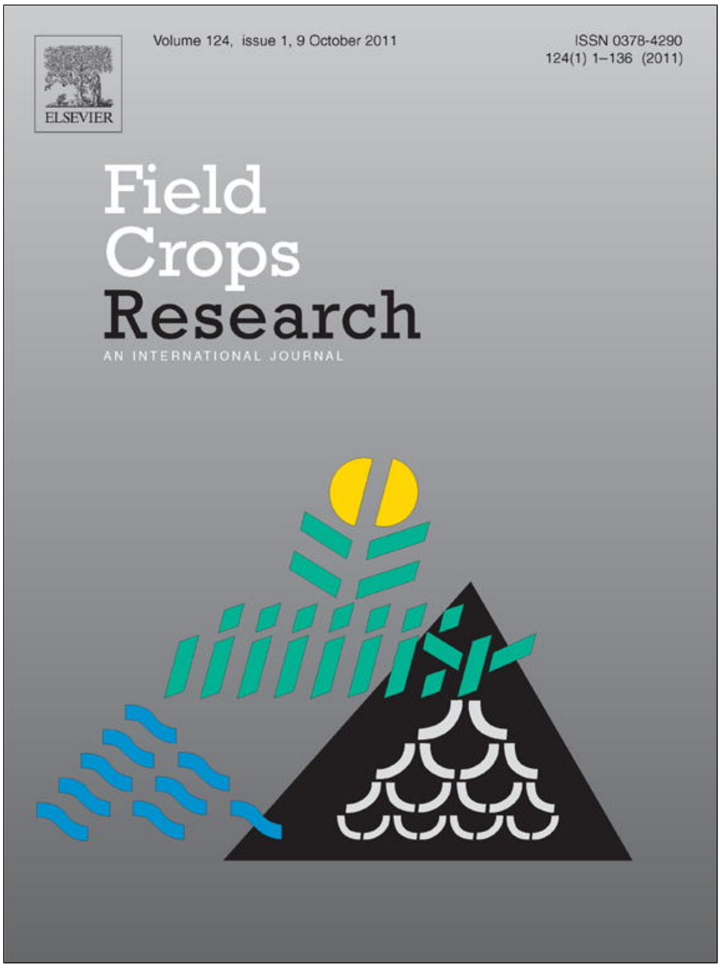
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Comparison of active and passive spectral sensors in discriminating biomass parameters and nitrogen status in wheat cultivars

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Several sensor systems are available for ground-based remote sensing in crop management. Vegetation indices of multiple active and passive sensors have seldom been compared in determining plant health. This work describes a study comparing active and passive sensing systems in terms of their ability to recognize agronomic parameters. One bi-directional passive radiometer (BDR) and three active sensors, including the Crop Circle, GreenSeeker, and an active flash sensor (AFS), were tested for their ability to assess six destructively determined crop parameters. Over 2 years, seven wheat (*Triticum aestivum* L.) cultivars were grown with nitrogen supplies varying from 0 to 220 kg ha^{-1}. 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, as percent of dry weight to fresh weight, *N* content, aboveground *N* uptake, and the nitrogen nutrition index. The majority of the tested indices, based on different combinations of wavelengths in the visible and near infrared spectral ranges, showed high r^2-values when correlated with the crop parameters. However, the accuracy of discriminating the influence of varying *N* levels on various crop parameters differed between sensors and showed an interaction with growing seasons and developmental stage. Visible- and red light-based indices, such as the NDVI, simple ratio (R_{780}/R_{670}), and related indices tended to saturate with increasing crop stand density due to a decreased sensitivity of the spectral signal. Among the destructively assessed biomass parameters, the best relationships were found for N-related 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 BDR, 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.

1. Introduction

Spectral remote sensing is widely used in land use management, agriculture, and crop management. Over time, satellite, airborne, and ground-based systems have been introduced to meet different spatial and temporal requirements. 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 providing radiation in specific waveband regions. Therefore, active sensors are 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 characteristics of plants defined by their light absorbance, transmittance, or reflectance are related to the physiological status and growth attributes of the crop. VIS reflectance depends mainly on the chlorophyll content of the palisade layer in leaves (Campbell, 2002) and is negatively correlated with leaf *N* content. There is a strong linear relationship between leaf chlorophyll concentration and leaf *N* concentration (Lamb et al., 2002). NIR reflectance depends on the structure of the mesophyll cells and the cavities between them (Campbell, 2002) and is positively correlated with 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, includ-

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ing that of wheat (Raun et al., 2001; Pinter et al., 2003; Prasad et al., 2007). The NDVI and related indices tend to become saturated when exceeding a leaf area index (LAI) of 2–3 (Aparicio et al., 2000; Mistele et al., 2004; Heege et al., 2008). In the meantime, a number of other indices have been developed to estimate agronomic parameters such as *N* content, aboveground *N* uptake, and nitrogen efficiency of crops (Li et al., 2008; Mistele and Schmidhalter, 2010a; Strenner and Maidl, 2010). In part, the newly developed indices rely more on NIR spectral ranges, which are supposed to be more resistant to high LAI. Therefore, 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 like Europe (Mistele et al., 2004; Heege et al., 2008; Reusch et al., 2010). However, some indices concentrate on the visible range of the reflection spectrum. Because they are primarily influenced by the absorbance capacity of chlorophyll, VIS-based indices are presumed to identify green vegetation over soil, biomass, and photosynthetic capacity (Peñuelas et al., 1995; Gamon et al., 1997; Aparicio et al., 2000).

Several commercial sensors are available, both passive and active types. In practice, both systems provide either identical or similar indices for estimating crop health. Passive sensors are mostly hyperspectral measuring a number of wavelengths in the VIS and NIR ranges. These measurements enable the calculation of different vegetation indices (VI), making passive sensors more flexible and applicable for a broad range of requirements (Pinter et al., 2003; Hatfield et al., 2008), although only under adequate light conditions. In contrast, active sensors are limited to comparatively few wavelengths according to the number and type of light sources; however, they can be used independently of solar radiation conditions in the field (Jasper et al., 2009).

The GreenSeeker (NTech Industries Inc., Ukiah, California) is a commercially available active device. This sensor uses light-emitting diodes (LEDs) as a light source and detects the reflection in the VIS and NIR spectral regions. The GreenSeeker has been used to determine management zones and nitrogen status in corn and wheat (Hong et al., 2007; Guo et al., 2008; Tremblay et al., 2009; Li et al., 2010; Shaver et al., 2010).

Another commercially available active sensor is the Crop Circle ACS-470® (Holland Scientific Inc., Lincoln, Nebraska), which works similarly to the GreenSeeker system and has been applied in the detection of green biomass and leaf area estimates in cereals (Trotter et al., 2008; Fitzgerald, 2010).

The capability of active and passive sensors to reproduce vegetation indices and their use in crop management has been compared. Sensor outputs from several devices have either been interrelated (Tremblay et al., 2009; Sudduth et al., 2010) or several indices from a single device have been related to diverse quantitative crop parameters (Trotter et al., 2008; Mistele and Schmidhalter, 2010b; Strenner and Maidl, 2010). In most cases, no direct relationship between various sensors' output, either active or passive, and quantitative crop parameters was demonstrated. Thus, the following question has been proposed: can multiple VIs of passive and active sensor systems be compared in terms of their ability to recognise agronomic parameters? Therefore, it is not sufficient that indices correlate well with the range of *N* application levels across a field; it is just as important to know whether these VIs precisely reflect the actual status of the crop. This status can only be verified by destructive assessments.

The purpose of this work was therefore to compare passive and active spectral sensor systems with each of several vegetation indices (i) to identify the crop nitrogen status, (ii) to evaluate the quality of their relationship to agronomic parameters in the field, and (iii) to find a possible ranking in the prediction of several agronomic parameters.

2. Materials and methods

2.1. Study site and biomass sampling

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). The fields used were mostly homogeneous Cambisols of silty clay loam. The fields are located in a hilly region sloping northwards with approximately 0.09 m m^{-1}. In this geographic area, the average yearly precipitation is approximately 800 mm, and the average temperature is 7.5 °C. Yields vary between 6 and 10 t per hectare, depending on the climate and soil conditions. In 2009, the soil was sampled and a representative sample was analysed for P (20 mg P_2O_5 per 100 g soil) and K (23 mg K_2O per 100 g soil) to ensure an adequate supply of these macronutrients. The fields were managed conventionally, adopting local standards. Residual soil nitrate 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.

The experiment was designed as a randomised block design with four replicates (Fig. 1). In the growing seasons 2009 and 2010, seven winter wheat (*Triticum aestivum* L.) varieties were sown with 320 kernels per square meter: *Tommi*, *Solitär*, *Impression*, *Pegassos*, *Ludwig*, *Cubus*, and *Ellvis*. Four *N* treatments 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 late-flowering stages. At each of the first and second application date 30, 60, and 90 kg N ha^{-1} were given for the *N* treatments 100, 160, and 220 kg ha^{-1}, respectively. At the late-flowering stage the three treatments received 40 kg N ha^{-1} each. No fertilizer was applied pre-planting. Fertiliser application at the late-flowering stage is frequently used to increase the quality of small cereals in Germany. The experimental plots were 2 m wide and 15 m long.

Biomass sampling was performed three times, at the Zadoks growth stages (ZS) 3, 4, and 6 (Zadoks et al., 1974) and was checked via growing degree days (GDD) for similar development in the two years of the study. For biomass sampling, a green forage chopper was used to cut an area 2 m wide by 3 m long from each plot (Thoren and Schmidhalter, 2009). The fresh biomass was put into plastic bags, immediately weighed, and then dried. The shoot fresh weight (FW) and the shoot dry weight (DW) (kg ha^{-1}) were recorded and dry matter content (DM) calculated as shoot dry weight divided by shoot fresh weight and expressed as a percentage value. The plant samples were milled, and 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). Furthermore, the aboveground *N* uptake (kg ha^{-1}) was calculated as the shoot dry weight multiplied by the total *N* content.

The Nitrogen Nutrition Index (NNI) was determined by Lemaire and Gastal (1997):

$$\mathrm{NNI} = \frac{\mathrm{Nact}}{N_c}$$

where N_c is the critical *N* content of the shoot dry weight described by the equation (Justes et al., 1997)

$$N_c = 5.35\,(\text{shoot dry weight}\,[\mathrm{t\ ha^{-1}}]^{-0.442})$$

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). Despite this assumption, we calculated the critical *N* content for each plot to reflect the individual *N* status of replicates and *N* treatments. This calculation takes into account that the relationship

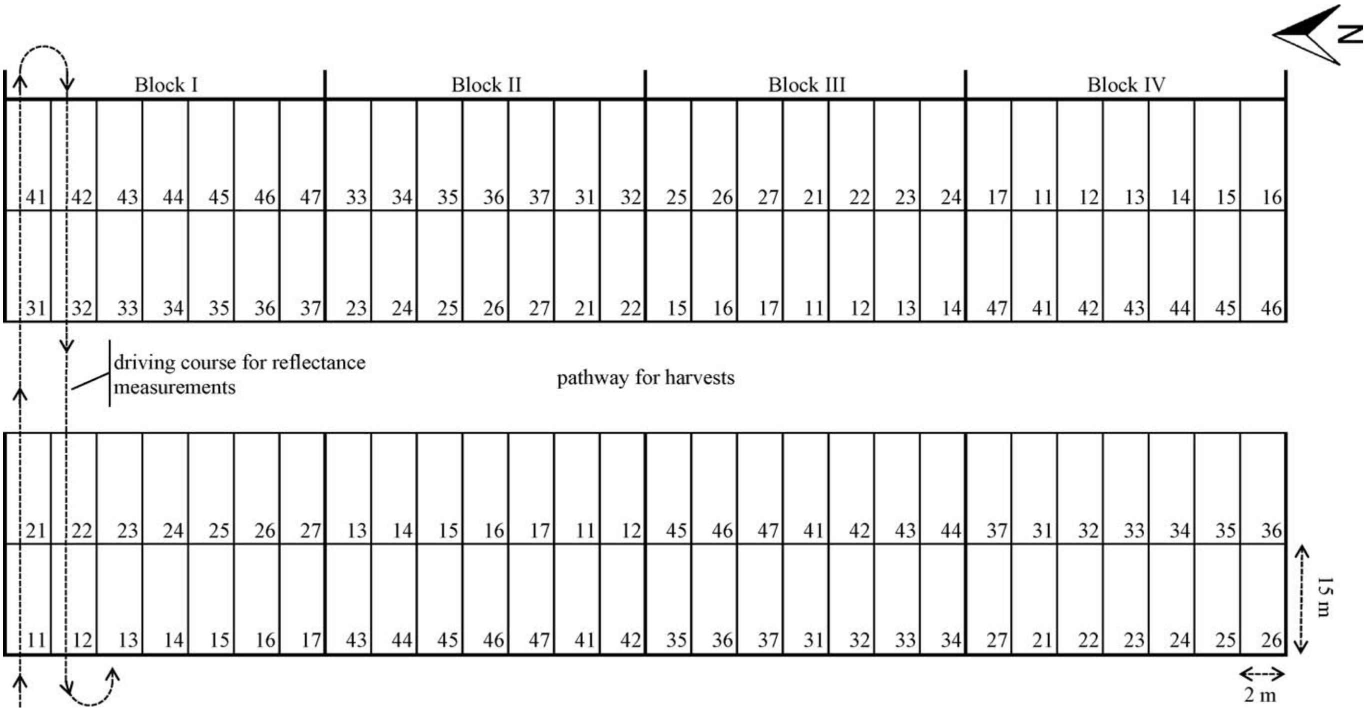


Fig. 1. Map of the trial layout with plots dimensions and the driving direction for reflectance measurements. Numbers indicate *N* treatment levels (first digit) with 0 kg N ha^{-1} = 1, 100 kg N ha^{-1} = 2, 160 kg N ha^{-1} = 3, 220 kg N ha^{-1} = 4, and cultivars (second digit) including *Tommi*, 1, *Solitär*, 2, *Impression*, 3, *Pegassos*, 4, *Ludwig*, 5, *Cubus*, 6, *Ellvis*, 7.

between spectral measurements and plant parameters is represented by a continuous function and therefore cannot be fitted to an absolute term (Mistele and Schmidhalter, 2008a).

2.2. Spectral reflectance measurements

Passive and active optical sensor systems were mounted, aligned in a row on a frame in front of a high clearance tractor. The tractor was driven from west to east to avoid any shading of the measuring unit (Fig. 1). The measurements were taken under clear sky conditions before or at noon to provide the best possible conditions for passive recording. The design of the tractor, with a ground clearance of 0.90 m, allowed passing over the plots without touching the canopy. Independent of the sensor system, all devices were used at a nadir position of approximately 1.40 m above the ground across the season. This height was chosen to constantly sense the central areas of the plots along the sowing direction and to avoid the unintended detection of boundary rows. While collecting information in the field, the sensor outputs were co-recorded along with the GPS coordinates from the TRIMBLE RTK-GPS (real-time kinematic global positioning system) (Trimble, Sunnyvale, CA, USA). Afterwards, up to 40 readings within one plot, sparing the forward and backmost borders, were averaged to single values per plot.

As a passive device, a bi-directional radiometer with modified electronics (tec5, Oberursel, Germany) to enable hyperspectral readings was used. This bi-directional radiometer (BDR) contained two Zeiss MMS1 silicon diode array spectrometers with a spectral detection range of 400–1700 nm and a bandwidth of 3.3 nm (Mistele and Schmidhalter, 2010b). One unit was linked to a diffuser detecting solar radiation as a reference signal. Simultaneously, the second unit measured the canopy reflectance with a 12° field of view (FOV) of circular shape, resulting in about 0.28 m^2 scanning area encompassing several plant rows at a time. The bi-directional radiometer was calibrated once with a $BaSO_4$ white standard and a grey scale standard (SphereOptics GmbH, Germany) in 2009 and 2010, respectively.

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, 2010a). The light source for this system was a flashing xenon light producing a spectral range of 650–1100 nm with 10 flashes per second and a circular FOV of about 0.15 m^2 scanning several plant rows at a time. Four different wavelengths could be measured simultaneously. The detected wavelengths could be selected independently, but in this experiment filters similar to those of the YARA ALS® system were chosen: 730, 760, 900, and 970 nm (Jasper et al., 2009).

Furthermore, the commercially available sensor systems GreenSeeker RT100® (NTech Industries, Inc., Ukiah, CA) and 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 61 by 1.5 cm (0.009 m^2) at a height of 66–112 cm above the plant canopy (NTech Industries, 2007) which was run crosswise to the sowing direction. The Crop Circle operates similarly to the GreenSeeker but allows for more flexibility in the wavelengths detected because it 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 ~32° by ~6° range (Holland-Scientific, 2008), resulting in approximately 0.09 m^2 area and was used crosswise to the sowing direction. With reference to the manufacturers' information, active sensors were calibrated before delivery and no additional calibration was further required.

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,

Table 1
Spectral indices selected for the comparison of active and passive sensors.

Abbreviation	Formula	Reference
NDVI	$(R_{780}-R_{670})/(R_{780}+R_{670})$	Rouse et al., 1974
SR	R_{780}/R_{670}	Pearson and Miller, 1972
NIR/NIR	R_{780}/R_{740}	Mistele and Schmidhalter, 2010b
WI	R_{900}/R_{970}	Peñuelas et al., 1993
REIP	$700+40((R_{670}+R_{780})/2-R_{700})/(R_{740}-R_{700})$	Guyot et al., 1988
PRI	$(R_{531}-R_{570})/(R_{531}+R_{570})$	Gamon et al., 1992
VARI	$(R_{550}-R_{650})/(R_{550}+R_{650}-R_{470})$	Gitelson et al., 2002

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 cell wall reflection (Guyot et al., 1988). The reflectance at 700 nm lies between the VIS and NIR spectral information but is sensitive to changes on either side. 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, 2010b). 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 WI is supposed to reflect structural changes caused by cell water content. 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. The PRI correlates with the photosynthetic efficiency and the nitrogen status of the canopies (Gamon et al., 1992, 1997). The VARI has been described as a good indicator of the fraction of green vegetation over the soil surface (Gitelson et al., 2002).

In the growing season 2009, the active sensors were not available for the whole season. Therefore, 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. The AIC criterion is based on a threepart equation of which one term is a constant value which therefore could be ignored. We used the shortform equation recommended by Webster and McBratney based on the number of observations, the residual sum of squares and the number of coefficients of a model. For further explanations of AIC we refer to Webster and McBratney (1989). 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.

Table 2
Wavelengths and indices of four sensor systems and their abbreviations.

Device	Wavelengths used	Index abbreviation
Bi-directional radiometer	R_{670}, R_{780}	BDR_NDVI
	R_{670}, R_{730}	BDR_R_{730}/R_{670}
	R_{670}, R_{760}	BDR_R_{760}/R_{670}
	R_{780}, R_{650}	BDR_R_{780}/R_{650}
	R_{730}, R_{760}	BDR_R_{760}/R_{730}
	R_{900}, R_{970}	BDR_WI
	R_{670}, R_{700}, R_{740}, R_{780}	BDR_REIP
	R_{531}, R_{570}	BDR_PRI
	R_{470}, R_{550}, R_{650}	BDR_VARI
Crop Circle	R_{670}, R_{760}	CC_NDVI
	R_{670}, R_{730}	CC_R_{730}/R_{670}
	R_{670}, R_{760}	CC_R_{760}/R_{670}
	R_{730}, R_{760}	CC_R_{760}/R_{730}
GreenSeeker	R_{656}, R_{774}*	GS_NDVI
	R_{656}, R_{774}*	GS_R_{774}/R_{656}
Active flash sensor	R_{730}, R_{760}	AFS_R_{760}/R_{730}
	R_{900}, R_{970}	AFS_WI

A bi-directional passive (BDR) and three active sensors (Crop Circle, CC; GreenSeeker, GS; active flash sensor, AFS) were compared.

* ~25 nm spectral width at 50% of peak (NTech Industries, 2007).

3. Results

3.1. *Differentiation of agronomical parameters and spectral indices at varying N rates*

3.1.1. *Agronomic parameters*

For all sampling dates across the seasons 2009 and 2010, the mean values of the destructively assessed agronomic parameters DM, DW, *N* content, aboveground *N* uptake, FW, and the NNI as influenced by the four *N* treatments were compared. In the growing season 2009, all the agronomic parameters except DW could be distinguished significantly (Fig. 2) and showed the same differentiation patterns. For the DW at ZS 3, the two highest *N*-application treatments, 160 and 220 kg ha^{-1}, could not be differentiated significantly. Overall, the differentiation patterns of the agronomic parameters in 2010 (Fig. 3) were less distinct than those in 2009. The effects of high *N* levels on the dry matter in 2010 could not be separated across the whole season as they were in the shoot fresh weight for ZS 3 and ZS 6.

3.2. *Spectral indices*

In 2009, AFS data were not available, whereas for the Crop Circle and GreenSeeker, only data for the first sampling date (ZS 3) were missing. Means of the SR indices (R_{730}/R_{670}, R_{760}/R_{670}, R_{780}/R_{650}), R_{760}/R_{730} for all sensors, the BDR_REIP, and the GS_NDVI could clearly be separated over all *N* application levels at all dates. Only the NDVI values obtained for the *N* rates 160 and 220 kg ha^{-1} could not be distinguished in 2009 (Fig. 2). As for the destructive differentiation of the agronomic parameters, spectral differentiations were less distinct in the growing season 2010 compared to 2009 (Fig. 3).

In 2010, all sensors were available throughout the whole season. Over the whole period, only the indices BDR_R_{760}/R_{730} and ALS_R_{760}/R_{730} could successfully distinguish all *N* levels. In contrast, other indices could also separate the different *N* levels but only for a limited number of spectral assessments over time. This finding was the case for the majority of the Crop Circle and GreenSeeker indices, as well as for BDR_REIP.

Inspecting only the higher *N* application rates of 160 and 220 kg ha^{-1}, differentiation was not possible by the bi-directional radiometer simple ratios BDR_R_{760}/R_{670}, BDR_R_{780}/R_{650}, and WI, as

(a) Zadoks stage 3

kg N ha^{-1}	DM [%]				DW [t ha^{-1}]				N content [%]				N uptake [kg ha^{-1}]				FW [t ha^{-1}]				NNI			
0	*31.7* *1.44*				1.07 *0.32*				2.07 *0.29*				21.9 *5.85*				3.38 *1.07*				0.39 *0.05*			
100		28.22 *1.42*				1.36 *0.24*				2.64 *0.23*				35.8 *6.11*				4.86 *0.95*				0.56 *0.05*		
160			*26.5* *1.38*				*1.62* *0.40*				*3.17* *0.29*				*51.3* *12.91*				6.17 *1.65*				0.73 *0.09*	
220				24.6 *1.60*			1.76 *0.30*					3.55 *0.38*				62.0 *10.81*				7.17 *1.33*				0.85 *0.10*

kg N ha^{-1}	BDR_NDVI				BDR_R$_{730}$/R$_{670}$				BDR_R$_{760}$/R$_{670}$				BDR_R$_{780}$/R$_{650}$				BDR_R$_{760}$/R$_{730}$				BDR_WI			
0	0.79 *0.06*				6.32 *1.76*				9.43 *3.05*				7.80 *2.21*				1.47 *0.07*				1.11 *0.01*			
100		0.89 *0.02*				9.42 *1.71*				16.79 *3.43*				13.81 *2.49*				1.78 *0.07*				1.13 *0.01*		
160			0.91 *0.03*				11.4 *2.43*				22.99 *5.55*				19.18 *4.29*				5.0 *0.11*				1.15 *0.02*	
220			0.93 *0.02*					12.56 *2.51*				27.38 *6.68*				23.18 *5.34*				2.16 *0.13*				1.16 *0.02*

kg N ha^{-1}	BDR_REIP				BDR_PRI				BDR_VARI				CC_NDVI				CC_R$_{730}$/R$_{670}$				CC_R$_{760}$/R$_{670}$			
0	721.4 *0.75*				-0.09 *0.01*				0.30 *0.09*															
100		724.4 *0.68*				-0.07 *0.01*				0.43 *0.06*			no data				no data				no data			
160			726.4 *0.87*				-0.06 *0.01*				0.5 *0.08*													
220				727.8 *0.97*				-0.05 *0.01*			0.53 *0.07*													

kg N ha^{-1}	CC_R$_{760}$/R$_{730}$				GS_NDVI				GS_R$_{774}$/R$_{656}$				AFS_R$_{760}$/R$_{730}$				AFS_WI							
0																								
100	no data				no data				no data				no data				no data							
160																								
220																								
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d

(b) Zadoks stage 4

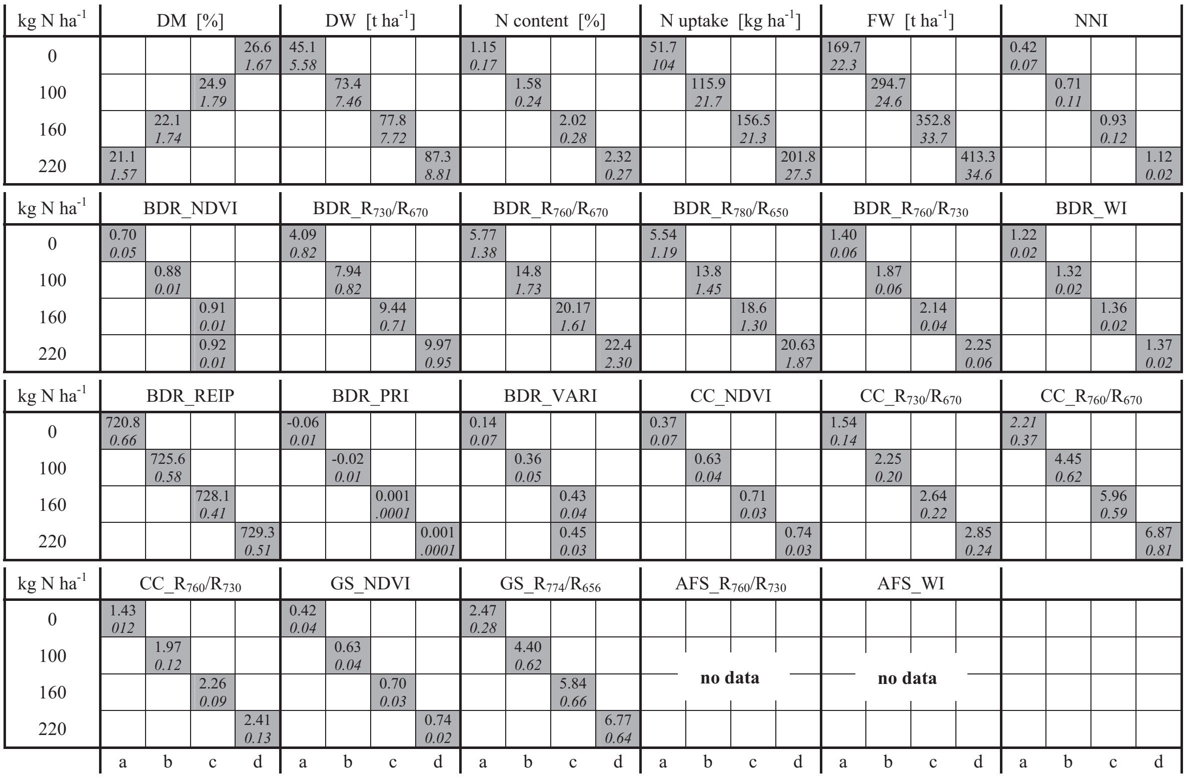
kg N ha^{-1}	DM [%]				DW [t ha^{-1}]				N content [%]				N uptake [kg ha^{-1}]				FW [t ha^{-1}]				NNI			
0				25.4 *0.93*	32.9 *5.22*				1.26 *0.16*				41.1 *6.70*				129.7 *3.85*				0.39 *0.05*			
100			21.6 *0.70*			50.9 *7.34*				1.95 *0.37*				99.2 *23.1*				235.6 *6.12*				0.75 *0.15*		
160		19.8 *1.39*					56.7 *7.45*				2.52 *0.28*				141.8 *19.4*				286.6 *31.1*				1.01 *0.10*	
220	18.8 *1.22*							64.4 *6.67*				2.84 *0.33*				181.8 *18.9*				344.9 *31.1*				1.22 *0.13*

kg N ha^{-1}	BDR_NDVI				BDR_R$_{730}$/R$_{670}$				BDR_R$_{760}$/R$_{670}$				BDR_R$_{780}$/R$_{650}$				BDR_R$_{760}$/R$_{730}$				BDR_WI			
0	0.65 *0.05*				3.43 *0.55*				4.73 *0.91*				4.69 *0.85*				1.37 *0.05*				1.19 *0.02*			
100		0.88 *0.02*				7.70 *1.06*				14.8 *2.24*				14.2 *0.38*				1.92 *0.07*				1.31 *0.02*		
160			0.92 *0.01*				10.2 *1.32*				22.7 *3.54*				21.7 *3.27*				2.22 *0.10*				1.34 *0.03*	
220			0.93 *0.01*					11.2 *1.90*				26.2 *5.87*				25.1 *5.56*				2.33 *0.14*			1.34 *0.04*	

kg N ha^{-1}	BDR_REIP				BDR_PRI				BDR_VARI				CC_NDVI				CC_R$_{730}$/R$_{670}$				CC_R$_{760}$/R$_{670}$			
0	720.8 *0.6*				-0.07 *0.01*				0.09 *0.05*				0.34 *0.06*				1.45 *0.13*				2.08 *0.30*			
100		726.2 *0.64*				-0.01 *0.01*				0.35 *0.06*				0.64 *0.05*				2.26 *0.28*				4.68 *0.75*		
160			728.7 *0.81*				0.02 *0.01*				0.48 *0.04*				0.74 *0.03*				2.83 *0.36*				6.81 *0.96*	
220				729.7 *1.03*				0.03 *0.001*				0.53 *0.02*			0.78 *0.04*					3.20 *0.40*				8.26 *1.21*

kg N ha^{-1}	CC_R$_{760}$/R$_{730}$				GS_NDVI				GS_R$_{774}$/R$_{656}$				AFS_R$_{760}$/R$_{730}$				AFS_WI							
0	1.43 *0.08*				0.36 *0.04*				2.14 *0.04*															
100		2.06 *0.11*				0.54 *0.04*				3.40 *0.34*			no data				no data							
160			2.41 *0.09*				0.63 *0.04*				4.45 *0.63*													
220				2.58 *0.15*				0.68 *0.05*				5.30 *0.90*												
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d

Fig. 2. Mean value comparisons indicated separately for each biomass and nitrogen status parameter as well as spectral indices for the three sampling dates at each *N* application rate (kg N ha^{-1}) in 2009. Differentiation patterns are depicted for spectral indices obtained from one bi-directional passive radiometer (BDR) and three active sensors (Crop Circle, CC; GreenSeeker, GS; active flash sensor, AFS) as well as for the agronomic parameters dry matter content (DM), shoot dry weight (DW), *N* content, aboveground *N* uptake, shoot fresh weight (FW), and nitrogen nutrition index (NNI). Different letters show significant differences at $p \leq 0.05$. For all parameters and indices (each $n = 28$) mean values and standard deviations (italic) are added.



(c) Zadoks stage 6

kg N ha^{-1}	DM [%]				DW [t ha^{-1}]				N content [%]				N uptake [kg ha^{-1}]				FW [t ha^{-1}]				NNI			
0				26.6 1.67	45.1 5.58				1.15 0.17				51.7 104				169.7 22.3				0.42 0.07			
100			24.9 1.79			73.4 7.46				1.58 0.24				115.9 21.7				294.7 24.6				0.71 0.11		
160		22.1 1.74					77.8 7.72				2.02 0.28				156.5 21.3				352.8 33.7				0.93 0.12	
220	21.1 1.57							87.3 8.81				2.32 0.27				201.8 27.5				413.3 34.6				1.12 0.02

kg N ha^{-1}	BDR_NDVI				BDR_R_{730}/R_{670}				BDR_R_{760}/R_{670}				BDR_R_{780}/R_{650}				BDR_R_{760}/R_{730}				BDR_WI			
0	0.70 0.05				4.09 0.82				5.77 1.38				5.54 1.19				1.40 0.06				1.22 0.02			
100		0.88 0.01				7.94 0.82				14.8 1.73				13.8 1.45				1.87 0.06				1.32 0.02		
160			0.91 0.01				9.44 0.71				20.17 1.61				18.6 1.30				2.14 0.04				1.36 0.02	
220			0.92 0.01					9.97 0.95				22.4 2.30				20.63 1.87				2.25 0.06				1.37 0.02

kg N ha^{-1}	BDR_REIP				BDR_PRI				BDR_VARI				CC_NDVI				CC_R_{730}/R_{670}				CC_R_{760}/R_{670}			
0	720.8 0.66				-0.06 0.01				0.14 0.07				0.37 0.07				1.54 0.14				2.21 0.37			
100		725.6 0.58				-0.02 0.01				0.36 0.05				0.63 0.04				2.25 0.20				4.45 0.62		
160			728.1 0.41				0.001 .0001				0.43 0.04				0.71 0.03				2.64 0.22				5.96 0.59	
220				729.3 0.51				0.001 .0001			0.45 0.03					0.74 0.03				2.85 0.24				6.87 0.81

kg N ha^{-1}	CC_R_{760}/R_{730}				GS_NDVI				GS_R_{774}/R_{656}				AFS_R_{760}/R_{730}				AFS_WI							
0	1.43 012				0.42 0.04				2.47 0.28															
100		1.97 0.12				0.63 0.04				4.40 0.62			**no data**				**no data**							
160			2.26 0.09				0.70 0.03				5.84 0.66													
220				2.41 0.13				0.74 0.02				6.77 0.64												
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d

Fig. 2. (*Continued*).

well as by the CC_NDVI and the ALS_WI for all three recording dates in 2010. This differentiation pattern was also obtained with other indices from the BDR, Crop Circle, and GreenSeeker; however, it was restricted to specific spectral assessment dates. Especially at ZS 6, the averages of the BDR indices NDVI, R_{730}/R_{670}, PRI, and VARI could not be distinguished between the N levels of 100–220 kg ha^{-1} (Fig. 3). There was only one index at a time, the GS_R_{774}/R_{656} at ZS 6, that did not show any differentiation between the four N levels.

In comparing the differentiation patterns of both agronomic parameters and spectral indices, a number of similarities were observed, especially in the growing season 2009. Biomass parameters and spectral indices behaved quite similarly in this growing season and could mostly differentiate individual N levels. While not separating the N levels 160 and 220 kg ha^{-1}, the DW at the first sampling date, however, was reflected by the NDVI and VARI. Through the course of the two subsequent sampling dates, only a few spectral indices from 2009 did not match the differentiation pattern of the dedicated agronomic parameters. Differentiation patterns were less distinct in 2010, which might be based on the higher biomass production in 2010 as compared to 2009, and consequent spectral saturation effects as discussed later. Decreased biomass production in 2009 as compared to 2010 was possibly caused by lower temperatures and wet conditions in spring. However, the majority of the indices showed patterns similar to the biomass parameters in this growing season, hence, indicating a related behaviour. Mainly at the third sampling date in 2010, certain differentiation patterns of the indices did not correspond to those of the plant parameters and could hardly distinguish higher N rates.

3.3. Relationship between agronomic parameters and spectral indices

Linear and curvilinear relationships were chosen depending on the AIC criterion (Webster and McBratney, 1989) to assess the relationship between agronomic parameters and spectral indices. In general, the majority of relationships was best depicted by quadratic relationships.

Over the three sampling dates, all 17 indices of the four sensor systems were correlated with the agronomic parameters (Table S3 of Supplementary Data) and r^2-values are shown for each growing season in Table 3. At ZS 3, the r^2-values obtained for the relationships between sensors and agronomic parameters were higher in 2010 than in 2009, with the coefficients being as high as 0.96. However, it must be considered that only the bi-directional radiometer was available at the first sampling date 2009, and the differences among the r^2-values in 2009 and 2010 were between 0.02 and 0.39, being highest for the relationship with N content. The largest differences in r^2-values in the two growing seasons were found for the indices BDR_WI followed by BDR_VARI and BDR_R_{730}/R_{670} over all agronomical parameters. In contrast, at the second and third sampling dates, the values for the coefficients of determination of most indices increased in 2009 relative to 2010. At ZS 4, the parameter dry matter content had r^2-values ranging from 0.70 to 0.84 in 2009 compared to values ranging from 0.48 to 0.62 in 2010. However, at ZS 6, the r^2-values of this parameter were lower in both growing seasons than for the other agronomic parameters.

Taken together over all three sampling dates, the best relationships between spectral and agronomic data were found for the parameters aboveground N uptake, shoot fresh weight, and NNI, independent of the chosen index. On the other hand, independent of the agronomic parameters or recording dates, four indices appeared to be highly and consistently related to the sampling data: BDR_R_{760}/R_{730}, BDR_REIP, CC_NDVI, and CC_R_{760}/R_{730}.

By augmenting these findings with information on the differentiation patterns, the relationship between biomass parameters and spectral indices can be even better illustrated. The coefficients of determination for which the patterns of the indices and

(a) Zadoks stage 3

kg N ha^{-1}	DM [%]				DW [t ha^{-1}]				N content [%]				N uptake [kg ha^{-1}]				FW [t ha^{-1}]				NNI			
0				26.6 *2.86*	14.3 *5.84*				2.14 *0.25*				31.2 *15.1*				56.1 *28.5*				0.46 *0.12*			
100			23.7 *1.25*			20.0 *4.22*				3.18 *0.22*				63.6 *13.7*				84.6 *19.6*				0.80 *0.09*		
160		21.5 *1.56*					24.5 *3.69*				3.92 *0.25*				95.6 *12.1*				114.8 *18.7*				1.08 *0.06*	
220	20.4 *1.66*						24.9 *5.70*					4.37 *0.28*				108.4 *22.4*			123.9 *33.8*					1.21 *0.11*

kg N ha^{-1}	BDR_NDVI				BDR_R_{730}/R_{670}				BDR_R_{760}/R_{670}				BDR_R_{780}/R_{650}				BDR_R_{760}/R_{730}				BDR_WI			
0	0.78 *0.10*				7.27 *3.09*				10.5 *5.56*				8.72 *4.41*				1.38 *0.16*				1.10 *0.03*			
100		0.90 *0.03*				11.6 *2.64*				20.1 *5.29*				17.1 *4.21*				1.72 *0.10*				1.14 *0.02*		
160			0.93 *0.01*				13.7 *2.17*				26.3 *4.62*				22.8 *3.72*				1.91 *0.08*				1.16 *0.02*	
220			0.93 *0.01*				14.1 *2.50*				28.3 *6.67*				24.8 *5.58*					1.99 *0.13*			1.17 *0.02*	

kg N ha^{-1}	BDR_REIP				BDR_PRI				BDR_VARI				CC_NDVI				CC_R_{730}/R_{670}				CC_R_{760}/R_{670}			
0	718.6 *2.34*				-0.03 *0.03*				0.35 *0.14*				0.32 *0.04*				1.45 *0.09*				*1.96* *0.18*			
100		723.0 *0.89*				0.01 *0.02*				0.52 *0.09*				0.58 *0.06*				2.05 *0.25*				3.91 *0.80*		
160			724.8 *0.70*				0.03 *.001*				0.58 *0.06*				0.68 *0.05*				2.42 *0.35*				5.50 *1.20*	
220			725.5 *1.12*				0.03 *.001*				0.60 *0.07*				0.70 *0.05*				2.51 *0.37*				5.77 *1.39*	

kg N ha^{-1}	CC_R_{760}/R_{730}				GS_NDVI				GS_R_{774}/R_{656}				AFS_R_{760}/R_{730}				AFS_WI							
0	1.35 *0.04*				0.47 *0.09*				2.89 *0.72*				1.44 *0.10*				0.99 *0.01*							
100		*1.89* *0.14*				0.60 *0.06*				4.05 *0.72*				1.66 *0.07*				1.00 *0.01*						
160			2.26 *0.16*				0.66 *0.04*				5.02 *0.72*				1.82 *0.08*				1.01 *0.01*					
220			2.28 *0.19*				0.68 *0.06*				5.42 *1.09*					1.89 *0.10*			1.02 *0.01*					
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d

(b) Zadoks stage 4

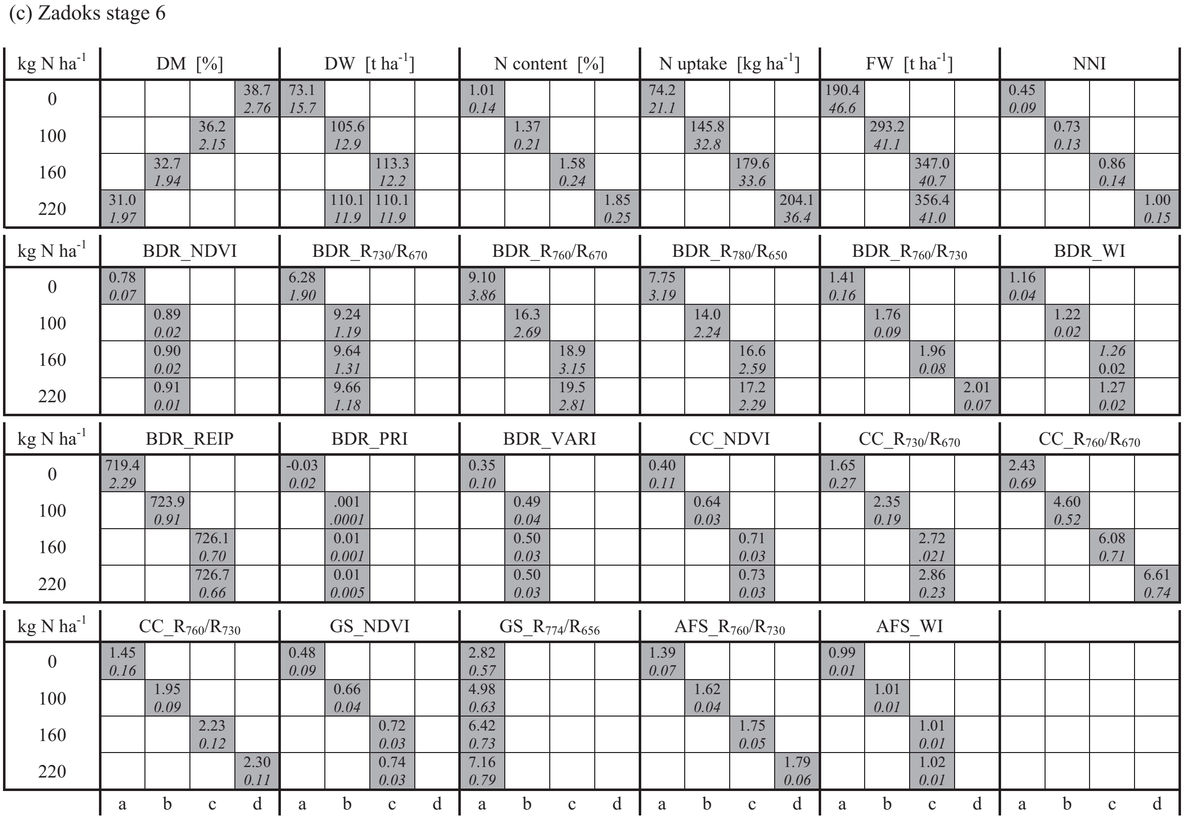
kg N ha^{-1}	DM [%]				DW [t ha^{-1}]				N content [%]				N uptake [kg ha^{-1}]				FW [t ha^{-1}]				NNI			
0				26.5 *2.46*	41.5 *12.0*				1.21 *0.19*				50.9 *19.2*				161.1 *57.5*				0.42 *0.10*			
100			22.9 *1.56*			57.5 *8.88*				1.63 *0.24*				93.5 *19.3*				255.7 *34.7*				0.66 *0.10*		
160		20.8 *1.10*					68.4 *9.15*				2.02 *0.33*				137.4 *24.7*				326.9 *28.6*				0.88 *0.13*	
220		20.0 *3.24*					72.3 *12.9*					2.32 *0.28*				167.3 *33.5*				363.6 *47.6*				1.03 *0.14*

kg N ha^{-1}	BDR_NDVI				BDR_R_{730}/R_{670}				BDR_R_{760}/R_{670}				BDR_R_{780}/R_{650}				BDR_R_{760}/R_{730}				BDR_WI			
0	0.71 *0.10*				4.48 *1.66*				6.82 *3.02*				6.23 *2.62*				1.37 *0.14*				1.19 *0.04*			
100		0.88 *0.01*				9.35 *1.17*				16.0 *2.20*				14.21 *1.56*				1.71 *0.06*				1.27 *0.02*		
160			0.91 *0.01*				10.9 *1.72*				21.2 *3.78*				19.0 *3.10*				1.93 *0.07*				1.30 *0.02*	
220			0.91 *0.01*				11.1 *1.85*				22.2 *4.23*				20.0 *3.48*					1.99 *0.07*			1.30 *0.02*	

kg N ha^{-1}	BDR_REIP				BDR_PRI				BDR_VARI				CC_NDVI				CC_R_{730}/R_{670}				CC_R_{760}/R_{670}			
0	719.5 *2.06*				-0.03 *0.02*				0.23 *0.11*				0.34 *0.14*				1.51 *0.32*				2.20 *0.81*			
100		723.7 *0.79*				0.02 *0.01*				0.48 *0.05*				0.64 *0.04*				2.39 *0.32*				4.72 *0.80*		
160			725.9 *0.65*				0.04 *.0001*				0.56 *0.04*				0.75 *0.03*				3.05 *0.33*				7.13 *0.93*	
220				726.6 *0.72*			0.04 *0.01*				0.57 *0.04*				0.78 *0.03*					3.31 *0.37*				8.13 *1.12*

kg N ha^{-1}	CC_R_{760}/R_{730}				GS_NDVI				GS_R_{774}/R_{656}				AFS_R_{760}/R_{730}				AFS_WI							
0	1.41 *0.20*				0.43 *0.10*				2.71 *0.74*				1.40 *0.08*				0.96 *0.01*							
100		1.97 *0.09*				0.64 *0.04*				4.81 *0.71*				1.63 *0.04*				0.99 *0.01*						
160			2.34 *0.09*				0.72 *0.06*				6.69 *0.84*				1.79 *0.04*				0.99 *0.01*					
220				2.45 *0.10*				0.76 *0.04*				7.62 *0.96*				1.84 *0.04*			1.00 *0.01*					
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d

Fig. 3. Mean value comparisons indicated separately for each biomass and nitrogen status parameter as well as spectral indices for the three sampling dates at each *N* application rate (kg N ha^{-1}) in 2010. Differentiation patterns are depicted for spectral indices obtained from one bi-directional passive radiometer (BDR) and three active sensors (Crop Circle, CC; GreenSeeker, GS; active flash sensor, AFS) as well as for the agronomic parameters dry matter content (DM), shoot dry weight (DW), *N* content, aboveground *N* uptake, shoot fresh weight (FW), and nitrogen nutrition index (NNI). Different letters show significant differences at $p \leq 0.05$. For all parameters and indices (each $n = 28$) mean values and standard deviations (italic) are added.



(c) Zadoks stage 6

kg N ha^{-1}	DM [%]				DW [t ha^{-1}]				N content [%]				N uptake [kg ha^{-1}]				FW [t ha^{-1}]				NNI			
0				38.7 *2.76*	73.1 *15.7*				1.01 *0.14*				74.2 *21.1*				190.4 *46.6*				0.45 *0.09*			
100			36.2 *2.15*			105.6 *12.9*				1.37 *0.21*				145.8 *32.8*				293.2 *41.1*				0.73 *0.13*		
160		32.7 *1.94*					113.3 *12.2*				1.58 *0.24*				179.6 *33.6*				347.0 *40.7*				0.86 *0.14*	
220	31.0 *1.97*					110.1 *11.9*	110.1 *11.9*					1.85 *0.25*				204.1 *36.4*			356.4 *41.0*					1.00 *0.15*

kg N ha^{-1}	BDR_NDVI				BDR_R_{730}/R_{670}				BDR_R_{760}/R_{670}				BDR_R_{780}/R_{650}				BDR_R_{760}/R_{730}				BDR_WI			
0	0.78 *0.07*				6.28 *1.90*				9.10 *3.86*				7.75 *3.19*				1.41 *0.16*				1.16 *0.04*			
100		0.89 *0.02*				9.24 *1.19*				16.3 *2.69*				14.0 *2.24*				1.76 *0.09*				1.22 *0.02*		
160		0.90 *0.02*				9.64 *1.31*					18.9 *3.15*				16.6 *2.59*				1.96 *0.08*				*1.26* 0.02	
220		0.91 *0.01*				9.66 *1.18*					19.5 *2.81*				17.2 *2.29*					2.01 *0.07*			1.27 *0.02*	

kg N ha^{-1}	BDR_REIP				BDR_PRI				BDR_VARI				CC_NDVI				CC_R_{730}/R_{670}				CC_R_{760}/R_{670}			
0	719.4 *2.29*				-0.03 *0.02*				0.35 *0.10*				0.40 *0.11*				1.65 *0.27*				2.43 *0.69*			
100		723.9 *0.91*				.001 *.0001*				0.49 *0.04*				0.64 *0.03*				2.35 *0.19*				4.60 *0.52*		
160			726.1 *0.70*			0.01 *0.001*				0.50 *0.03*					0.71 *0.03*				2.72 *.021*				6.08 *0.71*	
220			726.7 *0.66*			0.01 *0.005*				0.50 *0.03*					0.73 *0.03*				2.86 *0.23*					6.61 *0.74*

kg N ha^{-1}	CC_R_{760}/R_{730}				GS_NDVI				GS_R_{774}/R_{656}				AFS_R_{760}/R_{730}				AFS_WI							
0	1.45 *0.16*				0.48 *0.09*				2.82 *0.57*				1.39 *0.07*				0.99 *0.01*							
100		1.95 *0.09*				0.66 *0.04*			4.98 *0.63*					1.62 *0.04*				1.01 *0.01*						
160			2.23 *0.12*				0.72 *0.03*		6.42 *0.73*						1.75 *0.05*				1.01 *0.01*					
220				2.30 *0.11*			0.74 *0.03*		7.16 *0.79*							1.79 *0.06*			1.02 *0.01*					
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d

Fig. 3. (*Continued*).

the agronomic parameters agree are highlighted in Table 3. For the first sampling date, a quite controversial picture between the two growing seasons was obtained: on the one hand, most of the bi-directional radiometer indices in 2009 (except BDR_NDVI and BDR_VARI) matched the patterns of the parameters DM, *N* content, aboveground *N* uptake, FW, and NNI. On the other hand, in the growing season 2010, only one index, BDR_R_{760}/R_{730}, behaved analogously, except for FW, but the r^2-values in 2010 were in nearly all cases higher than those in 2009. For FW, each index agreed with the parameter's *N* level in both years at ZS 3, except for three indices, BDR NDVI, R_{760}/R_{730}, and VARI.

For the second sampling date, the sensor indices of the Crop Circle and the GreenSeeker, except for CC_NDVI, did match the pattern of differentiation for FW or for all three nitrogen parameters. However, for 2010, this was the case only for BDR_R_{760}/R_{730} and BDR_REIP. In the case of the bi-directional radiometer in 2009, the patterns' analogies of each agronomic parameter behaved comparably: all indices, except for BDR_NDVI and BDR_WI, fit the dedicated pattern and showed even higher r^2-values than in 2010. Similarly, at ZS 6 in 2009, the indices from the Crop Circle and the GreenSeeker as well as most indices of the BDR were in line with the patterns for each biomass parameter. Additionally, at the same date, relationships between the spectral and biomass data showed higher r^2-values in 2009 than in 2010.

Regarding both the differentiation patterns and the r^2-values, the bi-directional radiometer index BDR_R_{760}/R_{730} was most closely related to all biomass parameters over both seasons.

4. Discussion

Four reflectance sensors, including one passive bi-directional hyperspectral and three active sensors were tested over two seasons to detect differences in the nitrogen nutritional status and in crop biomass parameters. Spectral information was related to six destructively assessed parameters at ZS 3, 4, and 6. The observed biomass parameters were well described by selected indices throughout the two growing seasons, if only considering the coefficients of determination. However, the indices differed markedly in their ability to reflect the influence of the single *N* levels on destructively sampled biomass parameters as reflected in the ANOVA results (Figs. 2 and 3). 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.

Saturation effects with increasing *N* rates and dense canopies are more likely when using red light-dependent indices. With high biomass and LAI values, the reflectance of red spectral ranges tends to be saturated sooner than when using NIR-based reflectance indices (Hatfield et al., 2008; Mistele and Schmidhalter, 2008b). Therefore, reflectance patterns are strongly influenced by growing seasons and developmental stages (Prasad et al., 2007). This influence was evident from the first sampling date, when the shoot fresh weight could well be distinguished by the majority of the indices. However, such a differentiation was less distinct for the *N*-status parameters, *N* content, aboveground *N* uptake and NNI. At this stage, the *N* concentration was highest in all treatments with only small differences being observed. Detection of the *N* status of canopies with incomplete ground cover is quite complex due to the antagonism of high *N* concentration going along with low biomass amounts (Fitzgerald et al., 2010). With further biomass increases, the effect of dilution of *N* progresses because *N* uptake cannot keep pace with the biomass increase (Justes et al., 1997). At later stages, the saturation effect of red reflection increases with biomass, but a better segregation of *N* parameters is possible due to a favourable balance between biomass and *N* concentration.

Generally, for all sensors, the closest relationships were observed between spectral indices and the nitrogen status-related

Table 3
Coefficients of determination for the relationships between spectral indices obtained from one bi-directional passive radiometer (BDR) and three active sensors (Crop Circle, CC; GreenSeeker, GS; active flash sensor, AFS) and the agronomic parameters dry matter content (DM), aerial shoot dry weight (DW), *N* content, *N* uptake, shoot fresh weight (FW), and nitrogen nutrition index (NNI) for the three sampling dates at Zadoks stages 3, 4, and 6 in 2009 and 2010.

Zadoks stage 3	DM		DW		*N* content		*N* uptake		Z		NNI	
	’09	’10	’09	’10	’09	’10	’09	’10	’09	’10	’09	’10
BDR_NDVI	0.53	0.82	0.67	0.84	0.50	0.78	0.72	0.86	0.71	0.89	0.68	0.85
BDR_R_{730}/R_{670}	0.49*	0.68*	0.60	0.80	0.39	0.67	0.61	0.79	0.65	0.83	0.55	0.75
BDR_R_{760}/R_{670}	0.60	0.71*	0.62	0.83	0.49	0.73	0.71	0.86	0.71	0.87	0.69	0.82
BDR_R_{780}/R_{650}	0.64	0.72*	0.63	0.85	0.53	0.76	0.75	0.88	0.73	0.89	0.71	0.85
BDR_R_{760}/R_{730}	0.76*	0.78*	0.63	0.88	0.75	0.90	0.86	0.97	0.75	0.92	0.87	0.96
BDR_WI	0.59	0.80*	0.66	0.85	0.45	0.84	0.70	0.91	0.73	0.90	0.63	0.90
BDR_REIP	0.76*	0.78*	0.60	0.91	0.79	0.91	0.86	0.97	0.73	0.94	0.89	0.96
BDR_PRI	0.72*	0.78*	0.66	0.89	0.70	0.81	0.85	0.91	0.77	0.92	0.84	0.88
BDR_VARI	0.49*	0.73	0.65	0.80	0.40	0.68	0.64	0.80	0.69	0.84	0.57	0.76
CC_NDVI		0.77*		0.81*		0.83		0.90		0.89		0.89
CC_R_{730}/R_{670}		0.59*		0.71*		0.62		0.74*		0.74*		0.70*
CC_R_{760}/R_{670}		0.59*		0.73		0.64		0.77*		0.76*		0.74*
CC_R_{760}/R_{730}		0.73*		0.82		0.81		0.89		0.87		0.88
GS_NDVI		0.70		0.73		0.73		0.79		0.78		0.78
GS_R_{774}/R_{656}		0.59*		0.65*		0.63		0.70		0.69		0.69*
AFS_R_{760}/R_{730}		0.75*		0.83		0.84		0.92		0.88		0.91
AFS_WI		0.73*		0.72*		0.76*		0.83		0.81		0.82

Zadoks stage 4	DM		DW		*N* content		*N* uptake		FW		NNI	
	’09	’10	’09	’10	’09	’10	’09	’10	’09	’10	’09	’10
BDR_NDVI	0.83	0.61	0.87	0.78	0.80	0.59	0.92	0.81	0.94	0.90	0.90	0.77
BDR_R_{730}/R_{670}	0.75	0.52	0.75	0.62	0.72	0.60	0.82	0.73	0.84	0.74	0.80	0.71
BDR_R_{760}/R_{670}	0.73*	0.53	0.72*	0.63	0.70	0.65	0.80	0.78	0.82*	0.78	0.77	0.75
BDR_R_{780}/R_{650}	0.73*	0.54	0.72*	0.64	0.71	0.68	0.80	0.80	0.82*	0.80	0.77	0.78
BDR_R_{760}/R_{730}	0.82	0.60	0.79	0.73	0.82	0.73	0.90	0.88	0.89	0.91	0.89	0.85
BDR_WI	0.71	0.58	0.81	0.71	0.73	0.61	0.80	0.78	0.83	0.83	0.79	0.75
BDR_REIP	0.84	0.61	0.80	0.76	0.85	0.73	0.91	0.89	0.90	0.92	0.90	0.86
BDR_PRI	0.84	0.62	0.84	0.77	0.83	0.66	0.93	0.86	0.93	0.91	0.91	0.82
BDR_VARI	0.82	0.58	0.82	0.72	0.81	0.64	0.92	0.82	0.91	0.85	0.90	0.78
CC_NDVI	0.82	0.61	0.83	0.76	0.80	0.70	0.91	0.87	0.92	0.90	0.89	0.84
CC_R_{730}/R_{670}	0.70*	0.50	0.70	0.61	0.68	0.69	0.79	0.79	0.80	0.76	0.76	0.78
CC_R_{760}/R_{670}	0.75*	0.50	0.70	0.61	0.74	0.71	0.83	0.81	0.82*	0.78*	0.81	0.80
CC_R_{760}/R_{730}	0.83	0.58	0.77	0.71	0.83	0.75	0.91	0.89	0.88	0.88	0.90	0.86
GS_NDVI	0.83	0.58	0.74	0.72	0.81	0.70	0.87	0.85	0.85	0.86	0.86	0.83
GS_R_{774}/R_{656}	0.75	0.48	0.55	0.61	0.78*	0.70	0.75	0.80	0.68	0.77	0.77	0.79
AFS_R_{760}/R_{730}		0.57		0.69		0.75		0.88		0.86		0.86
AFS_WI		0.58		0.70		0.61		0.77		0.82		0.74

Zadoks stage 6	DM		DW		*N* content		*N* uptake		FW		NNI	
	’09	’10	’09	’10	’09	’10	’09	’10	’09	’10	’09	’10
BDR_NDVI	0.47	0.53	0.90	0.65	0.71	0.52	0.88	0.68	0.93	0.72	0.84	0.64
BDR_R_{730}/R_{670}	0.57*	0.43	0.80	0.49	0.73	0.44	0.86	0.53	0.89	0.55	0.82	0.52
BDR_R_{760}/R_{670}	0.61*	0.52	0.79	0.53	0.78	0.55	0.89	0.63	0.91	0.62	0.86	0.62
BDR_R_{780}/R_{650}	0.62*	0.55	0.80	0.54	0.79	0.58	0.90	0.66	0.91	0.64	0.87	0.65
BDR_R_{760}/R_{730}	0.58*	0.64	0.84	0.61	0.82	0.69	0.94	0.77	0.93	0.74	0.91	0.76
BDR_WI	0.51	0.63	0.84	0.62	0.72	0.60	0.86	0.72	0.90	0.74	0.82	0.70
BDR_REIP	0.59*	0.64	0.84	0.66	0.83	0.68	0.94	0.79	0.93	0.78	0.91	0.77
BDR_PRI	0.52	0.52	0.84	0.65	0.70	0.52	0.84	0.69	0.90	0.73	0.81	0.65
BDR_VARI	0.53*	0.42	0.81	0.56	0.69	0.41	0.83	0.57	0.89	0.61	0.79	0.53
CC_NDVI	0.56*	0.61	0.85	0.69	0.76	0.68	0.89	0.81	0.92	0.79	0.86	0.78
CC_R_{730}/R_{670}	0.63*	0.58	0.71	0.58	0.75	0.63	0.83	0.72	0.85	0.70	0.82	0.71
CC_R_{760}/R_{670}	0.67*	0.63*	0.69	0.57	0.79	0.67	0.85	0.74	0.86	0.72	0.84	0.73
CC_R_{760}/R_{730}	0.63*	0.67	0.76	0.63	0.79	0.70	0.87	0.79	0.88	0.77	0.86	0.78
GS_NDVI	0.57	0.61	0.84	0.65	0.78	0.68	0.91	0.79	0.93	0.76	0.88	0.77
GS_R_{774}/R_{656}	0.63*	0.62*	0.80*	0.54	0.78	0.66	0.86	0.72	0.87*	0.70*	0.85	0.72
AFS_R_{760}/R_{730}		0.67*		0.60		0.71		0.78		0.76		0.78
AFS_WI		0.47		0.63		0.52		0.67		0.69		0.63

[*] Models follow linear or quadratic courses, appropriateness assessed by the variable part of the AIC. Highlighted values indicate an analogous pattern of differentiation between an index and a parameter. All results were significant at $p < 0.001$ for $n = 112$.

parameters, *N* content, aboveground *N* uptake, and NNI, and these relationships are therefore primarily discussed. Spectral proximal sensing allowed us to differentiate the influence of the four *N* levels ranging from 0 to 220 kg N ha^{-1} on the *N*-status parameters across the seasons. Closer relationships were observed with *N* uptake and NNI than with *N* content. In agreement with this observation, similar findings have previously been reported for aboveground *N* uptake as compared to *N* content, independent of the illumination source or the viewing angle (Schmidhalter et al., 2003; Mistele and Schmidhalter, 2008a; Li et al., 2009; Fitzgerald et al., 2010). The BDR REIP was comparably well related to NNI and aboveground *N* uptake, thus, contrasting with a previous report that indicated a closer relationship between REIP and NNI for wheat plants (Mistele and Schmidhalter, 2008a). Whereas our measurements were conducted in the nadir direction, information was obtained from an oblique view in this previous study.

For all sensors, throughout the two observation years, the R_{760}/R_{730} index best predicted the investigated crop parameters. Among the passive reflectance indices, the REIP was comparable to the BDR_R_{760}/R_{730} index in its accuracy of prediction. Similar results were repeatedly found in wheat experiments (Mistele et al., 2004; Mistele and Schmidhalter, 2008b; Strenner and Maidl, 2010) and also for growth stages between ZS 3 and 6, when these indices were found to best predict aboveground N uptake. In accordance with Strenner and Maidl (2010), saturation of the REIP was observed with high N supply. This behaviour of the REIP can be explained by its dependency on red light being prone to saturation. Hence, despite displaying high r^2-values, the REIP cannot entirely reflect the N status of the crop. 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) and is, therefore, preferred for reflecting the N status in wheat. A high predictive quality was also found for the CC_R_{760}/R_{730}, which was the best index provided by the Crop Circle. However, the high predictive quality of this index was limited to the later growth stages, ZS 4 and ZS 6.

As has been shown previously, the NDVI is strongly prone to saturation with increasing biomass or LAI exceeding 2.5–3 (Aparicio et al., 2000; Serrano et al., 2000; Li et al., 2008). Saturation is frequent for dense crop stands in Europe with LAI values up to 8.0 (Heege et al., 2008). Considering that mostly quadratic relationships best described the spectral information, reflectance differences between higher N levels decrease, causing saturation. This response was observed earlier for the NDVI than for other spectral indices. The saturation response was apparent for any NDVI-based index throughout the experiment, except for GS_NDVI at ZS 4. This finding contrasts with other investigations done with the GreenSeeker in which the NDVI showed strong saturation effects in maize (Hong et al., 2007) and in wheat (Li et al., 2010) at similar growth stages. On the other hand, due to its characteristic asymptotic course with high crop densities, the NDVI is particularly sensitive at small biomass and low ground coverage (Fig. 3). Therefore, this index may be more suitable for differentiating plant canopies at early growth stages or in more sparsely grown crop stands.

The CC_NDVI reflected a similar behaviour related to the N parameters. This behaviour was also demonstrated in several comparisons of the Crop Circle and GreenSeeker sensors, primarily in maize canopies (Hong et al., 2007; Devadas, 2009; Sudduth et al., 2010). However, due to the flexibility in choosing specific wavelengths filters for the Crop Circle, we were able to calculate a R_{760}/R_{730} index as well for that device. This capability turned out to be strongly advantageous because, as for the bi-directional passive radiometer, the CC_R_{760}/R_{730} did not display any tendency to saturation with high coefficients of determination. In previous investigations, different indices have been calculated for the Crop Circle. Trotter et al. (2008) and Fitzgerald et al. (2010) used simple ratios, the soil adjusted vegetation index (SAVI), and the NDVI for Crop Circle measurements, but mainly limited their study to biomass and LAI characteristics of small grain cereals. As far as we know, no attempt has yet been made to choose interference filters to record wavelengths depicting NIR/NIR indices with the Crop Circle. The results of this study show that by choosing a high-performing vegetation index for the active Crop Circle sensor, we were able to successfully identify the wheat nitrogen status.

Disregarding the fact that the AFS was only available in 2010, its R_{760}/R_{730} index turned out to recognise the N status about as well as the other devices. Similar results have been found for comparable active flash devices by Jasper et al. (2009) and Mistele and Schmidhalter (2010a), however, with oblique viewing angles. As in our work, high r^2-values were observed and the ability to discriminate different N levels was demonstrated. Furthermore, the coefficients of determination were as high as those obtained for the passive reflectance sensor.

The predictive quality for DM, and also water content and DW differed strongly between growing seasons. The best relationships were found at the second sampling date, ZS 4, when leaves were fully developed but the spikes had not yet appeared. As structural components such as spikes strongly influence spectral reflectance, they can impact the sensitivity of the indices, which may decrease the predictive accuracy at later stages (Aparicio et al., 2002).

5. Conclusion

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. However, a potential saturation effect in the relationship between the vegetation index and the crop parameters was not well reflected by the coefficients of determination. An additional analysis of the sensors' ability to 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 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 identifying the investigated parameters due to saturation effects. With regard to the best R_{760}/R_{730} index, the estimates from the passive radiometer were slightly better than those from the Crop Circle and the AFS.

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

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.fcr.2011.06.007.

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