# COMPARISON OF ACTIVE AND PASSIVE SPECTRAL SENSORS IN DISCRIMINATING BIOMASS PARAMETERS AND NITROGEN STATUS IN WHEAT CULTIVARS

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## ABSTRACT

Several sensor systems are available for ground-based remote sensing in crops. Vegetation indices of multiple active and passive sensors have seldom been compared in determining plant health. This study was aimed to compare active and passive sensing systems in terms of their ability to recognize agronomic parameters. One bi-directional passive spectrometer (BDS) and three active sensors (Crop Circle, GreenSeeker, and an active flash sensor (AFS)) were tested for their ability to assess six destructively determined crop parameters. Over two years, seven wheat (*Triticum aestivum* L.) cultivars were grown with varying nitrogen supplies. At three developmental stages, the crop reflectance was recorded and sensor-specific indices were calculated and related to N levels and the crop parameters, fresh weight, dry weight, dry matter content, N content, aboveground N uptake, and the nitrogen nutrition index. The majority of the tested indices showed high $r^2$-values when correlated with the crop parameters. However, the accuracy of discriminating the influence of varying N levels differed between sensors, growing seasons and developmental stage. Visible- and red light-based indices, such as the NDVI or simple ratio ($R_{780}/R_{670}$), tended to saturate with increasing crop stand density. The best relationships were found for N-related biomass parameters with $r^2$-values of up to 0.96. The near infrared-based index $R_{760}/R_{730}$ was the most powerful and temporarily stable index indicating the N status of wheat. This index was delivered by the BDS, Crop Circle, and AFS. Active spectral remote sensing is more flexible in terms of timeliness and illumination conditions, but to date, it is bound to a limited number of indices. At present, the broad spectral information from bi-directional passive sensors offers enhanced options for the future development of crop- or cultivar-specific algorithms.

**Keywords:** precision farming, nitrogen content, nitrogen uptake, phenotyping, vegetation indices, active sensor, passive sensor

## INTRODUCTION

Spectral remote sensing is a widely used in plant production and crop management. For crop management on the field scale, ground-based systems are advantageous, as seen by their ability to deliver instantaneous information that can be applied online (Pinter et al., 2003; Hatfield et al., 2008). Spectral sensors work either passively or actively. Passive sensor systems depend on sunlight as the source of light, whereas active sensors are equipped with light-emitting components, thus, being more independent of changing irradiation conditions (Hatfield et al., 2008). However, both types of sensor systems, passive and active, measure the amount of light reflected by the crop by converting the light signal into electrical output. Light can be measured in the visible (VIS, app. 400-700 nm) and near infrared (NIR, app. 700-2500 nm) ranges. Reflectance in the VIS depends on the chlorophyll content in leaves (Campbell, 2002). Leaf chlorophyll concentration is linearly related to leaf N concentration (Lamb et al., 2002). NIR reflectance is dependent on the structure and interspaces of the mesophyll cells (Campbell, 2002) and is related to leaf N and biomass (Shaver et al., 2010).

The simple ratio (SR) and the refined normalised difference vegetation index (NDVI), both calculated from measurements of the reflected light from the red and NIR bands, have long been used as indirect measurement of biomass and crop yield, including that of wheat (Raun et al., 2001; Pinter et al., 2003; Prasad et al., 2007). However, the NDVI tends to become saturated when the leaf area index (LAI) is exceeding values of 2 - 3 (Aparicio et al., 2002; Mistele et al., 2004; Heege et al., 2008). A number of other indices have been developed to estimate crop parameters such as N content and aboveground N uptake of wheat (Li et al., 2008; Mistele and Schmidhalter, 2010b; Strenner and Maidl, 2010). The red edge inflection point (Guyot et al., 1988) and several NIR/NIR indices have been proven to offer more reliable signals in high biomass-producing areas (Mistele et al., 2004; Heege et al., 2008; Reusch et al., 2010). However, some indices concentrate on the visible range of the reflection spectrum and thus are primarily influenced by the absorbance capacity of chlorophyll. VIS-based indices are used to identify green soil cover and photosynthetic capacity (Peñuelas et al., 1995; Gamon et al., 1997; Aparicio et al., 2000).

Several commercial sensors, both passive and active types, are available at present. In practice, both systems provide either identical or similar indices. The GreenSeeker (NTech Industries Inc., Ukiah, California) is a commercially available active device using light-emitting diodes (LEDs) as a light source. The GreenSeeker has been used to determine nitrogen status in corn and wheat (Hong et al., 2007; Guo et al., 2008; Tremblay et al., 2009; Shaver et al., 2010). Another active sensor is the Crop Circle ACS-470® (Holland Scientific Inc., Lincoln, Nebraska), which works similarly to the GreenSeeker system and has been used to detect biomass and leaf are in cereals (Shearman et al., 2005; Trotter et al., 2008; Fitzgerald, 2010).

Active and passive sensors been compared to reproduce vegetation indices and their use in crop management. Sensor outputs from several systems have either been interrelated (Tremblay et al., 2009; Sudduth et al., 2010) or different indices from a single device have been related to crop parameters (Trotter et al., 2008; Mistele and Schmidhalter, 2010a; Strenner and Maidl, 2010). In most studies, no direct relationship between various sensors´ output, either active or passive, and quantitative crop parameters have been shown. Thus, the following objectives

have been proposed: Can multiple reflectance indices of passive or active sensor systems be compared in their ability to assess agronomic parameters? Therefore, it is not sufficient that indices correlate well with the range of N application levels; it is just as important whether these indices accurately reflect the status of the crop. This status can only be verified by destructive samplings.

The aim of this study was therefore to compare passive and active spectral sensors with each of several reflectance indices i) to identify the crop nitrogen status and ii) to evaluate the quality of their relationship to crop parameters in the field.

## MATERIAL AND METHODS

### Study site and biomass sampling

The field experiments were conducted at a research station of the Technische Universität München in southwestern Germany (11°41´60" E, 48°23´60" N). The soil was mostly homogeneous Cambisols of silty clay loam. The fields are located in a hilly region sloping northwards with approximately 0.09 m m$^{-1}$. Average yearly precipitation is approximately 800 mm, the average temperature is 7.5 °C and yields vary between 6 and 10 Mg per hectare. In 2009, the soil was sampled for P (20 mg P2O5 per 100 g soil) and K (23 mg K2O per 100 g soil) analysis to ensure an adequate supply of these macronutrients. Soil nitrate at re-greening was determined by a simplified soil nitrate quick-test method (Schmidhalter, 2005) indicating soil $NO_3$-N levels of 45 and 52 kg in 2009 and 2010, respectively.

In the growing seasons 2009 and 2010, seven winter wheat (*Triticum aestivum* L.) varieties, Tommi, Solitär, Impression, Pegassos, Ludwig, Cubus, and Ellvis, were sown. Four N supply levels were applied in both years, including rates of 0, 100, 160, and 220 kg N ha$^{-1}$. Fertiliser application was split similar to farmers' practice and done at the stem-elongation, booting and heading stages. Fertiliser application at heading is used to increase the quality of small cereals. No fertilizer was applied pre-planting. The experimental plots were 2 m by 15 m in space.

Biomass sampling was performed at the Zadoks growth stages (ZS) 3, 4, and 6 (Zadoks et al., 1974). A green forage chopper was used to cut an area 2 m wide by 3 m long from each plot (Thoren and Schmidhalter, 2009). Biomass samples were put into plastic bags, immediately weighed, and then dried. Shoot fresh weight (FW) and Shoot dry weight (DW) (kg ha$^{-1}$) were recorded and dry matter content (DM in %) calculated. The N content (g N g$^{-1}$ dry weight) was detected with mass spectrometry using an Isotope Radio Mass Spectrometer with an ANCA SL 20-20 preparation unit (Europe Scientific, Crewe, UK). Therewith, the aboveground N uptake (kg ha$^{-1}$) was calculated as the shoot DW multiplied by the total N content. The Nitrogen Nutrition Index (NNI) was determined by:

$$NNI = N_{act} / N_c \qquad \text{(Lemaire and Gastal, 1997)}$$

where $N_{act}$ is the actual N content and $N_c$ is the critical N content of the shoot dry weight described by the equation

$$N_c = 5.35 \text{ (shoot dry weight [t ha}^{-1}]^{-0.442}) \qquad \text{(Justes et al., 1997)}$$

based on investigations in winter wheat. The critical N content is assumed to be nearly constant at a mean value of 4.4 % for shoot dry weight values between 0.2 and 1.55 Mg ha$^{-1}$ (Justes et al., 1997). We calculated the critical N content for each plot to reflect the individual N status of the treatments whereas the relationship between spectral measurements and plant parameters is assumend to be represented by a continuous function (Mistele and Schmidhalter, 2008a).

**Spectral reflectance measurements**

Passive and active optical sensor systems were mounted on a measuring plattform which was driven from west to east to avoid any shading of the measuring unit. The measurements were taken before or at noon to provide the best possible conditions for passive recordings. Independent of the sensor system, all devices measured at nadir direction of 1.40 m above the ground across the season. The sensor outputs were co-recorded with the GPS coordinates. Up to 40 readings within one plot were averaged.

As a passive device, a bi-directional spectrometer to enable hyperspectral readings was used (Mistele and Schmidhalter, 2010b). Simultaneously, one spectrometer unit was linked to a diffuser detecting solar radiation as a reference signal, the second unit measured the canopy reflectance with a 0.28 m$^2$ field of view (FOV).

One of the three active devices used was an active flash sensor (AFS) similar to the N-Sensor ALS® (YARA International, ASA) but limited to a single sensor and USB interface (Mistele and Schmidhalter, 2010b). The light source for this system was a flashing xenon light producing a spectral range of 650 to 1100 nm with 10 flashes per second and a circular FOV of about 0.15 m$^2$. The four detectable wavelengths were chosen similar to those of the YARA ALS® system: 730, 760, 900, and 970 nm (Jasper et al., 2009).

Furthermore, the GreenSeeker RT100® (NTech Industries, Inc., Ukiah, CA) and the Crop Circle ACS-470® (Holland Scientific, Inc, Lincoln, NE) were used. The GreenSeeker uses two LEDs as a light source and detects the reflection of each in the VIS (656 nm, ~25 nm band width) and NIR (774, ~25 nm band width) spectral regions. The FOV of this device is a narrow strip of about 0.009 m$^2$. The Crop Circle operates similarly to the GreenSeeker but emits white light and offers a choice of selectable interference filters. Filters for the wavelengths 670, 730, and 760 nm were chosen to record reflectance data. The FOV of the Crop Circle is an oval of approximately 0.09 m$^2$.

Although some sensors offer calculated VIs as output, we used single wavelength reflection values to calculate the VIs aimed for in this project. Seven indices were selected to represent the different reflectance intensities in the VIS and NIR ranges of all the sensor systems used (Table 1). Because the active devices did not always detect exactly the wavelengths typical for these indices, similar wavelengths and combinations were used to calculate ratios (Table 2) based on the seven initial indices.

The normalised difference vegetation index (NDVI) and the simple ratio (SR) were calculated expressing spectral parameters of both the VIS and NIR spectral regions. The "red edge" inflection point (REIP) contains information about the chlorophyll absorption and lies between the VIS and NIR spectral information

and thus is sensitive to changes on either side (Guyot et al., 1988). An index of two similar NIR reflectances (NIR/NIR), which has been shown to be closely related to the N status of crops, was calculated (Mistele and Schmidhalter, 2008b). The water index (WI) is the ratio of the water absorption band at 970 nm and the NIR reference at 900 nm (Peñuelas et al., 1993). The photochemical reflectance index (PRI) and the visible atmospherically resistant vegetation index (VARI) were both developed from relationships of reflectance intensities in the visible range (Gamon et al., 1992; Gamon et al., 1997; Gitelson et al., 2002).

In the growing season 2009, at ZS 3, indices cannot be provided for all active devices. At ZS 4 and ZS 6, AFS data were not available but Crop Circle and GreenSeeker data were collected. In 2010, all the sensor devices worked throughout the growing season.

2.3 Statistical analysis

SPSS 11 (SPSS Inc., Chicago, USA) was used for statistical analysis. Linear and curvilinear models were used to establish relationships between spectral indices and dry matter content, shoot dry weight, shoot fresh weight, N content, N uptake, and the NNI for each biomass sampling. The Akaike Information Criterion (AIC) (Webster and McBratney, 1989) was used to assess the goodness-of-fit, and hence the best choice of linear or curvilinear models. A one-way analysis of variance (ANOVA) with Duncan's multiple comparison procedure based on the studentised range test with a p-value of 0.05 was applied to differentiate the means of the N treatments.

## RESULTS AND DISCUSSION

Testing and comparing one bi-directional hyperspectral passive and three active sensors, the shoot biomass and nitrogen status of wheat plants could well be estimated across two growing seasons with $r^2$ values of up to 0.96. The differentiation patterns of the agronomic parameters at three sampling dates in 2010 were less distinct than those in 2009. Due to beneficial climatic conditions in 2010, already lower N supply allowed for well crop biomass development (Table 2).

Biomass development in 2009 reached a maximum at ZS 6 of 8.7 t ha$^{-1}$ of dry weight (DW) whereas in 2010 a DW of up to 11.3 t ha$^{-1}$. In 2010, an additional N supply with N level $N_{220}$ did not result in a significant DW increase throughout the season (Table 3). However, in both years, the reflectance indices differed markedly in their ability to express the influence of the single N levels on destructively sampled biomass parameters. This lack of predictive quality can be ascribed to the lack of distinction between higher N supply levels as reflected by indices or crop parameters. With high N supply and consequently dense canopies and high LAI values, the reflectance of VIS spectral ranges tends to be saturated sooner than when using NIR-based reflectance indices (Hatfield et al., 2008; Mistele and Schmidhalter, 2008b).

Table 2: Destructively assessed biomass parameters of the vegetation periods 2009 and 2010 at the development stage of maximum biomass, Zadoks stage 6. Fresh weight (FW), dry weight (DW), dry matter content (DM), N content, N uptake and the nitrogen nutrition index (NNI) are shown for the N supply levels 0 kg ha$^{-1}$ ($N_0$), 100 kg ha$^{-1}$($N_{100}$), 160 kg ha$^{-1}$($N_{160}$), and 220 kg ha$^{-1}$($N_{220}$).

| N level | FW [t ha$^{-1}$] | DW [t ha$^{-1}$] | DM [%] | N content [%] | N uptake [kg ha$^{-1}$] | NNI |
|---|---|---|---|---|---|---|
| Vegetation period 2009 | | | | | | |
| $N_0$ | 16.9 | 4.5 | 26.6 | 1.15 | 51.7 | 0.42 |
| $N_{100}$ | 29.5 | 7.3 | 24.9 | 1.58 | 115.9 | 0.71 |
| $N_{160}$ | 35.3 | 7.7 | 22.1 | 2.02 | 156.5 | 0.93 |
| $N_{220}$ | 41.4 | 8.7 | 21.1 | 2.32 | 201.8 | 1.12 |
| Vegetation period 2010 | | | | | | |
| $N_0$ | 19.0 | 7.3 | 38.7 | 1.01 | 74.2 | 0.45 |
| $N_{100}$ | 29.3 | 10.6 | 36.2 | 1.37 | 145.8 | 0.73 |
| $N_{160}$ | 34.7 | 11.3 | 32.7 | 1.58 | 179.6 | 0.86 |
| $N_{220}$ | 35.6 | 11.0 | 31.0 | 1.85 | 204.1 | 1.00 |

Table 3: Mean value comparison for each biomass and nitrogen parameter at the development stage of maximum biomass, Zadoks stage 6, for the vegetation periods 2009 and 2010. Significant differences of fresh weight (FW), dry weight (DW), dry matter content (DM), N content, N uptake and the nitrogen nutrition index (NNI) between the N supply levels 160 kg N ha$^{-1}$ ($N_{160}$) and 220 kg N ha$^{-1}$ ($N_{220}$) are indicated as ○ = significantly different, ● not significantly different at p = 0.05.

| N level | FW [t ha$^{-1}$] | DW [t ha$^{-1}$] | DM [%] | N content [%] | N uptake [kg ha$^{-1}$] | NNI |
|---|---|---|---|---|---|---|
| Vegetation period 2009 | | | | | | |
| $N_{160}$ | ○ | ○ | ○ | ○ | ○ | ○ |
| $N_{220}$ | ○ | ○ | ○ | ○ | ○ | ○ |
| Vegetation period 2010 | | | | | | |
| $N_{160}$ | ○ | ○ | ○ | ○ | ○ | ○ |
| $N_{220}$ | ● | ● | ○ | ○ | ○ | ○ |

A potential saturation effect in the relationship between the vegetation index and the crop parameters was not well reflected by the coefficients of determination, especially when curvilinear relationships were chosen. A multiple comparison test was performed to identify the N levels as reflected by indices and crop parameters. Results for the development stage of maximum biomass, ZS 6, are shown in Table 4.

Table 4: Mean value comparison for spectral indices at the development stage of maximum biomass, Zadoks stage 6, for the vegetation periods 2009 and 2010. Significant differences between the N supply levels 160 kg N ha$^{-1}$ (N$_{160}$) and 220 kg N ha$^{-1}$ (N$_{220}$) of the spectral indices of the bi-directional spectrometer (BDS), the Crop Circle (CC), the GreenSeeker (GS) and the active flash sensor (AFS) are indicated as ○ = significantly different, ● not significantly different at p = 0.05.

| N level | BDS | | | | | | | | | CC | | | | C |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | NDVI | $R_{730}/R_{670}$ | $R_{760}/R_{670}$ | $R_{780}/R_{650}$ | $R_{760}/R_{730}$ | WI | REIP | PRI | VARI | NDVI | $R_{730}/R_{670}$ | $R_{760}/R_{670}$ | $R_{760}/R_{730}$ | NDVI |
| Vegetation period 2009 | | | | | | | | | | | | | | |
| N$_{160}$ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| N$_{220}$ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ○ |
| Vegetation period 2010 | | | | | | | | | | | | | | |
| N$_{160}$ | ● | ● | ○ | ○ | ○ | ○ | ○ | ● | ● | ○ | ○ | ○ | ○ | ○ |
| N$_{220}$ | ● | ● | ● | ● | ○ | ● | ● | ● | ● | ● | ● | ○ | ○ | ● |

The ability to distinguish differences in FW, DW, and DM content was strongly dependent on the developmental stage and the growing season (Prasad et al., 2007). Differentiation was well performed by all spectral indices and sensor systems for the N application levels $N_0$ and $N_{100}$. Especially the plant parameters and spectral indices of the high N supplied varieties, $N_{160}$ and $N_{220}$ did strongly differ in the ability of differentiation. As has been shown previously, the NDVI is strongly prone to saturation with increasing biomass or (Aparicio et al., 2000; Serrano et al., 2000; Li et al., 2008) similar to the REIP (Strenner and Maidl, 2010) Saturation is frequent for dense crop stands in Europe with LAI values up to 8.0 (Heege et al., 2008). However, due to its characteristic asymptotic course with high crop densities, the NDVI is particularly sensitive at small biomass and low ground coverage. Therefore, this index may be more suitable for differentiating plant canopies at early growth stages or in more sparsely grown crop stands.

In contrast, the $R_{760}/R_{730}$ index of the passive radiometer has been shown to be more resistant to saturation effects (Heege et al., 2008; Strenner and Maidl, 2010) The $R_{760}/R_{730}$ index provided by the passive bi-directional radiometer, the Crop Circle and the active flash sensor, was the most powerful and temporally stable index for detecting the N status of wheat. However, sensors offering NDVI-based indices, such the GreenSeeker, were less suited to identify the investigated parameters due to saturation effects.

## CONCLUSIONS

Testing and comparing one bi-directional passive and three active sensors, the shoot biomass and nitrogen status of wheat plants could well be estimated. However, a potential saturation effect of the vegetation indices due to dense crop stands was not well reflected by the coefficients of determination. An additional analysis to spectrally identify four incremental N levels as reflected by indices and crop parameters was performed. The ability to distinguish differences in FW, DW, and DM was strongly dependent on the developmental stage and the growing season. The $R_{760}/R_{730}$ index provided by the passive spectrometer, the Crop Circle, and the active flash sensor, was the most powerful and temporally stable index for detecting the N status of wheat. However, sensors offering NDVI-based indices, such the GreenSeeker, were less suited to identifying the investigated parameters due to saturation effects.

Using active sensor devices is more flexible in terms of light conditions and timeliness. However, future investigations, particularly in plant breeding and also management, will ask for broad-range spectral information for phenotyping specific plant traits. Optimisation and developments of new reflectance indices may then depend on the availability of broad spectral information and thus will be restricted to passive spectrometers at the present. After successful validation and implementation, novel sensing algorithms might be transferred into active sensors.

## ACKNOWLEDGEMENTS

## REFERENCES

Aparicio, N., Villegas, D., Araus, J.L., Casadesus, J., Royo, C., 2002. Relationship between growth traits and spectral vegetation indices in durum wheat. Crop Sci. 42, 1547-1555.

Aparicio, N., Villegas, D., Casadesus, J., Araus, J.L., Royo, C., 2000. Spectral vegetation indices as nondestructive tools for determining durum wheat yield. Agron. J. 92, 83-91.

Campbell, J.B., 2002. Introduction to remote sensing. The Guilford Press, New York.

Fitzgerald, G.J., 2010. Characterizing vegetation indices derived from active and passive sensors. Int. J. Remote Sens. 31, 4335-4348.

Gamon, J.A., Peñuelas, J., Field, C.B., 1992. A narrow-waveband spectral index that tracks diurnal changes in photosynthetic efficiency. Remote Sensing of Environment 41, 35-44.

Gamon, J.A., Serrano, L., Surfus, J., 1997. The photochemical reflectance index: an optical indicator of photosynthetic radiation use efficiency across species, functional types, and nutrient levels. Oecologia 112, 492-501.

Gitelson, A.A., Kaufman, Y.J., Stark, R., Rundquist, D., 2002. Novel algorithms for remote estimation of vegetation fraction. Remote Sensing of Environment 80, 76-87.

Guo, J., Wang, X., Meng, Z., Zhao, C., Yu, Z., Chen, L., 2008. Study on diagnosing nitrogen nutrition status of corn using Greenseeker and SPAD meter. Plant Nutr. Fertil. Sci. 2008-1, 513.

Guyot, G., Baret, F., Major, D.J., 1988. High spectral resolution: Determination of spectral shifts between the red and the near infrared. Int. Arch. Photogr. Remote Sens. 11, 750-760.

Hatfield, J.L., Gitelson, A.A., Schepers, J.S., Walthall, C.L., 2008. Application of Spectral Remote Sensing for Agronomic Decisions. Agron. J. 100, S-117-131.

Heege, H.J., Reusch, S., Thiessen, E., 2008. Prospects and results for optical systems for site-specific on-the-go control of nitrogen-top-dressing in Germany. Precis. Agric. 9, 115-131.

Hong, S.-D., Schepers, J.S., Francis, D.D., Schlemmer, M.R., 2007. Comparison of ground-based remote sensors for evaluation of corn biomass affected by nitrogen stress. Commun. Soil Sci. Plant Anal. 38, 2209-2226.

Justes, E., Jeuffroy, M., Mary, B., 1997. Wheat, Barley, and Durum Wheat. In: Lemaire, G. (Ed.), Diagnosis of the Nitrogen Status in Crops. Springer-Verlag, pp. 73-92.

Lamb, D.W., Steyn-Ross, M., Schaare, P., Hanna, M.M., Silvester, W., Steyn-Ross, A., 2002. Estimating leaf nitrogen concentration in ryegrass (*Lolium*

spp.) pasture using the chlorophyll red-edge: theoretical modelling and experimental observations. Int. J. Remote Sens. 23, 3619-3648.

Lemaire, G., Gastal, F., 1997. N uptake and distribution in plant canopies. In: Lemaire, G. (Ed.), Diagnosis of the Nitrogen Status in Crops. Springer-Verlag, Berlin, Heidelberg.

Li, F., Gnyp, M.L., Jia, L., Miao, Y., Yu, Z., Koppe, W., Bareth, G., Chen, X., Zhang, F., 2008. Estimating N status of winter wheat using a handheld spectrometer in the North China Plain. Field Crops Res. 106, 77-85.

Mistele, B., Gutser, R., Schmidhalter, U., 2004. Validation of field-scaled spectral measurements of nitrogen status in winter wheat. In: Mulla, D. (Ed.), 7th International conference on Precision Agriculture and other precision resources management., Minneapolis, Minnesota, USA, pp. 1187-1195.

Mistele, B., Schmidhalter, U., 2008a. Estimating the nitrogen nutrition index using spectral canopy reflectance measurements. Eur. J. Agron. 29, 184-190.

Mistele, B., Schmidhalter, U., 2008b. Spectral measurements of the total aerial N and biomass dry weight in maize using a quadrilateral-view optic. Field Crops Res. 106, 94 - 103.

Mistele, B., Schmidhalter, U., 2010a. A comparison of spectral reflectance and laser-induced chlorophyll fluorescence measurements to detect differences in aerial dry weight and nitrogen uptake of wheat. In: Khosla, R. (Ed.), 10th International Conference of Precision Agriculture, Denver, Colorado.

Mistele, B., Schmidhalter, U., 2010b. Tractor-based quadrilateral spectral reflectance measurements to detect biomass and total aerial nitrogen in winter wheat. Agron. J. 102, 499-506.

Peñuelas, J., Filella, I., Biel, C., Serrano, L., Savé, R., 1993. The reflectance at the 950-970 nm region as an indicator of plant water status. Int. J. Remote Sens. 14, 1887-1905.

Peñuelas, J., Filella, I., Gamon, J., 1995. Assessment of photosynthetic radiation-use efficiency with spectral reflectance. New Phyt. 131, 291 - 296.

Pinter, P.J., Hatfield, J.L., Schepers, J.S., Barnes, E.M., Moran, M.S., Daughtry, C.S.T., Upchurch, D.R., 2003. Remote sensing for crop management. Photogramm. Eng. Remote Sens. 69, 647-664.

Prasad, B., Carver, B.F., Stone, M.L., Babar, M.A., Raun, W.R., Klatt, A.R., 2007. Potential use of spectral reflectance indices as a selection tool for grain yield in winter wheat under great plains conditions. Crop Sci. 47, 1426-1440.

Raun, W.R., Solie, J.B., Johnson, G.V., Stone, M.L., Lukina, E.V., Thomason, W.E., Schepers, J.S., 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. 93, 131-138.

Reusch, S., Jasper, J., Link, A., 2010. Estimating crop biomass and nitrogen uptake using CropSpec TM, a newly developed active crop-canopy reflectance sensor., 10th International Conference on Precision Agriculture, Denver, Colorado.

Schmidhalter, U., 2005. Development of a quick on-farm test to determine nitrate levels in soil. J. Plant Nutr. Soil Sci. 168, 432-438.

Serrano, L., Filella, I., Penuelas, J., 2000. Remote sensing of biomass and yield of winter wheat under different nitrogen supplies. Crop Sci. 40, 723-731.

Shaver, T.M., Khosla, R., Westfall, D.G., 2010. Evaluation of two ground-based active crop canopy sensors in maize: growth stage, row spacing, and sensor movement speed. Soil Sci. Soc. Am. J. 74, 2101-2108.

Shearman, V.J., Sylvester-Bradley, R., Scott, R.K., Foulkes, M.J., 2005. Physiological Processes Associated with Wheat Yield Progress in the UK. Crop Sci. 45, 175-185.

Strenner, M., Maidl, F.-X., 2010. Comparison of different vegetation indices and their suitability to describe N-uptake in winter wheat for presision farming. In: Khosla, R. (Ed.), 10th International Conference of Precision Agriculture, Denver, Colorado.

Sudduth, K., Kitchen, N., Drummond, S., 2010. Comparison of three canopy reflectance sensors for variable-rate nitrogen application in corn. In: Khosla, R. (Ed.), 10th International Conference on Precision Agriculture, Denver, Colorado.

Thoren, D., Schmidhalter, U., 2009. Nitrogen status and biomass determination of oilseed rape by laser-induces chlorophyll fluorescence. Eur. J. Agron. 30, 238-242.

Tremblay, N., Wang, Z.J., Ma, B.L., Belec, C., Vigneault, P., 2009. A comparison of crop data measured by two commercial sensors for variable-rate nitrogen application. Precis. Agric. 10, 145-161.

Trotter, T., Frazier, P., Trotter, M., Lamb, D., 2008. Objective biomass assessment using an active plant sensor (Crop Circle), preliminary experiences on a variety of agricultural landscapes. In: Kholsa, R. (Ed.), 9th International Conference on Precision Agriculture, Colorado State University, Fort Collins, Colorado.

Webster, R., McBratney, A.B., 1989. On the Akaike Information Criterion for choosing models for variograms of soil properties. Journal of Soil Science 40, 493-496.

Zadoks, J.C., Chang, T.T., Konzak, C.F., 1974. A decimal code for the growth stages of cereals. Weed Res. 14, 415-421.