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VALIDATION OF FIELD-SCALED SPECTRAL MEASUREMENTS OF THE NITROGEN STATUS IN WINTER WHEAT

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ABSTRACT

Fields with spatial differences in soil conditions require a variable, locally adjusted nitrogen fertilisation during the growing season. Recently a new sensor was introduced which can be used to detect the N-status of the canopy, combined with a fertilizing algorithm in a real time system makes it possible to control the amount of nitrogen fertilizer being applied. The present study investigates the potential of this new technique to detect biomass, N-concentration and N-uptake in winter wheat. For the spectral measurements an oligo view, tractor based spectrometer in a field scaled experiment with 25 m² calibration areas was used. The results obtained show that strong correlations exist between reflectance indices and N-uptake from the end of tillering through flowering.

Keywords: biomass detection, spectral reflectance, oligo view optic, N-concentration

INTRODUCTION

It is well known that the N demand of a crop varies within single fields due to spatial differences in soil conditions (McBratney AB and Pringle MJ, 1999; LaRuffa JM et al., 2001). Existing methods of soil and plant analysis are costly and time consuming in delivering information on the actual and spatially resolved N demand. However, previous research has shown that spectral measurements can indirectly describe biomass, N content and N uptake of plants. This technique has been tested in crops in plot experiments with the vision to gather information from the plants to improve the nitrogen fertilization management. However most of the spectral measurements that had been conducted in the past used handheld sensors (Reusch S, 1997) in small areas with small plots and under homogeneous conditions. Our aim was to validate reflectance measurements from a newly developed sensor under field conditions in big plots of about 800 m² and with calibration areas of about 25 m².

In our experiment we validated these measurements on field scaled dimensions with a tractor based spectrometer, the first system which is also commercially available as an operative instrument to control fertilizer spreading in real time. Spectral measurements are frequently influenced by the zenith angle. To avoid the zenith angle associated error we used a new oligo view measuring optic which averages the optical signal from four directions. This geometry provides advantages over nadir measurements. Always one optic measures the sun side of the plants and one the shade side of the plants. The resulting averaged signal is nearly stable at changing zenith angle (Reusch S , 2003). Another practical advantage of the geometry is that the measured field is outside of the shade of the tractor and the spectrometer. Finally the oblique view increases the amount of biomass in the field of view. Thus we expect less interference of the soil reflectance and measurements to be possible in earlier development stages.

MATERIALS AND METHODS

The investigations have been conducted at the research station of the Technical University Munich in Bavaria in the south west of Germany in 2002 and 2003. As experimental plant winter wheat (*Triticum aestivum* cv. Ludwig) was used. In this geographical area yearly average precipitation is around 800 mm and the yearly average temperature is 7.5 °C.

The experimental field was around 3 hectare in size and contained five N-treatments with 5 replications. Each plot was 15 m wide and 50–60 m long. The fertilization rates were 0, 90, 130, 170, 210 kg nitrogen per hectare, and 250 kg/ha in 2003 respectively. The fertilizer was applied at four growth stages, in BBCH 22 (Maier U, 1997) for tillering, in BBCH 30 to increase the number of spikelets, in BBCH 40 to increase the number of glumes and in BBCH 50 for high protein content.

Spectral Reflectance Measurements

A tractor based radiometer, manufactured by Yara, was used to measure the reflectance. It contained two units of Zeiss MMS1 silicon diode array spectrometers with a spectral detection range from 400 to 1000 nm and a pixel distance of 3.3 nm. One unit was linked with a diffuser and measured the sun radiation as a reference signal. Simultaneously the other unit measured the canopy reflectance with an oligo view optic (Lammel J et al., 2001). Therefore the spectrometer was connected with a four in one light fibre and the signal was optically averaged. The optical inputs were positioned with an azimuth angle of 80° between the front and rear side and 100° between the right and left side of the tractor. The zenith angle was 58°, +/- 6° to avoid some influence of the shade of the tractor (Reusch S, 2003; Schmidhalter U et al., 2003). The signal intensity was not homogeneous in the measuring ellipse. It was twice as high at the spectrometer side as on the opposite end. This effect is explained by the fact that the light intensity decreases in a quadratic relationship with distance to its source. Plant canopies do not represent Lambertian reflector and an influence of the solar azimuth angle always remains. It is possible to eliminate this bi-directional influence nearly completely with an oligo view optic (Reusch, 2003). With the readings from the spectrometer units the canopy reflectance was calculated and corrected with a calibration factor, estimated with $BaSO_4$ standards. In front of the tractor the sensor system was mounted 1.90 m above the canopy. The field of view consisted of four ellipsoids with 1.23 m in length, together around 4.5 m^2. Two measurements were conducted just before fertilizing.

The reflectance was measured at five wavelengths, which were at 550, 670, 700, 740 and 780 nm respectively. The reflectance spectra can be divided in two parts. The first part is the visible range from 400 to 700 nm which is mainly influenced by plant pigments, first of all chlorophyll (Buschmann C et al., 2000). The second part is the near infrared area from 700 through 1000 nm, which is mainly characterized by the amount of different optical densities between water saturated cell walls and intercellular air spaces and chiefly corresponds with the biomass (Gates DM et al., 1965; Guyot G, 1990).

In this study we calculated the normalized difference vegetation index (NDVI) for which the reflectance at 670 nm is the minimum reflectance because the chlorophyll has its maximum absorbance.

$$NDVI = \frac{R_{780} - R_{670}}{R_{780} + R_{670}}$$

We calculated as well the reflectance intensity ratio between near infrared (NIR) and red (RR).

$$NIR / RR = \frac{R_{780}}{R_{670}}$$

The NIR to green reflectance intensity ratio was estimated, with the reflectance at 550 nm (green) being influenced by both, chlorophyll and carotenoid pigments.

$$NIR / G = \frac{R_{780}}{R_{550}}$$

The red edge is an interesting area, because it contains both areas, the chlorophyll absorption, the cell wall reflection and the alteration between those main effects. The reflectance at 700 nm (R) is beyond the chlorophyll maximum absorbance and the beginning of the red edge but the absorbance is still high.

$$R / NIR = \frac{R_{700}}{R_{780}}$$

With increasing N-contents, not only the height of the reflection in this areas changes, but also the inflection point. In the study we used a linear fitting for the red edge and a simplified formula to calculate the red edge inflection point (REIP) (Guyot G et al., 1988).

$$REIP = 700 + 40\frac{(R_{670} + R_{780})/2 - R_{700}}{R_{740} - R_{700}}$$

Furthermore the ratio between two closely related wavelengths in the NIR was estimated.

$$NIR/NIR = \frac{R_{740}}{R_{780}}$$

Biomass and Nitrogen Measurement

We cut plants shortly after the spectral measurements to estimate the above ground biomass. Small plots on both sides of the tractor were harvested, 1.5 m in width and around 8 m in length, matching exactly the measured area. For this purpose we used a green forage chopper, equipped with a weighing unit. Spectral measurements were averaged over this area. A representative sub-sample was removed and dried after weighing to estimate the total dry matter. The dried samples were grained and analysed for total N-content with a macro N elementary analyser. The N-uptake was calculated as biomass x N-concentration.
For the statistical analysis we used SPSS 11. We did not focus on the mean value analysis as we expected big differences from plot to plot, independent of the fertilizer rate due to heterogeneous soil conditions.

RESULTS

The distribution of destructively measured parameters of plants, grown at different nitrogen supplies is shown in Table 1.

The N-treatments show in all three destructively measured parameters highly significant differences between N-concentration, biomass and N-uptake with exception of biomass in the second cut in 2002 and the second cut in 2003.
At the first cut, N-uptake (determined as biomass times N-concentration) is stronger correlated with biomass (r^2= 0,92 and 0,91) than N-concentration (r^2=0,74 and 0,58), respectively. Later the influence of the biomass decreases (r^2=0,83 in 2002 and r^2= 0,80 and 0,86 in 2003) whereas the influence of the N-concentration increases (r^2=0,84 in 2002 and r^2= 0,59 and 0,80 in 2003). Similar responses were observed by others (Baret F and Fourty TH, 1997). The relationship between N-concentration and biomass was stable in 2002 with an r^2 of 0,50 and varied in 2003 with 0,32, 0,17 and 0,49 at the respective cuts.

Table1: Range of destructively measured parameters N-concentration, biomass and N-content in 2002 and 2003.

2002

Growth stage (BBCH)	**N concentration (%)**				**Biomass (kg/ha)**				**N-content (kg/ha)**			
	min.	max.	average	Stddv	min.	max.	average	Stddv	min.	max.	average	Stddv
32	1.95	3.31	2.59	0.38	924	4208	2970	850	18	131	79	30
55	1.33	2.83	1.95	0.35	3340	8739	6390	1346	45	247	128	44

2003

	N concentration (%)				**Biomass (kg/ha)**				**N-content (kg/ha)**			
	min.	max.	average	Stddv	min.	max.	average	Stddv	min.	max.	average	Stddv
30	1.92	3.37	2.61	0.33	209	1551	1022	307	6	47	27	10
39	1.56	2.99	2.46	0.44	1311	3949	2674	641	23	108	67	22
65	1.13	2.44	1.87	0.38	3609	9229	6621	1420	41	194	128	45

Four spectral readings in 2002 and six in 2003 had been conducted. In Tables 2 to 4 the coefficients of determination (R^2-values) are indicated. All results are highly significant at the 0.001 level with exception of the NDVI versus N-concentration at both measurements for the first cut in 2003 and the measurement at May 29, 2002, together with the NIR/RR index. These results are also significant but at a lower level.

The biomass is best described with the NDVI and NIR/RR with a quadratic regression. The NDVI shows at higher biomass a flattened relationship. Especially in 2002, the upper 60% of the regression between biomass and NDVI were totally plain, whereas for the NIR/RR this relationship was curvilinear. The REIP and the NIR/NIR relationships were relatively constant at all readings but at a lower level. They show nearly linear relationships for all measurements with exception of the last one. In 2002 the relationships were less linear than in 2003 for all indices and parameters. This demonstrates, that a saturation effect occurred in 2002. The relatively low correlation of the REIP at the second cut can be explained by the low correlation of the N-concentration and biomass. All indices in 2003, and in 2002 the REIP and NIR/NIR, decrease in their ability to predict biomass as the plants grow.

N-concentration is best described by the indices REIP and NIR/NIR. Both show in 2003 linear relationships, in 2002 only at the first reading. The NIR red indices like the NDVI and NIR/RR are not useful to predict the N-concentration. Especially at the first cut and also at the second cut in 2003 the correlation is weak. One reason for this may be the low biomass. For all indices the R^2 increases with time in 2003. This is probably the same effect which is described above as the influence of biomass and N-concentration as part of the N-uptake. This relationship could however not be derived from the 2002 data.

Table 2 : Coefficients of determination (R^2) of linear and quadratic relationships between biomass and reflectance indices at different spectral readings in 2002 and 2003.

Biomass		**2002**				**2003**					
		1. Cut		2. Cut		1.Cut		2.Cut		3.Cut	
		15.05.	16.05.	29.05.	03.06.	03.05.	05.05.	16.05.	19.05.	04.06.	05.06.
REIP	lin.	0.77	0.77	0.72	0.69	0.77	0.78	0.62	0.58	0.56	0.73
	quad.	0.83	0.84	0.79	0.74	0.77	0.78	0.63	0.58	0.73	0.83
NDVI	lin.	0.59	0.59	0.65	0.70	0.83	0.81	0.73	0.69	0.38	0.65
	quad.	0.93	0.91	0.90	0.89	0.93	0.93	0.79	0.72	0.60	0.87
NIR/RR	lin.	0.72	0.70	0.61	0.74	0.86	0.82	0.79	0.75	0.33	0.71
	quad.	0.84	0.85	0.82	0.88	0.89	0.89	0.82	0.77	0.44	0.71
NIR/G	lin.	0.74	0.75	0.69	0.71	0.88	0.88				
	quad.	0.79	0.80	0.79	0.78	0.90	0.92				
R/NIR	lin.	0.76	0.75	0.68	0.72	0.88	0.88	0.61	0.56	0.49	0.64
	quad.	0.80	0.81	0.79	0.79	0.91	0.93	0.65	0.59	0.75	0.87
NIR/NIR	lin.	0.76	0.77	0.72	0.70	0.78	0.82	0.66	0.61	0.54	0.73
	quad.	0.82	0.83	0.79	0.75	0.79	0.82	0.67	0.61	0.69	0.83

Table 3 : Coefficients of determination (R^2) of linear and quadratic relationships between N-concentration and reflectance indices at different spectral readings in 2002 and 2003.

N-concentration		**2002**				**2003**					
		1. Cut		2. Cut		1.Cut		2.Cut		3.Cut	
		15.05.	16.05.	29.05.	03.06.	03.05.	05.05.	16.05.	19.05.	04.06.	05.06.
REIP	lin.	0.78	0.78	0.57	0.67	0.72	0.71	0.75	0.80	0.86	0.89
	quad.	0.88	0.90	0.72	0.87	0.72	0.72	0.77	0.81	0.89	0.93
NDVI	lin.	0.40	0.42	0.24	0.37	0.21	0.18	0.36	0.54	0.74	0.78
	quad.	0.59	0.60	0.50	0.65	0.21	0.18	0.39	0.57	0.76	0.86
NIR/RR	lin.	0.65	0.65	0.22	0.38	0.44	0.41	0.38	0.35	0.77	0.87
	quad.	0.74	0.76	0.48	0.66	0.53	0.43	0.38	0.55	0.77	0.87
NIR/G	lin.	0.81	0.82	0.51	0.63	0.47	0.39				
	quad.	0.87	0.91	0.70	0.85	0.47	0.39				
R/NIR	lin.	0.81	0.81	0.50	0.64	0.43	0.38	0.69	0.75	0.83	0.81
	quad.	0.88	0.91	0.68	0.84	0.43	0.38	0.72	0.79	0.88	0.90
NIR/NIR	lin.	0.79	0.79	0.56	0.66	0.67	0.65	0.72	0.78	0.85	0.89
	quad.	0.88	0.91	0.70	0.86	0.67	0.65	0.73	0.79	0.87	0.93

Table 4 : Coefficients of determination (R^2) of linear and quadratic relationships between N-uptake and reflectance indices at different spectral readings in 2002 and 2003.

N-uptake		2002				2003					
		1. Cut		2. Cut		1.Cut		2.Cut		3.Cut	
		15.05.	16.05.	29.05.	03.06.	03.05.	05.02.	16.05.	19.05.	04.06.	05.06.
REIP	lin.	0.85	0.84	0.69	0.72	0.91	0.92	0.91	0.90	0.77	0.91
	quad.	0.92	0.93	0.86	0.91	0.91	0.92	0.94	0.93	0.90	0.99
NDVI	lin.	0.52	0.53	0.42	0.52	0.75	0.71	0.76	0.84	0.57	0.76
	quad.	0.84	0.84	0.78	0.86	0.87	0.85	0.81	0.89	0.73	0.95
NIR/RR	lin.	0.75	0.73	0.39	0.56	0.90	0.86	0.83	0.92	0.56	0.88
	quad.	0.86	0.88	0.74	0.88	0.90	0.87	0.86	0.92	0.58	0.90
NIR/G	lin.	0.86	0.86	0.63	0.70	0.91	0.87				
	quad.	0.90	0.92	0.86	0.93	0.94	0.94				
R/NIR	lin.	0.87	0.86	0.62	0.72	0.89	0.86	0.86	0.85	0.68	0.78
	quad.	0.91	0.92	0.85	0.93	0.94	0.94	0.93	0.92	0.89	0.97
NIR/NIR	lin.	0.86	0.86	0.69	0.72	0.93	0.94	0.94	0.92	0.75	0.91
	quad.	0.92	0.93	0.86	0.91	0.93	0.94	0.96	0.94	0.87	0.99

N-uptake is also best described by the REIP, NIR/NIR and NIR/G. The index R/NIR is also a good predictor for the N-uptake but it shows a stronger saturation effect, which is pointed out by the bigger difference between the R^2-values from the linear and quadratic regressions. Both red NIR based indices are not useful to predict N-uptake. The results demonstrate, that for spectral measurements obviously the biomass is more important than the growth stage. The results at BBCH 32 in 2002 are better than at BBCH 39 in 2003 because the biomass in early 2002 was bigger than in the second cut 2003.

DISCUSSION

The comparison of reflectance indices to canopy parameters demonstrates that it is possible to obtain N-status estimates in intact canopies with a tractor based spectrometer in the field. This scanning method is rapid, easy, non-destructive, tractor based and applicable to field-scaled dimensions.
The results demonstrate that early measurements at BBCH 30 give a reliable estimation of the N-status. In comparison with results from measurements in the nadir direction (Liebler J et al., 2001) a positive effect of the oblique view could be observed.

Another effect of the oblique view is that the LAI increases theoretically with a factor of 1.87. Some varieties may have more planar leaves so that the factor is not as high but there is still an increased amount of biomass in the field of view to

expect. A consequence of increased biomass in the field of view is a stronger saturation effect compared to nadir measurements (Liebler J. 2003), especially in the red area, because of the high absorption. The differences in this area are low in spite of the technical high contrast of the spectrometer because of the high sensitivity of the silicon array in this area. Also in nadir measurements saturation effects are known up to LAI (leaf area index) 3, mainly by LAI but also by LAI*Chlorophyll whereas the NDVI shows a perfect saturation and the NIR/R relationship is curvilinear (Serrano L et al., 2000; Aparicio et al., 2000). This observation is in compliance with the results obtained in 2002; in 2003 however the saturation effect was weaker.
For all non-linear regressions the quadratic function was used. The expected situation for light reflectance in a high absorbance canopy is a saturation effect which is best described by a power function. But most of the regressions were best fit with quadratic functions which were also used by other scientists (Carter GA and Spiering BA, 2002; Read JJ et al., 2002). This peculiarity could be caused by a particular feature which increases in a quadratic relationship.
The results of our field studies are in line with other studies obtained under well controlled experimental plot conditions with hand-held spectrometers (Reusch S, 1997; Liebler J et al., 2001). However the R^2 of the regressions for N-uptake in our results were on a constant high level whereas the results of others were sometimes as good and sometimes much worse. This may be ascribed to the measuring geometry, caused by the mixed signal from the four edges of the tractor, together with the big area for the calibration cuts.

CONCLUSION

The spectrometer used is a tractor based device for easy measurements of N-status and biomass in crops. All tested indices showed good results. The NDVI and NIR/RR was only useful for detection of biomass whereas the REIP, NIR/NIR, NIR/G and NIR/R turned out to be useful indices to estimate the N-status in the field. The measuring geometry showed several advantages in comparison to results obtained with a nadir optic. We could show with this study that the type of field spectrometer we used is a useful tool to measure the N-status of a canopy and to deliver the information required for proper nitrogen management on farms. The system reliably detects nitrogen depleted and well-supplied plants in heterogeneous fields.

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