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Spectral measurements of the total aerial N and biomass dry weight in maize using a quadrilateral-view optic

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Abstract

Heterogeneous crop stands require locally adapted nitrogen fertilizer application based on rapid and precise measurements of the local crop nitrogen status. In the present study, we validated a promising technique for the latter, namely a tractor-mounted field spectrometer with an oblique quadrilateral-view measuring optic, measuring solar radiation and canopy reflectance in four directions simultaneously. Dry matter yield (kg ha^{-1}), total N content (g N g^{-1} dry matter) and total aerial N (aboveground N-uptake) (kg N ha^{-1}) in maize were determined in 10 m^2 calibration areas in 60 plots differing in their N treatment and seeding density three times in each of three years under field conditions. Results show that the sensor used can reliably determine total aerial N ranging from as little as 5 kg N to 150 kg N ha^{-1} with R^2-values $\geq$0.81 in 2002 and 2004, and with R^2-values ranging from $\geq$0.57 to 0.84 in 2003. Dry matter yields from as low as 0.3–4.2 t ha^{-1} could be determined with R^2-values ranging from 0.67 to 0.91 in 2002 to 2004. The capacity to ascertain DM yield spectrally was drastically reduced in the higher yield range ($>$6 t ha^{-1}) probably due to decreased sensitivity of the spectral signal. N-contents were generally not well determined. Taken together there is a good potential to determine reliably differences in total aerial N or DM yield from the five leaf stages unfolded to the five node stage where typically nitrogen applications are carried out.

Weather conditions and zenith angles of up to 30° hardly influenced the results appreciably. We conclude that the tractor-based oblique quadrilateral-view optic reflectance sensor represents a suitable instrument to quickly and non-destructively determine crop nitrogen status and therefore allows for site-specific fertilizer application when coupled with a fertilizer algorithm and variable-rate applicator.

Keywords: Nitrogen content; Nitrogen uptake; Precision farming; Reflectance; Sensor; Tractor

1. Introduction

Soil conditions such as water and nutrient supply and the terrain factors exposition and inclination vary on heterogeneous field sites and can lead to local differences in plant growth (Auerswald et al., 1997). Similarly, differences in soil organic matter content, soil water availability and soil temperature can influence nitrogen mineralization and thus nitrogen supply (Cambardella et al., 1994; Cahn et al., 1994): warm and humid soil conditions enhance nitrogen supply, whereas dry periods decrease it. Under rainfed conditions both situations can occur, with their relative occurrence varying from year to year (Kolberg et al., 1999). Thus, spatially targeted and temporally optimized nitrogen fertilizer application is highly desirable for both economic and ecological reasons (Schmidhalter et al., 2006). Current fertilization management is generally based on soil analysis, but this practice disregards any local variation in either nitrogen demand or nitrogen mineralization. Analysis of the plants themselves can be used as indicator for the N supply from the soil within the growth period (Olfs et al., 2005); however, the destructive methods that are currently in use are time-consuming and cannot sufficiently reflect the spatial variability. Also optical transmission measurements with a handheld chlorophyll meter (SPAD) are time consuming, however accurate on the measured spot (Blackmer et al., 1994; Cartelat et al., 2005).

Instead, spectral measurements show great promise in determining the crop nitrogen status. Several studies have evaluated the relationship between leaf chlorophyll content and leaf reflectance (Cartelat et al., 2005; Gitelson et al., 2003), with the former potentially giving an indirect estimate of the nutrition status given that much of the leaf nitrogen is integrated

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in chlorophyll (Cartelat et al., 2005; Read et al., 2002). In addition, chlorophyll content is also closely related to plant stresses like drought or nutrient deficiencies (Carter and Knapp, 2001). Previous studies indicate that the strongest relationships between leaf reflectance and chlorophyll content occur in either the green spectrum near 550 nm or the far red spectrum near 700 nm (Gitelson et al., 2003; Carter and Spiering, 2002; Read et al., 2002). To estimate biomass dry weight per unit area using spectral techniques, reflectance measurements in the near infrared (NIR) waveband are most useful. Reflectance in this range is mainly characterized by the difference in the optical densities between the water saturated cell walls and the intercellular region, and so is chiefly determined by biomass dry weight per unit area (Major et al., 2003; Gates et al., 1965).

The full potential offered by spectral techniques has not been realized because of limitations in their current implementation. Many studies employing spectral measurements have been conducted with handheld sensors measuring in the nadir with small calibration areas used on homogeneous fields (Reusch, 1997). In maize, this means that handheld sensors usually measure a relatively small area (one row at most) with the potential of high variability caused by interrow differences in leaf area. To account for the latter, it has been suggested that at least 2.5 rows in the field of view should be measured (Major et al., 2003). Techniques based on proximate sensors suffer from a FOV smaller than the required 2.5 rows and the sensitivity to the position of the sun with respect to row orientation as function of the BRDF characteristics of maize (Major et al., 2003).

To avoid the error, associated with the zenith angle different principles are available. Active sensor systems like the GreenSeeker (Ntech Industries, USA) (Lukina et al., 2001; Raun et al., 2002), N-Sensor ALS (Yara GmbH & Co. KG, Germany) and the laser sensors (Planto, Germany) (Bredemeier and Schmidhalter, 2003), (Fritzmeier, Germany) (Schächtl et al., 2005) use their own light source. To investigate whether or not such limitation could be overcome with passive sensor systems, we conducted field studies with a hyperspectral oblique quadrilateral-view field spectrometer mounted on a tractor to enable field-scale measurements (Schmidhalter et al., 2003). From this oblique quadrilateral-view, one can expect measurements to be nearly independent from the solar zenith angle because one optic always measures the side of the plants that is exposed to the sun, whereas another always measures that in the shadow (Mistele et al., 2004; Reusch, 2003). Two additional optics measure in two other directions, such that it is expected that the average signal will be nearly constant at any solar zenith angle. As such, the specific aim of this investigation was to validate spectral measurement techniques based on an oblique quadrilateral-view optical setup in maize on a field scale with different soil and growth conditions.

2. Material and methods

2.1. Experimental fields

The investigation was conducted on the research station Dürnast located near Freising, Germany and belonging to the Chair of Plant Nutrition of the Technical University of Munich. Maize (*Zea mays* cv. *Banguy*) was grown in three yearly field experiments at longitude 11.70E and latitude 48.40N. The use of different seeding densities and nitrogen treatments along with spatially variable soils led to a broad range in growth, development and N status of the maize plants. A brief description of the experimental conditions is given in Table 1.

For each of the three experimental years, different fields were chosen for investigation, each comprising heterogeneous soil conditions as indicated in Table 1. The differences in elevation within each site ranged between 12 m and 18 m. In 2002, the experimental field had a gentle slope; in 2003 and 2004, parts of the field sites included relatively steep slopes. The different soil classifications and the large range in the apparent electrical conductivity indicate sizeable differences in soil texture in the upper 1–2 m of the soil profile. The average annual temperature in Dürnast is 7.5 C°. The annual precipitation averages 800 mm with highest monthly rainfall in summer.

Five nitrogen treatments and three seeding densities (6, 10 and 14 plants/m^2) were evaluated in the field experiments. Nitrogen fertilization used Alzon (46% N) (SKW, Wittenberg, Germany), a long term urea-N fertilizer with ammonification inhibitor, with 0, 70, 120, 170 and 220 kg/ha nitrogen applied at

Table 1
Experimental fields and field conditions in the years from 2002 to 2004, including the range of the apparent electrical conductivity obtained with EM38 (EC_a = apparent electrical conductivity)

	Year		
	2002	2003	2004
Location	D 1	D 4	Haunerfeld
Size of experiment (ha)	3.6	3.8	3.8
Elevation (m)	462–474	458–475	486–498
Orientation	EES–WWN	EES–WWN	N–S
EC_a (mS m^{-1})	n.m.	20–72	17–52
Soil classification	Cambisol: silty clay loam, silty loam, loam	Cambisol: silty clay loam, silty loam, loam, sandy loam, skeletic cambisol, cumulic cambisol, cumulic anthrosol	Cambisol: silty loam, loam, clay loam

The soil classification follows FAO nomenclature (FAO et al., 1998).

plant emergence. At sowing, an additional 18 kg N/ha was applied as diammoniumphosphate and placed below the seeds. A split-plot experimental design with four replicate plots was used, with seeding density as the main plot and N treatments as the subplots. Each of the 60 total plots was 15 m in width and around 50 m in length.

2.2. Spectral measurements

Two sensors were used for the measurements with the spectral set-up being technically similar to the commercially available N-sensor (Yara N-sensor) (Yara GmbH & Co. KG, Dülmen, Germany) with fibre optics oriented to four directions. Wavelengths used by the Yara N-sensor are not known. Therefore, in the years 2002 and 2003 a five-wavelength scan mode was used for the first sensor, whereas for the second sensor a modified electronic (tec5, Oberursel, Germany) allowed to take hyperspectral readings for the second measurement in 2003 and all other measurements in 2004. The sensors used can measure 256 bands with a spectral detection range from 400 to 1000 nm and a bandwidth of 3.3 nm. To smooth the spectral readings, a weighted average over 5 pixels of about 16.5 nm was used in 2002. In 2003 and 2004, a fourth-order fit over five pixels was calculated to improve accuracy. In contrast to the Yara sensor configuration the sensor was not placed on the tractor roof, but in front of the tractor that allowed positioning the sensor set-up at comparable heights above the crop stand during the season. This allowed obtaining comparable fields of view.

This sensor contains two spectrometer units that measure reflectance and incident radiation simultaneously. One unit is linked to a cosine-corrected diffuser and measures the global radiation to compensate for any errors associated with different light conditions. The second unit is linked to a four-in-one light fiber to create an optical mixed signal encompassing four fields of view, and measuring the canopy at the four edges of the sensor. The optical inputs were positioned with azimuth angles of 80° between the front and rear sides and 100° between the left and right sides of the tractor. The zenith angle was set at $58 \pm 6^\circ$ to minimize the influence of the shadow from the tractor (Reusch, 2003). The sensor was mounted in front of the tractor two meters above the canopy. This enabled the sensor to measure four ellipses, each 1.25 m in length or around 5 m^2 in total.

The oblique view used has three advantages. First, the apparent biomass in the field of view increases theoretically with a factor, F, of 1.9, calculated as $F = (\sin 32^\circ)^{-1}$. Second, the oblique view, however, increases the plant:soil reflectance ratio and third, the oblique quadrilateral-view reduces the effect caused by the zenith angle because separate optical systems are continuously measuring both the sunlight exposed and shady sides of the plants.

The reflectance was measured at five wavelengths that contain information from either the visible (550, 670 and 700 nm) or the near infrared (NIR) parts (740 and 780 nm) of the spectrum. The reflectance intensity (R) at visible wavelengths is mainly influenced by plant pigments, and by chlorophyll in particular (Buschmann et al., 2000). By contrast, the reflectance intensity in the NIR is essentially characterized by the difference in the optical densities between the water saturated cell walls and intercellular air spaces, and corresponds strongly with biomass dry matter per area (Guyot, 1990; Gates et al., 1965). Selected indices summarizing the different reflectance intensities in the visible and NIR ranges were calculated as depicted in Table 2.

Table 2
Spectral indices

Abbreviation	Formula	Reference
NDVI	(R780 − R670)/(R780 + R670)	Rouse et al. (1973)
SR	R780/R670	Pearson and Miller (1972)
NIR/G	R780/R550	Takebe et al. (1990)
NIR/R	R780/R700	Mistele et al. (2004)
NIR/NIR	R780/R740	Mistele et al. (2004)
REIP	700 + 40((R670 + R780)/2 − R700)/(R740 − R700)	Guyot et al. (1988)

The normalized difference vegetation index (NDVI), the reflectance intensity ratio between NIR and red (SR) and the NIR to green (G) reflectance intensity ratio where calculated, with the reflectance at 550 nm (green) being influenced by both chlorophyll and carotenoid pigments.

The red edge of the reflection intensity signature is of interest because it contains information about both the chlorophyll absorption and the cell wall reflection, as well as the alteration between these main effects. Although the reflectance at 700 nm is beyond the maximum absorbance of chlorophyll and the beginning of the red edge, the absorbance is still high. With increasing N content, both the intensity of the reflection and the inflection point in the red edge changes. Therefore, we used a linear fitting for the red edge and a simplified formula to calculate the red-edge inflection point (REIP) (Guyot et al., 1988). The value for REIP determined using this formula is mainly determined by the reflectances at 780 nm and 740 nm because of the low arithmetic values of R_{670} and R_{700}. An additional index (NIR/NIR) was calculated as the ratio between the two similar NIR wavelengths.

Spectral measurements were conducted twice just before biomass sampling. The prevailing conditions throughout the measurements are described in Table 3. Measurement days were carefully chosen to be able to compare instrument performance under various weather conditions (cloudy, rainy, sunny) and at different sun angles. In particular, we wanted to evaluate the influence of either a low zenith angle or cloudy or rainy weather, conditions that a farmer is likely to experience and ones that cannot be used for measurements in the nadir with a single spectrometer.

2.3. Dry matter yield and nitrogen measurements

Shortly after the spectral measurements, the plants were harvested 4 cm above ground with a green forage chopper fitted with a weighing unit to determine the above-ground biomass (Mistele et al., 2004). Plots of 1.5 m in width and 2–6 m in length on both sides of the tractor within the FOV were

Table 3
Spectral measurement conditions in the years 2002, 2003 and 2004

	Year					
	2002					
Biomass sampling	1st		2nd		3rd	
Growth stage (BBCH)	16		32		67	
Dry matter yield (kg ha^{-1})	516		2956		6051	
Date	June 18	June 20	June 26	July 1	July 17	July 22
Time (h, min)	12:00	8:50	13:00	15:20	13:40	8:45
Zenith angle (°)	61	32 ± 2	63 ± 1	54 ± 2	61 ± 1	29 ± 3
Global radiation (W m^{-2})	921	619	870	565	475	597
Weather conditions	Sunny	Sunny	Sunny	Hazy	Cloudy	Sunny

	Year				
	2003				
Biomass sampling	1st	2nd		3rd	
Growth stage (BBCH)	17	34		69	
Dry matter yield (kg ha^{-1})	522	3494		8656	
Date	June 11	June 25	June 26	July 8	July 11
Time (h, min)	10:20	12:10	10:55	16:25	16:30
Zenith angle (°)	48 ± 3	60 ± 2	51 ± 3	44 ± 4	43 ± 5
Global radiation (W m^{-2})	627	528	748	524	490
Weather conditions	Sunny	Cloudy	Sunny hazy	Sunny/cloudy	Cloudy

	Year					
	2004					
Biomass sampling	1st		2nd		3rd	
Growth stage (BBCH)	15		17		36	
Dry matter yield (kg ha^{-1})	317		1232		4292	
Date	June 23	June 23	July 5	July 6	July 19	July 20
Time (h, min)	12:25	17:00	10:55	13:15	15:30	12:40
Zenith angle (°)	62 ± 1	40 ± 3	52 ± 4	63 ± 1	50 ± 4	61 ± 1
Global radiation (W m^{-2})	327	111	289	647	555	804
Weather conditions	Hazy	Rainy	Sunny/cloudy	Hazy	Cloudy	Sunny

Parameters for the destructive harvests (growth stage according to the BBCH-scale, dry matter yield) used for the spectral validation is further indicated. BBCH stands for Biologische Bundesanstalt, Bundessortenamt and Chemical industry. The BBCH-scale is based on the well-known cereal code developed by Zadoks et al. (1974).

harvested. A representative sub-sample was collected and dried after weighing to estimate the total dry matter yield (kg ha^{-1}). The dried samples were ground and analyzed for total N content (g N g^{-1} dry matter) with an Duma elementary analyzer (Macro-N, Foss Heraeus, Hanau, Germany). The total aerial N (aboveground N-uptake) (kg N ha^{-1}) was calculated as dry matter yield × total N content.

SPSS 11 (SPSS Inc., Chicago, USA) was used for statistical analysis. We used curvilinear models to establish a relationship between spectral indices and dry matter yield, total aerial N or total N content per harvest. Each relationship included measurements of all individual plots with varying fertilizer application rates, soil and terrain conditions.

3. Results

3.1. Dry matter yield, total nitrogen content and total aerial N

Mean, minimum and maximum values and standard deviations for dry matter yield, total N content and total aerial N of plants grown at different nitrogen supplies are shown in Table 4.

In 2002, both the coefficient of variation (CV) and standard deviation for both total N content and to a lesser degree total aerial N were higher than in the two subsequent years. In 2004, both the CV and the standard deviation for dry matter yield were higher than in the previous years. These results correspond with the visual inspection of the plants, with both weakly developed, light green and strongly developed, dark green crop stands been found in 2002.

This observation is also indirectly revealed in Table 5, where the correlation between total aerial N and total N content was higher in 2002 than in either 2003 or 2004. In fact, there was no correlation between total N content and total aerial N in 2004, but instead a strong correlation between total aerial N and dry matter yield. This latter result demonstrates further that the three years differed in their canopy development.

In 2002, a close relationship between N application and total aerial N existed. As the plants developed throughout the growing season, the differences between N treatments with respect to dry matter yield, total N content and total aerial N increased. By contrast, dry matter yield showed no consistent response to nitrogen application in 2003 and 2004. In 2003, total N content was related to the nitrogen application and was

Table 4
Minimum and maximum values, standard deviation and coefficient of variation (CV) of the destructively sampled plant parameters dry matter yield and total nitrogen content as well as for the calculated total aerial N, indicated for each of three years and three sampling times

Year	Biomass sampling	Dry matter yield				Total N content					Total aerial N (kg ha^{-1})				
		Minimum kg ha^{-1}	Maximum kg ha^{-1}	Average kg ha^{-1}	S.D. kg ha^{-1}	CV %	Minimum %	Maximum %	Average %	S.D. %	CV %	Minimum kg ha^{-1}	Maximum kg ha^{-1}	Average kg ha^{-1}	S.D. kg ha^{-1}	CV %
2002	1st	195	898	516	169	33	2.11	3.65	2.99	0.42	14	7	29	15.6	5.9	38
	2nd	1414	5706	2956	841	28	1.65	3.02	2.35	0.36	15	25	163	70	27	39
	3rd	2275	8416	6051	1294	21	0.93	2.13	1.46	0.28	19	23	139	90	28	31
2003	1st	198	898	512	177	35	2.75	3.79	3.39	0.18	5	7	30	17	5.7	34
	2nd	2138	4884	3494	686	20	1.58	2.75	2.25	0.22	10	47	116	78	16	21
	3rd	5855	10828	8656	1142	13	1.09	1.93	1.5	0.17	11	75	173	129	19	15
2004	1st	65	745	317	148	47	2.85	4.19	3.78	0.24	6	2	30	12	5.8	48
	2nd	317	2327	1232	446	36	2.02	2.99	2.47	0.2	8	7	57	30	10	33
	3rd	1818	6139	4292	1083	25	1.64	2.6	2.22	0.25	11	42	142	94	20	21

probably affected as well by the drought conditions present in this year. As such, the biomass production was probably influenced more strongly by water availability than by any potential N limitation.

Dry matter yield varied most strongly as influenced by the seeding density and the year, whereas total aerial N varied mostly depending on the fertilizer rate and as influenced by the year (Table 6).

3.2. Validation of spectral measurements

Shortly before the three harvests in the growing season, paired spectral readings under different weather conditions were taken with exception of the harvest in 2003. In Fig. 1, coefficients of determination of the relationships between reflectance indices and canopy parameters are indicated. Spectral measurements summarized by the NIR/NIR index generally described total aerial N the best, with an average R^2 of 0.79. However, the quality of the relationships did vary across and during the years. Total aerial N was consistently well described by both REIP and NIR/NIR with constant high R^2-values in 2002 and 2004. In 2003, the first measurement was of the same high level, but measurements for the second and third sampling were noticeably poorer. For REIP, the earliest sampling in 2004 represented an exception, with the results being much worse than those obtained with the other indices, implying that REIP is not useful for crop stands with only 300 kg ha^{-1} biomass dry weight. For all other measurements, both NIR/NIR and REIP reflected total aerial N with the same high quality. The NIR/G and NIR/R indices were also generally useful for describing total aerial N except for the measurements of the last sampling in 2003. SR and NDVI performed the worst among all indices at describing total aerial N, especially after flowering as shown by the last measurements in 2003 and 2004.

Spectral measurements based on the NIR/NIR index detected biomass dry weight with an average R^2 of 0.72, although dry matter yield was best described at early samplings across all years and indices. Relationships between indices and biomass were strongest early in the season, with exception of 2004 when DM yield were low at the first harvest. Similarly the dry matter yield was described by all indices.

Indices were most strongly related to dry matter yield in harvest 1 and 2 in 2003 and all harvests in 2004, in contrast to all other harvests where R^2 values were higher for total aerial N. Total N content was generally not well reflected in the spectral measurements in either 2003 or 2004. At best, only the indices REIP and NIR/NIR correlated weakly with total N content and then only for the last measurements in 2003. By contrast, R^2 values increased in relationships between indices and N content at higher biomass. Here, the best results were achieved with the indices REIP and NIR/NIR. The indices NIR/R and NIR/G presented comparable results to the previous two indices, whereas SR and NDVI were weakly related to N content.

Spectral indices in general were most influenced by seeding density, followed by the influence of the year and least by the fertilizer rate (Table 6). These results are in line with

Table 5
Correlation between any of seeding density, N fertilizer application, total aerial N and each of the destructively harvested plant parameters dry matter yield (DM), total N content (N %) as well as the calculated total aerial N

Year	Sampling	Correlation coefficients between							
		Seeding density and			N application rate and			Total aerial N and	
		DM	N%	Aerial N	DM	N%	Aerial N	DM	N%
2002	1st	0.47**	−0.32*	0.31*	0.26	0.74**	0.48**	0.95**	0.50**
	2nd	0.44**	−0.45**	0.20**	0.44**	0.61**	0.60**	0.91**	0.52**
	3rd	0.34*	−0.30*	0.06	0.60**	0.78**	0.82**	0.84**	0.79**
2003	1st	0.67**	−0.28*	0.65**	0.02	0.67**	0.14	0.98**	−0.08
	2nd	0.80**	−0.28*	0.66**	0.04	0.66**	0.37**	0.86**	0.25
	3rd	0.68**	−0.20	0.45**	0.12	0.56**	0.54**	0.69**	0.51**
2004	1st	0.46**	−0.10	0.43**	0.03	0.36**	0.08	0.99**	0.36**
	2nd	0.41**	−0.18	0.38**	0.17	0.26*	0.25	0.98**	−0.09
	3rd	0.58**	−0.37*	0.53**	0.19	0.25	0.39**	0.87**	−0.14

* $P < 0.05$.
** $P < 0.01$.

Table 6
Variance analysis for dry matter yield, total aerial N and canopy reflectance of NIR/NIR index with the factors seeding density, fertilizer rate and biomass sampling

Parameters	Dry matter yield			Total aerial N			NIR/NIR		
	DF[a]	*F* value[a]	Sig.[a]	DF[a]	*F* value[a]	Sig.[a]	DF[a]	*F* value[a]	Sig.[a]
Seeding density	2	148	***	2	18	***	2	857	***
Fertilizer rate	4	75	***	4	69	***	4	435	***
Biomass sampling	14	143	***	14	53	***	14	741	***

[a] Factors.
*** $P < 0.001$.

measurements of Rodriguez et al. (2006) in wheat for early growth stages.

To compare the influence of measurement conditions on spectral detection actual index values NIR/NIR obtained under various weather conditions (S, sunny; H, hazy; C, cloudy; R, rainy) and at different sun zenith angles from the same or next measurement days as a function of different DM yields in 2002, 2003 and 2004 have been depicted in Fig. 2.

Although paired comparisons for each sampling differ statistically from each other, differences were small and are largely ascribed to slight biomass increases between the different measurement days. The decrease in NIR/NIR values in the 3rd sampling in 2002 was probably caused by the low zenith angle of 32–26° with the statistical difference (paired *T*-test) between the measurements being very low with 0.01 NIR/NIR values with a confidence interval of 0.007–0.012 compared to the total range of 0.25 values. More clearly were differences for the first sampling in 2004 where rainy conditions probably increased the index values. Another comparable sensor was used for the 2nd measurement in 2003 and for all measurements in 2004 with a different calibration.

4. Discussion

The comparison of reflectance indices to measured crop parameters demonstrates that strong relationships exist between indices such as REIP or NIR/NIR and total aerial N, particularly in 2002 and 2004, with a tractor-based spectrometer under field conditions. This scanning method is rapid, easy, non-destructive, and, because it is tractor based, applicable to field-scaled dimensions. Moreover, spectral detection was not influenced by different soil conditions: the relationship between total aerial N and canopy reflectance could be estimated with a single curve for crop stands grown on either sandy or clay soils. This result is in contrast to other reports that indicate an influence on the canopy reflectance signal by the soil colour (Broge and Leblanc, 2001; Daughtry et al., 2000; Huete et al., 1985).

The results of our field studies are in line with those from other studies obtained under well controlled experimental plot conditions with nadir measurements 5–10 m above the canopy (Osborne et al., 2002), although they seem to be more constant. This result may be due to the measuring geometry, which generates mixed signals from four edges of the tractor, together with the large areas used for the destructive validations. Another positive effect of the oblique view used is that the LAI increases theoretically with a factor *F* of 1.9 because the light rays pass a longer way across the canopy. This effect is particularly interesting in maize, where the intercepted radiation per LAI is not as high as in other crops (Ehlert, 1996). Measurements made earlier in the season are therefore possible with such a measurement device, as demonstrated by those made at BBCH 15 (BBCH-scale), which yielded a reliable estimate of the N status. In comparison to results

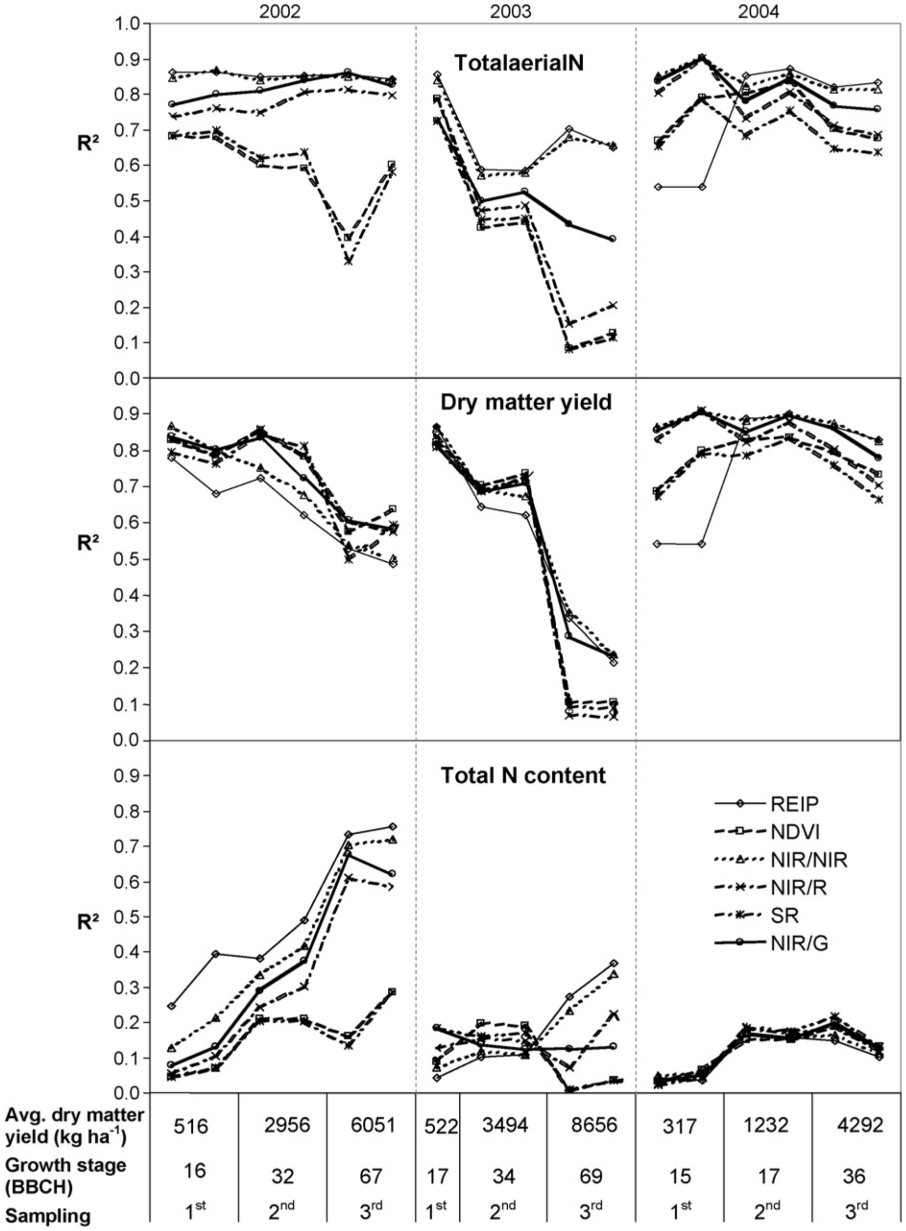

Fig. 1. Coefficients of determination (R^2-values) between reflectance indices and each of the canopy parameters dry matter yield, total aerial N and total N content for each of three experimental years.

obtained from early measurements the amount of variation in DM yield, total aerial N and N content explained a positive effect of the oblique view.

A consequence of the increased dry matter yield being measured in the field of view is a stronger saturation effect especially in the red area. In this area, the differences in reflectance are low despite of the high technical contrast of the spectrometer. As a likely consequence of this saturation effect, the last measurements in 2003, which had the highest dry matter yield, proved to be the most difficult for which to estimate the N status with spectral measurements. As an effect of this saturation, the SR index was only useful to describe the biomass dry weight up to values 3000 kg ha^{-1}. Although saturation effects are also present in nadir measurements (Schlemmer et al., 2005; Aparicio et al., 2000), they are not as severe, such that measurements in the nadir may reduce the saturation effect.

Further positive effects related to the measuring geometry (i.e., use of four optics and measuring canopy reflectance and sun irradiance simultaneously) are that the measurements are more independent of both the weather conditions and the time of day, and are no longer limited to being performed in the 10 a.m.–2 p.m. window as is commonly done for nadir measurements. Although suboptimal weather conditions (i.e., not sunny conditions) and zenith angles of up to 30° caused a shift of the reflectance values, they had little influence on the quality of the results as indicated by the high R^2-values. Moreover, because the areal performance in fertilizer application is often in excess of 20 ha/h, the shift of the reflectance values is not detrimental in practice given that fertilizing a field

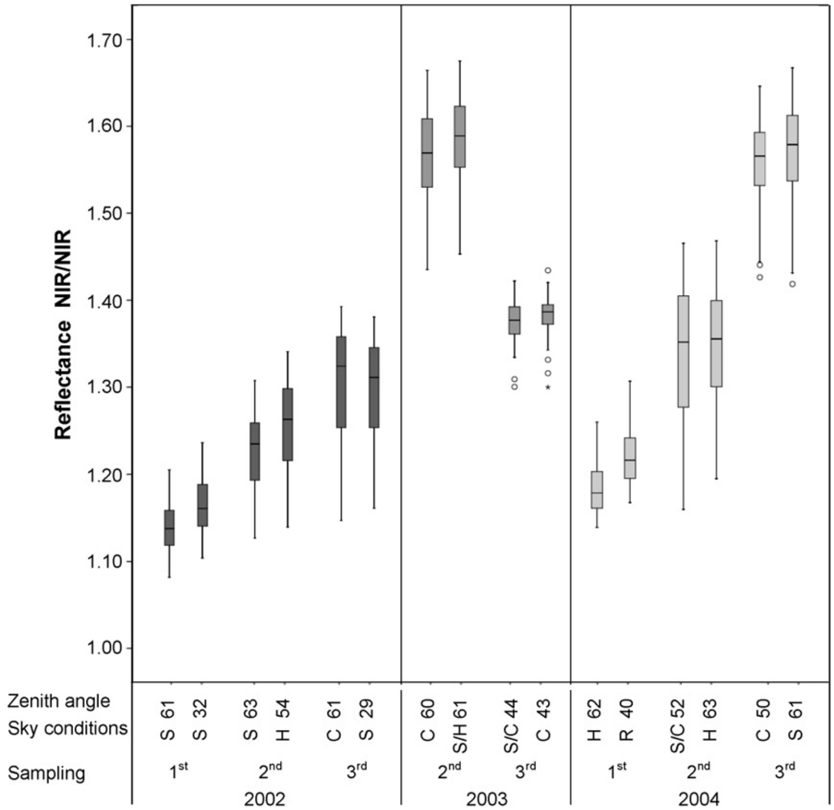

Fig. 2. Box-plots of paired comparisons of actual index values NIR/NIR obtained under various weather conditions (S, sunny; H, hazy; C, cloudy; R, rainy) and at different sun zenith angles from the same or next measurement days as a function of different DM yields in 2002, 2003 and 2004. Measurements were conducted with two comparable sensors with the second being used for the 2nd measurement in 2003 and for all measurements in 2004 using a different calibration.

typically needs no longer than 2 h and that the system has to be newly calibrated on the next field. That being said, further investigations are necessary to describe the shift in reflectance values caused by the zenith angle and weather conditions more precisely so as to increase the performance of the method further.

In maize, variation in the annual development of different crop stands in terms of their dry matter yield and total N content occurs probably as a result of differences in climatic factors, water availability and nitrogen supply. For instance, plants that are well supplied with nitrogen and water differ mainly in terms of their dry matter yield and less in terms of their total N content and nitrogen deficiency (Gastal and Lemaire, 2002; Olesen et al., 2002; see also Osborne et al., 2002). Two reasons could be seen for this. First, the CVs varied between years and between crop stand parameters (Table 4), with the CVs occasionally being the highest for total aerial N in some samplings and for dry matter yield in others. As indicated in Fig. 1, those parameters with the higher CVs (Table 4) generally yielded higher R^2 values, with a strong correlation between CV and R^2 existing for dry matter yield, total aerial N and N content. Second, a relationship also existed at different times between the crop stand parameters total aerial N and total N content (Table 5). In particular, total aerial N correlates with total N content only in 2002 and in the third sampling in 2003. In all other samplings, total aerial N correlates only with dry matter yield.

In this study, clear differences in the weather conditions were apparent between the three years that caused differences in crop growth. The summer of 2003 was fairly dry and warm with the total rainfall from April to August being only 200 mm. As such, the plants were clearly drought-stressed in June, that probably influenced nitrogen translocation and N response negatively and also caused a reduction in the variation between crop stands and a low CV for all crop stand parameters. In 2004, by contrast, no nitrogen response was observed at all, with yield being at a maximum. This result could have been caused by a high N supply from the soil, which might have been abnormally elevated from the high residual total nitrogen content from the previous year. Moreover, the seeding density in 2004 was slightly negatively correlated with N content, but positively correlated with dry matter yield and total aerial N. In 2003, the dry matter yield was clearly influenced by the seeding density, but likely also by the drought conditions, especially in terms of the reduced CV recorded for it in this year.

These results illustrate that the spectral measurements appeared to be influenced by the plant water stress that occurred in 2003. This observation agrees with those of Schlemmer et al. (2005) who reported spectral measurements in water-stressed maize plants with different nitrogen statuses and found that water stress increased leaf reflectance and disturbed the spectral detection of the N status. Serrano et al. (2000) also found a weak relationship between NDVI and water status. Although all these results are suggestive, further researches into the influence of any water deficits on reflectance measurements on the canopy level with a spectral-measurement system are still required.

5. Conclusions

The tractor-mounted spectrometer investigated here allows for fast, accurate measurements of the total aerial N and dry matter yield in maize, even in heterogeneous fields. However, because the annual development of biomass and total N content often differed, the spectral measurements differed as to whether they detected dry matter yield or total aerial N better, depending on the respective CVs, with accuracy increasing with increasing variation in either variable. Drought conditions appeared to influence spectral measurements negatively. In addition to its apparent accuracy, the measuring geometry of the system shows several advantages in comparison to a nadir optic (e.g., independence from weather conditions and time of day). As such, this study shows that this type of field spectrometer is a useful tool to measure the N status, at least in maize, and so to provide the information required for optimized nitrogen management. In particular, the system should facilitate the development of site-specific variable-rate fertilizer application for maize crops. Fertilizer applications can be split either by applying the second rate at growth stage BBCH 17 with liquid fertilizer or with a high clearance tractor up to BBCH 36. In this way, it is possible to detect the site-specific total aerial N of the canopy and the applied N rate can be adjusted to the site-specific biomass development and total aerial N for maize.

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