target distance

Measurements at sensor-object distances from 10 cm to 200 cm partly resulted in highly variable spectral reflectance values. The variability became most markedly manifest at the low measuring heights (Fig. 1). The reflectance values obtained from distances lower than 50-70 cm – depending on the sensor – showed a strong variation in the displayed indices and for each single wavelength. A specific range existed for each sensor, where the common sensor indices remained nearly stable. These ranges were quite different for each sensor. Fig. 1 shows that the NDVI, provided by the GreenSeeker reflectance data, did not change much at measuring heights from 70 to 110 cm. For the AFS sensor, the R_{760}/R_{730} index was constant from 50 cm to 200 cm. For the CropCircle, the same index did not vary significantly from a distance of 100 to 140 cm.

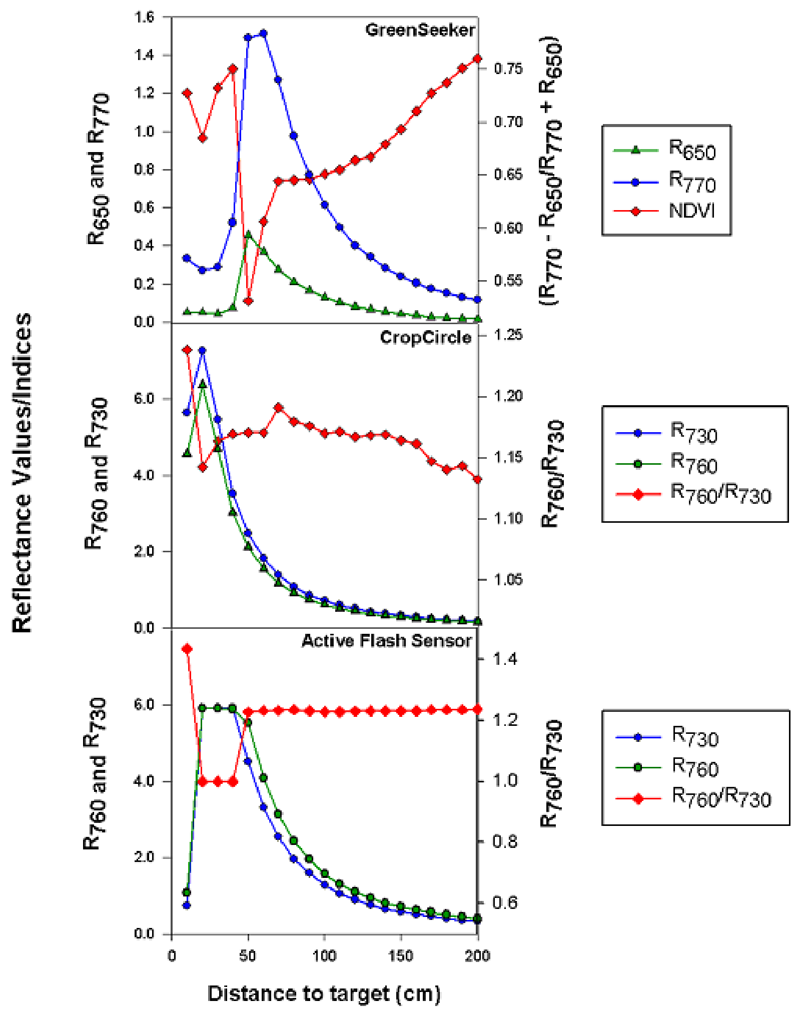

Figure 1: Sensor output values (indices and wavelengths) of three active sensors dependent on varying measuring distances (10-200 cm) to a green tissue reference target.

Within this tolerance range, which is unique for each sensor, the effects of changing sensor-target distances on spectral indices are nearly non-existent because the sensor output values are stable even though the measuring height varies. This information is crucial for the in-field application of active sensors. Table 1 compares the manufacturers' recommendations concerning the optimum distance to the target with the experimental results. It is evident that the retrieved distances are more or less similar to the manufacturers', but in the case of the CropCircle, suggested values up to 213 cm are outside the region where the index value remains stable. With knowledge of the optimum measuring heights, it is possible to adapt the sensor-to-target distance to specific plant heights. Taking into account that heterogeneous plant populations in the field naturally exist, this information should be considered to provide enhanced quality when assaying crop parameters non-destructively. Handheld sensor systems may be particularly prone to varying distances and may require increasing attention to maintain measurements within optimised distances. Mobile sensor platforms allow for fixed distances but may also require adjustment to varying plant heights.

Optimum distances to the target will be linked to the problem of how dense the canopy is. The penetration depth of the sensor's light signal will differ between sparse or dense canopies. Tracking optimum distances will be more difficult in row crops if not directly measured above the row and with exclusion of the inter-row compared with dense stands of non-row crops. For row crops such as maize, it is difficult to determine from which leaf levels the reflectance signals are captured by the sensors. Differences are also expected between cultivars that have either planophil or erectophil leaves, and varying information may also be obtained at different growth stages. The contribution of different leaf levels to the output signal may therefore vary depending on the plant architecture and the growth stage. The mixing of information may influence the interpretation of the data and confound differences recorded among cultivars. These aspects will require further intensive investigations. The influence of varying distances is probably augmented in taller row crops compared with denser and shorter cereal stands. It may even be difficult to identify optimum measuring distances for active sensors using real plant populations (Solari, 2006). These factors stress that further investigations are necessary to evaluate what role the leaf architecture plays and how deep active sensors signals penetrate into the canopy.

Table 1: Comparison of optimum distances to the reference target investigated in this study and manufacturer´s advices for active canopy sensors.

	Optimum distance to target	Manufacturer´s instruction
GreenSeeker (GS) RT100	70 – 110 cm	81 – 122 cm
CropCircle (CC) ACS470	30 – 160 cm	25 – 213 cm
Active Flash Sensor (AFS)	50 – 200 cm (and more)	not specified

Device temperature

An increase of ambient temperature led to a simultaneous increase in the device temperature of each sensor. After a while, a constant temperature value was reached. The analysis of the device temperature profile of each sensor showed a linear relationship between the device temperature and sensor output values in terms of common reflectance indices (Fig. 2). Increasing the device temperatures of the GreenSeeker caused decreases in NDVI values, while for the CropCircle and the AFS, the R_{760}/R_{730} index increased when the device temperature increased.

The challenge of this phenomenon is to answer whether the temperature affects the light source or the detector's performance. That the output values of each wavelength change differently suggests that the light source reacts sensitively to

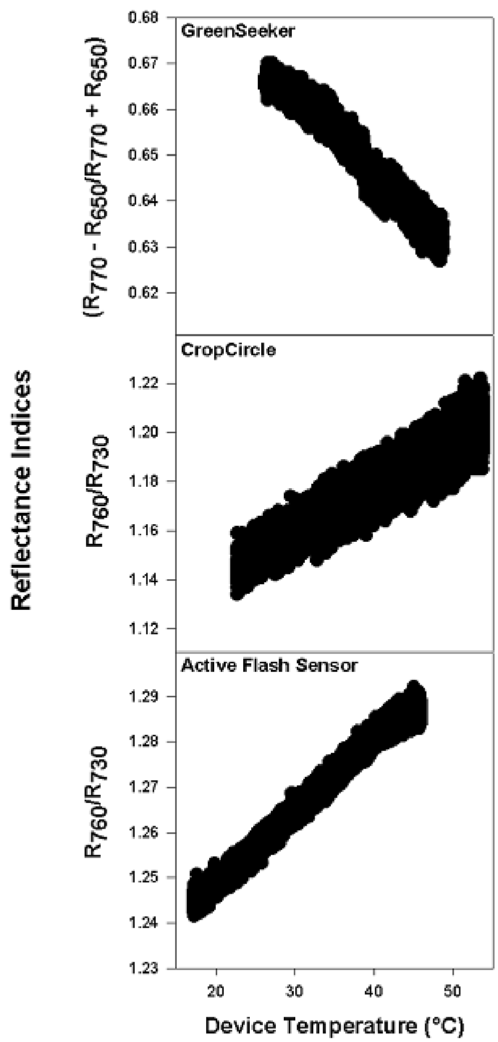

Figure 2: Variation of sensor indices of three active sensors at varying device temperatures.

changing temperature conditions. In the case of the GreenSeeker, which captures the light of every wavelength with one single detector, it becomes apparent that the device temperature does not affect the detector's performance. Otherwise, the reflectance values of each wavelength should show the same shift. Thus, the temperature affects the light quality of several light diodes (one diode for one wavelength) in different ways.

Consequently, it must be considered that active canopy sensors are influenced by ambient temperature, which is caused by solar radiation and vary depending on the diurnal course. Long-term measurements over a period of a couple of hours are susceptible to such influences because, during the course of a day, sunny and cloudy conditions and changing daytime temperatures may affect the device temperature.

The linear relationship between the indices and device temperature made it possible to display the index variation with great accuracy when the device temperature shifted by ±1°C (Tab. 2).

Table 2: Calculation of variation in sensor specific indices for temperature shifts of 1°C.

Active Sensor	Δ index/°C
GreenSeeker (NDVI)	± 0.0022
CropCircle (R_{760}/R_{730})	± 0.0028
Active Flash Sensor (AFS) (R_{760}/R_{730})	± 0.0018

This index variation was compared with the experimental data of a field trial with the winter wheat cultivar "Tommi" under four different nitrogen application rates (0, 100, 160, 220 kg N ha^{-1}). The results from this field experiment (Fig. 3) show typical spectral reflectance values of plots that are indicative of low or high nitrogen application rates.

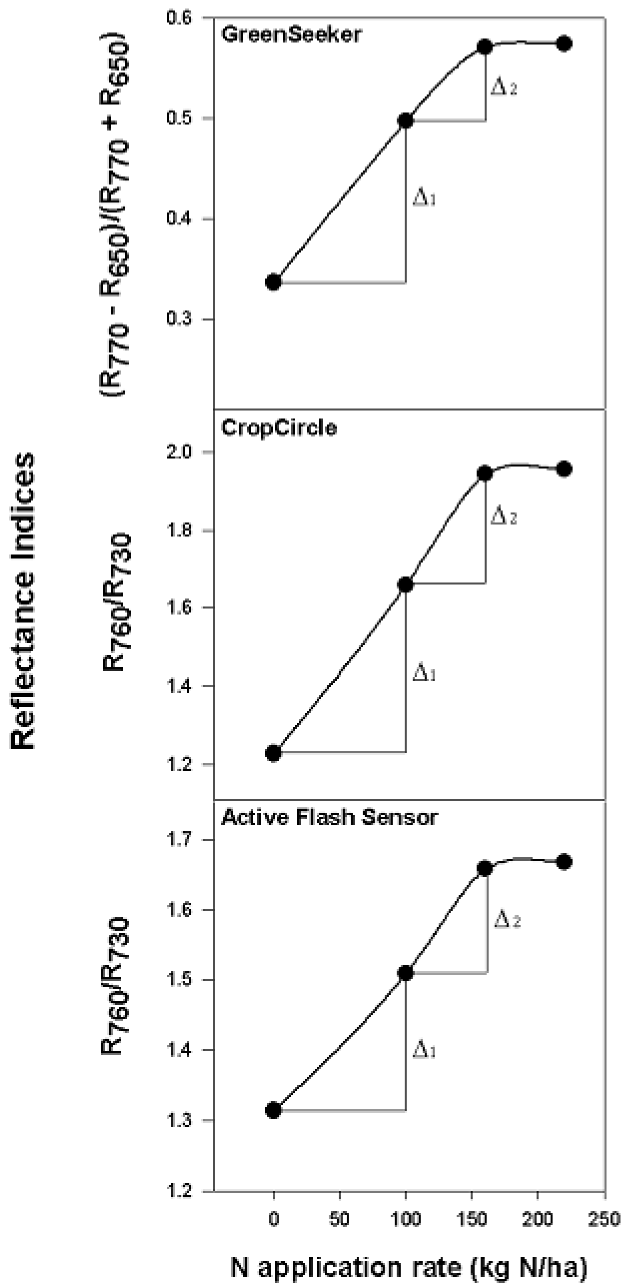

Figure 3: Spectral readings from field experiments with the winter wheat cultivar "Tommi" with different nitrogen application rates of 0, 100, 160, and 220 kg N/ha. Differences between the first three nitrogen application rates are displayed as Δ1 and Δ2.

While the differences in spectral index values of 0 N, 100 N, and 160 N are obviously strong, the index values are not significantly different due to the saturation effects in plots receiving high amounts of nitrogen (100-120 kg N ha^{-1}). A mean index variation per kg N ha^{-1} was calculated in relation to the index differences between each N level (Δ_1, Δ_2) (Tab. 3). By dividing the device temperature shift of ±1°C (Tab. 2) by the mean index variation per kg N ha^{-1}, it can be shown how strongly a temperature shift of 1°C may affect the accuracy of spectral information from plots receiving different nitrogen application levels expressed as kg N ha^{-1} (Tab. 3). For each °C of changed device temperatures, the reflectance data would produce nitrogen errors rates (Tab. 3) of approximately 1.8 kg N for the GreenSeeker, 0.65 kg N for the CropCircle, and approximately 1 kg N for the AFS up to a nitrogen application level of 160 kg N ha^{-1}. Differentiating nitrogen doses between 160 and 220 kg N ha^{-1} by spectral data is nearly impossible if the device temperature is not stable because the difference between the index values is extremely low and even a small change in temperature could lead to enormous misinterpretations in the applied doses of nitrogen.

Table 3: Analysis of a field experiment in which one wheat variety ("Tommi") was fertilized at four different nitrogen application rates (0, 100, 160, and 220 kg N/ha). Each plot was measured with three active sensors and index variations per kg N ha^{-1} were calculated. In combination with index variations per °C device temperature shift (table 3) potential error rates in kg N ha^{-1} could be estimated for device temperature variation of 1°C.

		Δ index/ kg N ha^{-1}	Δ index/°C	Error rate (kg N ha^{-1}/°C)
GreenSeeker (NDVI)	Δ1: N0 → N100	0.00161	± 0.0022	± 1.37
	Δ2: N100 → N160	0.00123	± 0.0022	± 1.79
	Δ3: N160 → N220	0.00005	± 0.0022	± 44
CropCircle (R_{760}/R_{730})	Δ1: N0 → N100	0.00431	± 0.0028	± 0.65
	Δ2: N100 → N160	0.00475	± 0.0028	± 0.59
	Δ3: N160 → N220	0.00018	± 0.0028	± 15.6
AFS (R_{760}/R_{730})	Δ1: N0 → N100	0.00195	± 0.0018	± 0.92
	Δ2: N100 → N160	0.00248	± 0.0018	± 0.72
	Δ3: N160 → N220	0.00015	± 0.0018	± 12

Kim et al. (2010) reported that there is no significant impact of device temperature on the performance of the GreenSeeker, but this study shows that such impacts may occur. If small differences between plant canopies are measured, it is especially crucial to exclude device temperature effects.

Light intensity

No external effect of ambient light intensities could be shown. The output values did not change for different light intensities (Fig. 4). Only marginal and very small variations could be detected.

This "non-effect" of varying light conditions can be explained by the technical features of active sensors. Active sensors emit their own light source at one or more wavelengths, which are reflected by the target. The detector inside the sensor measures the incoming reflectance, and the electrical circuits are able to filter and differentiate between the emitted "artificial" light and the ambient light originating from the sun. Thus, the assumption that active sensors are susceptible to varying light conditions as observed for other sensor systems, such as laser-induced chlorophyll fluorescence (Thoren et al. 2010), cannot be confirmed. Instead, the results agree with other experiments in terms of the influence of light on sensor performance (Solari et al., 2004; Jasper et al., 2009; Kim et al. 2010).

External light could be seen to have a temperature effect on the accuracy of active sensors because increase in light generates higher temperatures, which again affects the device temperature and, consequently, the sensor output data, as shown above.

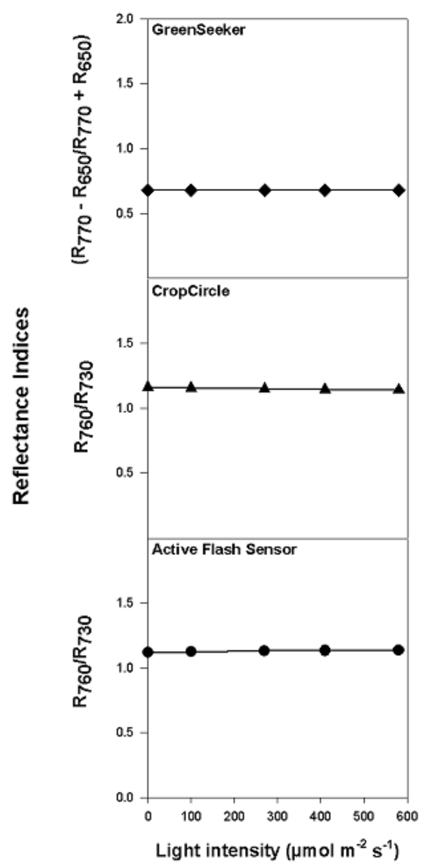

Figure 4: Spectral indices of three active sensors under varying light intensities.

CONCLUSIONS

The aim of this study was to evaluate whether ambient factors affect the accuracy of three different active canopy sensors. Active sensors can work completely independently of bright daytime and dark night-time conditions. Varying device temperatures were found to considerably influence the performance of all sensors in this study. The common indices of each sensor show a linear response to increasing temperature. If not considered and corrected, changing temperatures can lead to misinterpretations when analysing the reflectance values obtained under field conditions.

To enable accurate field measurements with active sensors, the optimum distance to the plant canopy must be investigated and adjusted for each sensor. A small range of measuring heights exists where the sensors generate stable reflectance data. However this work should be expanded to include comparable measurements using real plant canopies to determine from where the signals are derived, how deeply and effectively the sensor light penetrates the canopy and from which distances it is received by the active sensors as recently shown for a passive reflectance sensor by Winterhalter et al. (2012).

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