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The performance of active spectral reflectance sensors as influenced by measuring distance, 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, increasingly, 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 active sensors' performance. 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). The distance between sensor and target surface was the major factor to be considered, depending on the sensor type. Optimised measuring distances to crop canopies that enable stable sensor outputs were determined from 10 to 200 cm sensor–object distance (GreenSeeker: 70–140 cm, CropCircle: 30–200 cm and ALS N-Sensor: 50–200 cm) and compared to manufacturer's recommendations for correct use of the sensors. In addition, the device temperature had variable results depending on sensor and spectral index. In contrast, varying light conditions, including nocturnal usage, hardly affected 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, further research into optimising the sensor performance with respect to the measuring distance and the device's temperature are needed to improve the application of this technology under field conditions.

1. Introduction

Active sensors are increasingly being used in precision farming to convert spectral information directly into fertilisation recommendations (Dellinger et al., 2008; Barker and Sawyer, 2010), thereby enabling a cost-effective, site-specific application of fertilisers (Hatfield et al., 2008; Scharf et al., 2011). Different active sensors have been developed for such purposes. Whereas handheld systems are suitable for taking stationary "spot" samples (Govaerts et al., 2007; Verhulst et al., 2009), tractor-mounted sensors can be used for on-the-go precision farming (Mayfield and Trengove, 2009; Reusch, 2004; Tremblay et al., 2009). A related emerging field is the application of proximal high-throughput phenotyping as a non-invasive method to determine various plant characteristics in plot experimentation or for breeding purposes (Erdle et al., 2011; Schmidhalter, 2005; Thoren and Schmidhalter, 2009).

Active sensors differ from passive sensors insofar that the light reflectance of plants, soil, or other surfaces is measured based on light emitted in one or more specific wavebands from the sensor itself rather than from ambient light. Although active sensors are independent of solar radiation (Jasper et al., 2009; Solari et al., 2004), the choice of light source (e.g., LEDs or Xenon flash) and viewing angle (e.g., nadir or oblique) can still have important implications. For instance, the light source in combination with optical filters is crucial for the detected light and emitted wavebands. In addition, the measuring area (footprint size) is specific for each sensor and varies with distance. The footprint size depends inter alia on the sensor's construction because the light signal is physically collimated, resulting in different viewing angles. Thus, at a given viewing angle, the footprint size changes according to the measuring distance, and the area monitored by the sensor also changes simultaneously. The footprints of several commercially available sensors vary from oval (CropCircle ACS 470) to circular (N-Sensor ALS) to elongated (GreenSeeker RT100) types.

In addition, other potentially important factors that might affect the performance of active sensors include the measuring distance and the resulting field of view depending on the sensors' positioning height (footprint size). Even with fixed sensor positions, differences in plant height in the field can change the measuring distances at fixed sensor positions. Handheld operating systems, where constant distances are not easy to maintain, will be more prone to such errors. Although the manufacturers of the active sensors recommend optimum measuring distances, it has not been

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demonstrated how the sensors' output values vary when the distance to the target changes during measurement, even within the recommended distances. Despite this, varying measuring distances have been adopted in different studies and some of the distances have been outside the manufacturers' recommended distances of 81–122 cm for GreenSeeker and 25–213 cm for CropCircle (Table 1). For example, the GreenSeeker and CropCircle were used at measuring distances from 25 to 100 cm and 150 cm to 250 cm (Fitzgerald, 2010; Roberts et al., 2009; Scharf et al., 2007), although another study recommended distances of 60–110 cm for the CropCircle and 80–110 cm for the GreenSeeker (Solari, 2006). By contrast, the N-Sensor ALS can be used at distances of 140 cm (Portz et al., 2012) or more. However it is challenging to determine proper measuring distances between sensor and plant canopies considering that the penetration depth of the sensor signal is unknown.

When evaluating measuring distances, it must be considered that emitted light from a point source follows the inverse square law, which means the light intensity decreases four times when the measuring distance doubles. Thus, the spectral readings of a single waveband will change with varying distances to the target (Holland et al., 2012). Assuming that single wavelengths are sensitive to changing distances, a distance effect could be excluded by building spectral indices of two wavelengths. Thus, enabling spectral measurements, which are independent of varying distances, requires uniform changes in the reflectance magnitude of each wavelength. However, the stability of spectral indices with respect to measuring distance has not been tested by previous studies or suppliers' recommendations.

Other ambient factors that could affect the sensor performance are temperature and solar radiation/illumination. Both solar radiation and air temperature can affect the temperature of the sensor itself such that the device temperature may vary widely on measurement days with changing cloudy or sunny conditions. For the successful 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. However, information regarding the effect of temperature or light intensity is rarely reported by sensor suppliers, and there are currently no associated relevant studies. Given the dependency of an active sensing system based on laser-induced chlorophyll fluorescence on ambient light and temperature conditions (Thoren et al., 2010), it remains to be tested whether such effects may also occur for other spectral reflectance sensor systems.

Despite the obvious reliance of the performance of the active sensors, only little research has been done to assess the potential effect of external and internal factors on the active sensors' performance. An exception is the study of Kim et al. (2010), who studied the effects of varying temperature and light intensity on the performance of the active sensor GreenSeeker. However, such general knowledge is indispensable, particularly when only small differences in plant canopies or between cultivars need to be detected and might be obscured by inherent measuring errors of the devices. Therefore we analysed the impact of three external factors (measuring distance, device temperature, and amount of ambient light) on the performance of three different active sensor systems (NTech GreenSeeker RT100, Holland Scientific CropCircle ACS 470, YARA N-Sensor ALS). Our findings will be an important initial step in assessing any inherent limitations of active sensor technology under field conditions as well as potentially suggesting practical solutions to these problems.

2. Materials and methods

2.1. Active sensors used

Three different active sensors were investigated in this study: a GreenSeeker RT100 (NTech Industries, Ukiah, CA), a CropCircle ACS 470 (Holland Scientific, Lincoln, NE), and an Active Flash Sensor (AFS). The AFS is similar to the N-Sensor ALS (Yara International ASA, Oslo, Norway) except for being limited to a single sensor and USB interface (Mistele and Schmidhalter, 2010) and being used in the vertical instead of an oblique orientation. The former is to be preferred for measurements conducted on the small-scale plot level and allows for a direct comparison to the other tested sensors. Both orientations had previously been tested and found to deliver reliable results in both orientations. The mode of operation is generally similar among all three sensors, each of which contains a light source that emits specific light energy, photodetectors that collect the reflected light, and electronic filters that remove background reflections. Differences amongst the three systems concern the light source itself, the pulsation of the emitted light and the detector system.

The GreenSeeker RT100 possesses two separate light-emitting diodes (LEDs) emitting modulated light in either the near infrared (NIR, 770 nm) or the red region (650 nm) of the spectrum (see Fig. 1); the wavelengths are fixed and cannot be changed. The LEDs alternate their pulses, with each emitting 40 light pulses in 1 ms (= 40 kHz) before pausing for the other LED. A single silicon photodiode detector captures the reflected light of both LEDs. The most common index that can be generated by using the GreenSeeker's wavelengths is the normalised difference vegetation index (NDVI = $(R_{770} - R_{650})/(R_{770} + R_{650})$), which can be used to estimate the photosynthetic area (biomass) or N-uptake of plant canopies.

A single LED is implemented in the CropCircle ACS 470, which with the use of PolySource light source technology (Holland Scientific, Lincoln, NE) is able to emit polychromatic light in wavelengths from 430 nm to 850 nm (Fig. 1). To split the light signal into three different channels, optical interference filters are installed in front of the detector to regulate the incoming light reflectance and to enable the user to select the desired wavelengths. In this study, filters for 670, 730, and 760 nm were used. For the detection of the incoming reflectance, the CropCircle is equipped with a three-channel silicon photodiode array with a spectral range of 320–1100 nm (Holland-Scientific, 2008). The signal output rate for the CropCircle sensor is programmable within a range of 1 to 100 measurements per second. Compared with the GreenSeeker, the Crop Circle supports a broader range of plant indices

Table 1
Optimum distances to the reference target as determined in this study compared to the manufacturer's recommendations for three active canopy sensors and their field of view (FOV) at 1 m measuring height.

Sensor device	Optimum distance to target	Manufacturer's recommendation	FOV (at 1 m measuring height)
GreenSeeker NDVI	70–140 cm	81–122 cm	~60 cm
GreenSeeker (R_{770}/R_{650})	70–110 cm		
CropCircle (R_{760}/R_{730})	30–200 cm	25–183 cm	~ 54 × 25 cm
CropCircle NDVI	30–200 cm		
Active Flash Sensor	50–200 cm (and more)	Not specified	Not specified