COMPARISON OF DIFFERENT VEGETATION INDICES AND THEIR SUITABILITY TO DESCRIBE N-UPTAKE IN WINTER WHEAT FOR PRECISION FARMING

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ABSTRACT

To avoid environmental pollution and to minimize the costs of using mineral fertilizers, an efficient fertilization system tailored to the plants' needs becomes increasingly important. For this purpose, essential information can be determined by detecting certain crop parameters, like above-ground plant biomass, nitrogen (N) content and N-uptake. There parameters may be ascertained using reflectance measurements of the canopy with subsequent mathematical analyses.

Over a three-year period, from 2007 to 2009, two different plot trials in winter wheat were conducted. The first trial consisted of seven different cultivars of winter wheat and four N-rates (0, 100, 160 and 220 kg N ha^{-1}). The second trial consisted of only one cultivar with eight N-rates from 0 to 260 kg N ha^{-1}. Each trial was conducted as a double plot trial with four replications. One plot was for non-conducting sensor measurements and harvesting with the plot combine, whilst the other plot was for biomass sampling during the vegetation period. Biomass samples for nitrogen analysis as well as sensor measurements were conducted five times during the vegetation period.

The N-uptake of different growth stages of winter wheat was well represented by using reflectance measurements. Especially the Red Edge Inflection Point (REIP) vegetation index was adequate for this purpose because of the high coefficient of determination to the N-uptake. Another advantage of the REIP was that the effect of the different cultivars was negligible. The coefficient of determination was lower when using the Normalized Differentiated Vegetation Index (NDVI) in comparison to the other vegetation indices. A saturation effect could be observed especially in canopies with well-provided N. The results were different when using other spectral regions in the red and near-infrared wavelength range, calculated with the NDVI-formula. With this combination, the saturation effect almost disappeared and the coefficient of determination between NDVI and crop parameters increased considerably.

Keywords: Reflectance measurements; Winter wheat, Fertilization; Vegetation indices

INTRODUCTION

In winter wheat production, the aim of the farmer is to optimize the yield and protein quality with a minimum usage of mineral fertilizer. For this purpose it is necessary to know which amount of mineral-N should be given.

The challenge to the farmer is the derivation of an optimal N supply for the plants. A condition of nitrogen deficiency leads to a distinct yield loss, whereas an increasing amount of mineral N results in higher grain yield, as well as an increase in plant height, total number of plants/m^2, number of grains/spike, number of spike/m^2, spike weight and grain protein content (Hussain et al., 2006). To get a maximum grain yield with high protein content, farmers often apply an excessive amount of mineral N-fertilizer. These very high doses of mineral-N lead to NO_3 leaching into groundwater (Jacinthe and Lal., 2003; Köhler et al., 2006).

Nevertheless, the N supply of the canopy is very important. It is a result of soil-borne N mineralization and supplemental application of N fertilizer (Moraghan et al., 2003). In common practice, the entire amount of mineral N fertilizer is split into several parts, given at certain growth stages to get a maximum in yield and quality.

As growth and development of plants are dependent on the actual nutrient status, plants themselves are the best indicators for the estimated N requirement. By using reflective sensor measurements, farmers can fertilize as and when required to get an optimum yield with minimum environmental burden.

The N status can be easily determined with sensors that detect the reflectance of light of different wavelengths. Such sensors have previously proved their ability to guide nitrogen fertilization in winter wheat (Link et al., 2002). Furthermore, Philips et al. (2004) showed that sensor values are well correlated with the actual N-uptake of the plants. However, reflectance spectra of the canopies are influenced by soil reflection (Huete, 1987). In cereal production, this effect becomes evident only in young growth stages when the soil is visible. To avoid this fact, measurements can be taken at a certain angle that deviates from the vertical position.

The aim of this study was to compare various vegetation indices regarding their suitability to indicate certain crop parameters like N-uptake in combination with growth stage, cultivar and different N fertilization stages.

MATERIAL AND METHODS

Trial site and weather data

Winter wheat (*Triticum aestivum* L.) trials were conducted at three different trial sites of the Technische Universität München, near Freising in Southern Bavaria from 2007 to 2009. The soil was a silty loam with a good fertility for wheat production. Monthly precipitation and mean daily temperature during the three vegetation periods 2007 to 2009, as well as the long term average, are shown in figures 1 and 2. These values were taken from the weather station in Freising, approximately 3 to 7 km away from the trial sites.

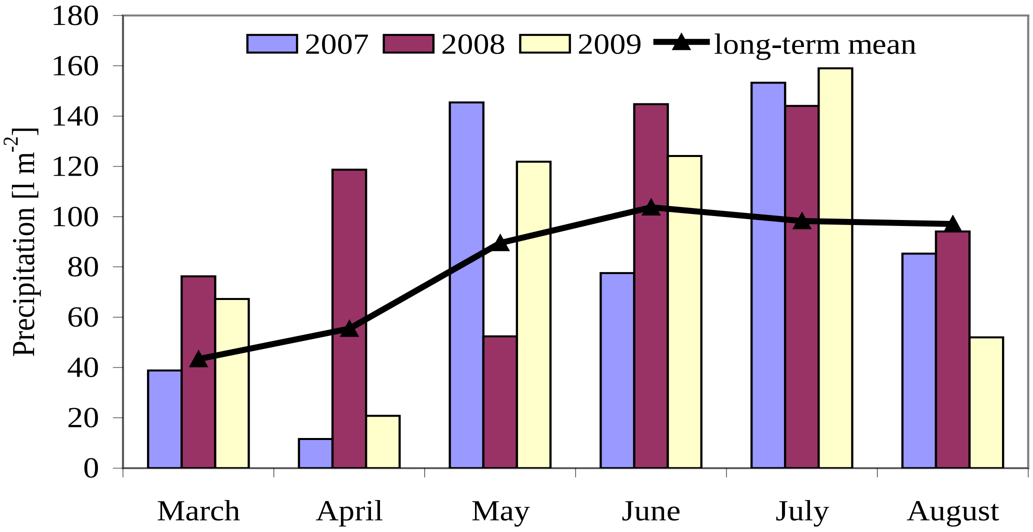

Figure 1: Monthly precipitation [l m^{-2}] during growth period 2007-2009 and long-term average (weather station Freising).

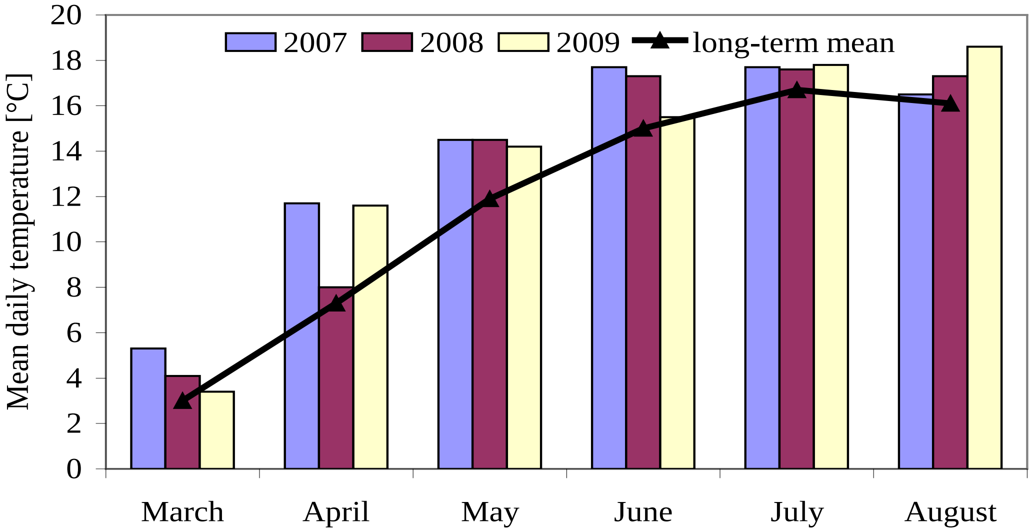

Figure 2: Daily mean daily temperature [°C] during the vegetation period 2007-2009 and long-term average (weather station Freising).

Management and layout of field trials

The winter wheat field trials consisted of two separate trials. One was a system of ‘N-optimization’ and the other was a trial of wheat cultivars. The randomized double-plot design of both field trials was composed of four replicates. One plot was for the sensor measurements and the other was for biomass sampling. The trial factor ‘N-treatment’ on the trial site ‘N-optimization’ (Table 1) consisted of eight factor levels. N fertilizer doses ranged from 0 to 240 kg N ha^{-1}, split and applied at different growth stages. The trial of wheat cultivars consisted of seven different cultivars, treated with four different application rates of mineral-N, split at different growth stages (Table 2). Calcium ammonium nitrate (27 % N) was used as the N fertilizer.

Table 1: N treatments for the N-optimization field trials from 2007 to 2009

Growth stage	Application rate [kg N ha^{-1}]							
EC 25	0	30	30	40	60	60	90	60
EC 30	0	0	0	0	0	40	0	40
EC 32	0	30	30	40	60	40	90	60
EC 49	0	0	40	40	40	40	40	80
Σ	0	60	100	120	160	180	220	240

Table 2: Cultivars and N treatments for the wheat cultivars trials from 2007 to 2009

Cultivars:
Cubus, Ellvis, Impression, Ludwig, Pegassos, Solitär, Tommi

Growth stage	Application rate [kg N ha^{-1}]			
EC 25	0	30	60	90
EC 32	0	30	60	90
EC 49	0	40	40	40
Σ	0	100	160	220

Biomass samples

Above-ground biomass samples were gathered five times during the vegetation period, at the growth stages EC 30, EC 32, EC 37, EC 49 and EC 65. For each biomass sampling, one row of a plot was harvested. The samples were subsequently weighed and chopped. A sub-sample was then oven-dried and re-weighed to calculate the above-ground dry matter yield. The values were then converted into units of mass per ha. A part of the sample was ground and the N-content was subsequently analyzed using a vario MAX auto-analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). Dry matter yield and N concentration in dry matter were multiplied to compute N uptake in above-ground biomass.

Measurement device for detecting reflectance spectra

The handheld sensor device for detecting reflectance spectra was a two channel field spectrometer (tec5 AG, Oberursel, Germany), which simultaneously recorded irradiation and reflection with a spectral resolution of 3 nm over a range from 360 nm to 1050 nm. An optical fibre receiver within the device, with a viewing angle of 25°, was used to determine the reflection. A diffuser plate on top of the device detected irradiance within a 180° viewing angle. To calculate spectral reflectance, emission was divided by irradiance and corrected with an internal standard spectrum.

Reflectance spectra were measured at the same time as biomass samples were gathered. The sensor device was held approximately 50 cm above the canopy in a vertical position. This resulted in each measurement covering an area of 0.17 m^2. Seven readings were recorded in each plot and merged to generate a mean value. The measurements were made between about 11 AM and 1 PM, to ensure that the position of the sun was approximately at its zenith.

Various wavelengths of the spectra were used to calculate twelve vegetation indices (VI): REIP, NDVI, IR/R, IR/G, IRI 1, IRI 2, SAVI, NDI 1, NDI 2, SR 1, SR 2 and Yara_ALS. The formulae, as well as the references, are given in Table 3.

Table 3: Formulae and references of the vegetations indices

Vegetation index	Formula	Reference
REIP	$700 + 40\frac{0.5(R_{670} + R_{780}) - R_{700}}{R_{740} - R_{700}}$	Guyot and Baret (1988)
NDVI	$(R_{780}-R_{670})/(R_{780}+R_{670})$	Rouse et al. (1974)
IR/R	R_{780}/R_{670}	Pearson and Miller (1972)
IR/G	R_{780}/R_{550}	Takebe et al. (1990)
IRI 1	R_{740}/R_{730}	Reusch (1997)
IRI 2	R_{740}/R_{720}	Reusch (1997)
SAVI	$\frac{1.5(R_{780} - R_{670})}{R_{780} + R_{670} + 0.5}$	Huete (1988)
NDI 1	$(R_{750}-R_{780})/(R_{750}+R_{780})$	Müller (2008)
NDI 2	$(R_{780}-R_{740})/(R_{780}+R_{740})$	Müller (2008)
SR 1	R_{740}/R_{780}	Müller (2008)
SR 2	R_{780}/R_{740}	Müller (2008)
Yara_ALS	$100(\ln(R_{760})-\ln(R_{730}))$	Jasper et al. (2009)

Statistical analysis

Analysis of variance (ANOVA) and regression were calculated with the statistical software package SPSS 15.0 (SPSS Inc.). The ANOVA was performed with a general linear model. Mean values were compared when the main factor ‘N fertilization’ showed significance with a Tukey-b-test. Furthermore, regression analyses of the vegetation indices on N uptake of the above-ground biomass were calculated.

RESULTS

Coefficients of determination

The R^2-values of the linear regression analyses between N-uptake and different VIs for the winter wheat N-optimization field trial are given in figure 3. There were large differences between the VIs. All results were significant at p=0.000, except SAVI at EC 30, which was not significant.

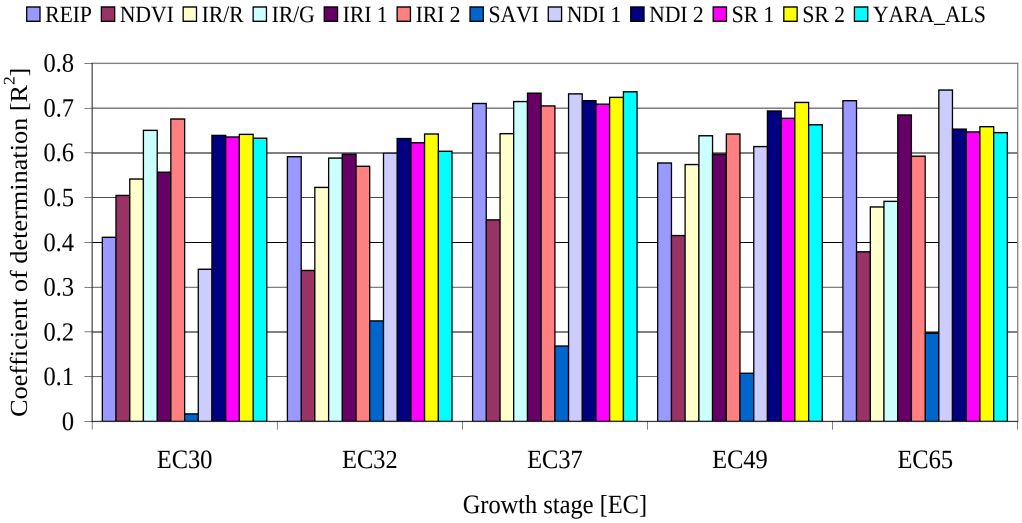

Figure 3: Coefficient of determination between the different vegetation indices and growth stages

Figure 3 show that SAVI consistently had the lowest coefficients of determination. The best results were achieved for REIP and SR 2. The highest coefficients for nearly all VIs could be observed at the growth stage EC 37.

Analysis of variance of the N-optimization and saturation effect

The analysis of variance of the twelve VIs demonstrates how exactly the various N-treatment levels could be differentiated. This is one of the most important aspects of this study. A precision fertilization tailored to the plants' needs by using a vegetation index can only be made if the N levels can be well differentiated. Table 4 shows the results of the ANOVA of the VIs. The 'N-treatment' column describes the total amount of mineral N given during the whole vegetation period, as detailed above. The designated letters in the VI columns indicate the ability of an index to differentiate the N-treatments (or not).

Table 4: Comparison of the results of the ANOVA of the various VIs according to the N-treatment levels (2007 to 2009).

	Vegetation index											
N-treatment	REIP	NDVI	IR/R	IR/G	IRI 1	IRI 2	SAVI	NDI 1	NDI 2	SR 1	SR 2	Yara_ALS
kg N ha^{-1}												
EC 30												
0	a	a	a	a	a	a	a	a	a	a	a	a
100	b	b	b	b	b	b	b	b	b	b	b	b
120	b	b	b	b	b	b	b	b	b	b	b	b
160	b	b	b	b	b	b	b	b	b	b	b	b
220	c	b	c	c	c	c	b	c	c	c	c	c
EC 32												
0	a	a	a	a	a	a	a	a	a	a	a	a
100	b	b	b	b	b	b	b	b	b	a	b	b
120	b	b	b	b	b	b	b	b	b	a	b	b
160	bc	b	bc	b	bc	bc	b	bc	b	b	b	bc
180	cd	b	cd	c	cd	cd	b	cd	c	b	c	cd
220	c	b	d	c	d	d	b	d	c	b	c	d
240	d	b	d	c	d	d	b	d	c	c	c	d
EC 49												
0	a	a	a	a	a	a	a	a	a	a	a	a
60	b	b	b	b	b	b	bc	b	b	ab	b	b
100	b	b	bc	b	b	b	bc	b	bc	ab	bc	b
120	bc	b	bc	bc	bc	bc	bc	bc	bc	bc	bc	bc
160	bc	b	bc	bc	bc	bcd	c	bc	cd	cd	c	bc
180	cd	b	bc	c	c	cd	c	cd	de	cd	d	cd
220	cd	b	bc	c	c	cd	c	cd	de	d	d	cd
240	d	b	c	c	c	d	c	d	e	e	d	d

The results show that NDVI could only differentiate the N-treatment between 0 kg N ha^{-1} and the rest, whereas the other VIs were better differentiated. Especially REIP and SR 2 were more effective in the differentiation between the various N-treatments.

This effect can also be observed in the graphs of the regression analysis in EC 37 (figures 4 and 5). The coefficients of determination were significant at $p=0.000$.

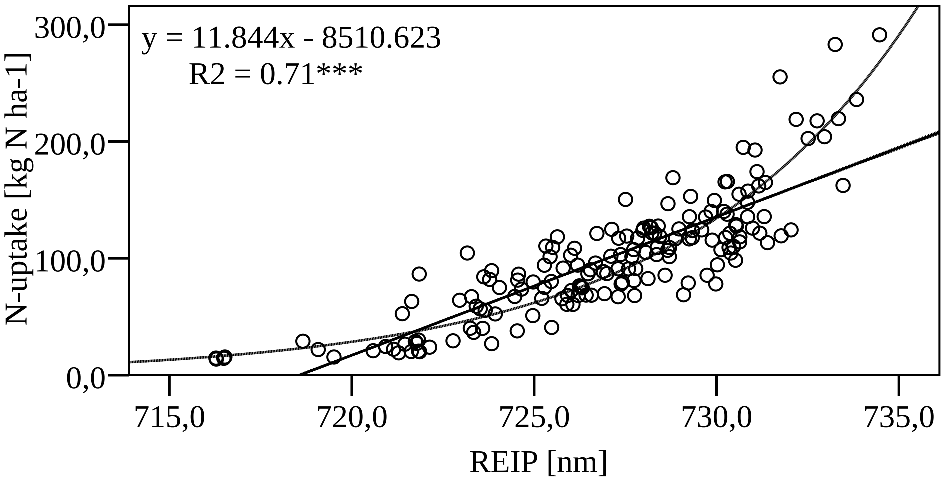

Figure 4: Regression analysis of the VI REIP with N-uptake at EC 37 (2007 to 2009)

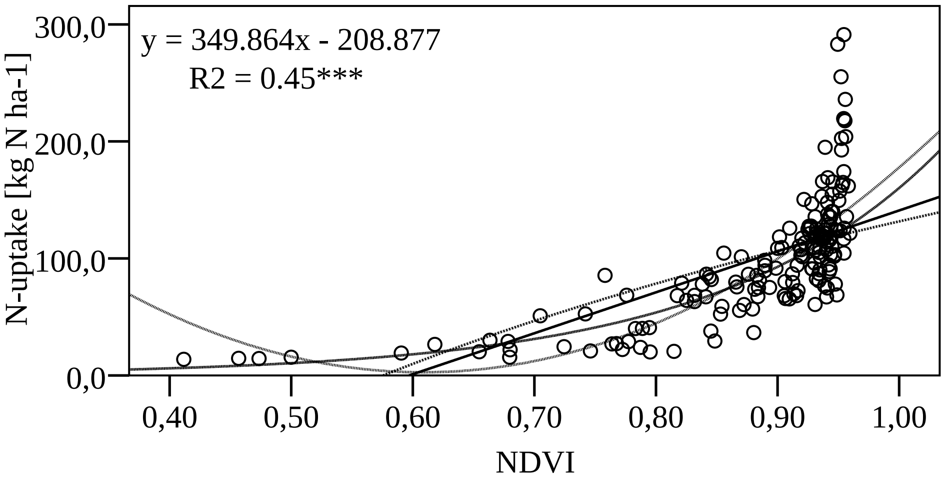

Figure 5: Regression analysis of the VI NDVI with N-uptake at EC 37 (2007 to 2009)

The regression analysis of the NDVI shows that there is a concentration of the data at about NDVI 0.95. This is significant for the saturation effect, because this indicates that the various N-uptakes could not be differentiated.

Influence of the various cultivars

Other than the aforementioned aspect of the differentiation of the N-treatments, the influence of the cultivars is also important. To use determined VIs for fertilization, the influences of the cultivars on the results of measurements should be as small as possible. To analyze this topic, an analysis of variance of the various cultivars was performed (table 5).

Table 5: ANOVA of the influence of the cultivars on the vegetation indices.

	Vegetation index											
Cultivar	REIP	NDVI	IR/R	IR/G	IRI 1	IRI 2	SAVI	NDI 1	NDI 2	SR 1	SR 2	Yara_ALS
EC 30												
Cubus	a	a	a	a	a	a	a	a	a	a	a	a
Ellvis	a	a	a	a	a	a	a	a	a	a	a	a
Impression	a	ab	ab	a	a	a	a	a	a	a	a	a
Ludwig	a	ab	ab	a	a	a	a	a	a	a	a	a
Pegassos	a	a	ab	a	a	a	a	a	a	a	a	a
Solitär	a	ab	ab	a	a	a	a	a	a	a	a	a
Tommi	a	b	b	a	a	a	a	a	a	a	a	a
EC 32												
Cubus	a	a	a	a	a	a	a	a	a	a	a	a
Ellvis	a	a	a	a	a	a	a	a	a	a	a	a
Impression	a	ab	ab	a	a	a	ab	a	a	a	a	a
Ludwig	a	ab	ab	a	a	a	ab	a	a	a	a	a
Pegassos	a	a	a	a	a	a	a	a	a	a	a	a
Solitär	a	ab	ab	a	a	a	ab	a	a	a	a	a
Tommi	a	b	b	a	a	a	b	a	a	a	a	a
EC 49												
Cubus	a	a	a	a	a	a	a	a	a	a	a	a
Ellvis	a	a	a	a	a	a	a	a	a	a	a	a
Impression	a	a	a	a	a	a	a	a	a	a	a	a
Ludwig	a	a	a	a	a	a	a	a	a	a	a	a
Pegassos	a	a	a	a	a	a	a	a	a	a	a	a
Solitär	a	a	a	a	a	a	a	a	a	a	a	a
Tommi	a	a	a	a	a	a	a	a	a	a	a	a

Table 5 shows that the influence of the cultivar on the VIs is irrelevant. Only three VIs, NDVI, IR/R and SAVI were affected by the various cultivars. Figures 6 and 7 show this effect at growth stage EC 32 for the VIs REIP and NDVI, respectively. All results were significant at p=0.000 (***).

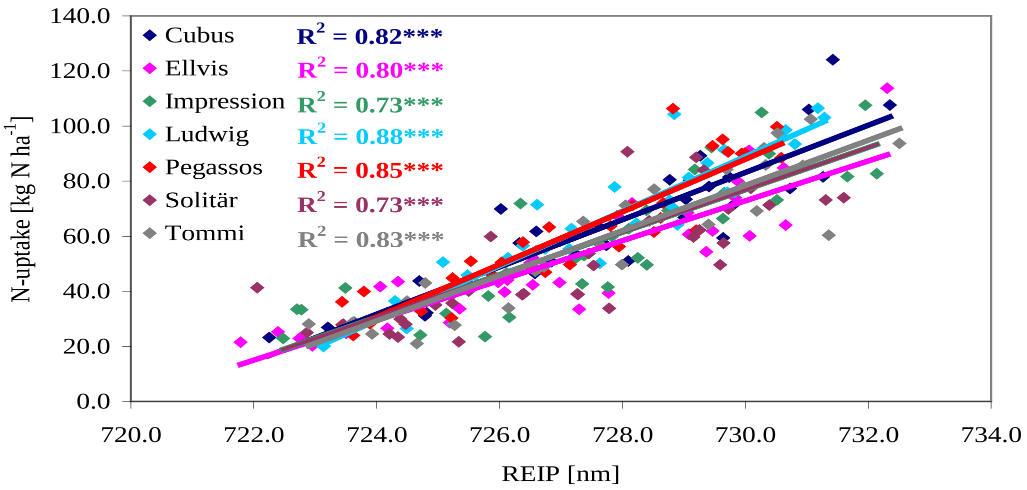

Figure 6: Linear regressions of REIP with N-uptake of the cultivars at EC 32 (2007 to 2009)

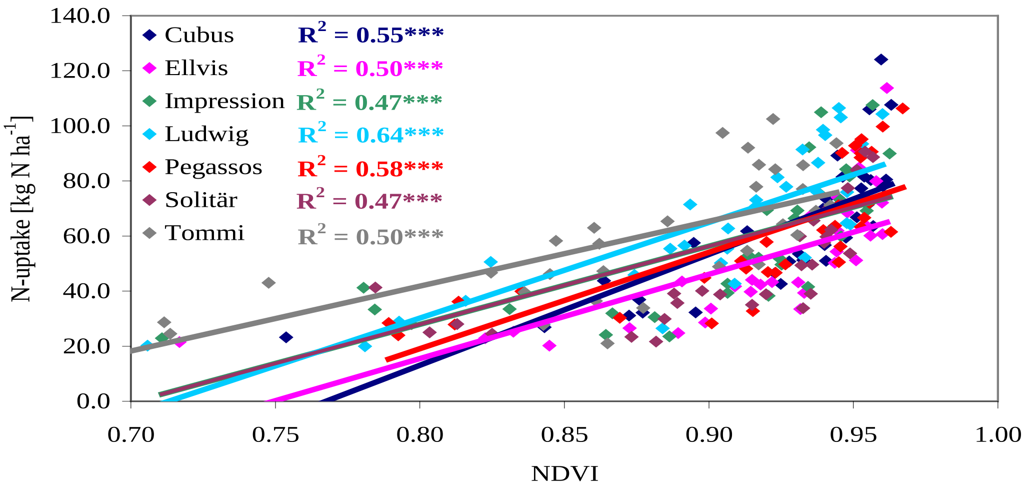

Figure 7: Linear regressions of NDVI with N-uptake of the cultivars at EC 32 (2007 to 2009)

While REIP shows that an influence could be observed on a very low level only in areas with higher N-uptake, the results of the NDVI are completely different. Due to the saturation effect at higher N-uptakes a high influence on the results of the reflective measurements is evident. This can also be confirmed with the results of the ANOVA, shown in table 5.

Influences of the growth stages

The influence of the growth stage on the VIs is widespread. Figure 8 illustrates this relationship using the example of the VI REIP, which increases with higher growth stages. The difference between EC 49 and EC 65 is low because of the growing allotment of spikes in the reflection of light. The results were significant at p=0.000 (***).

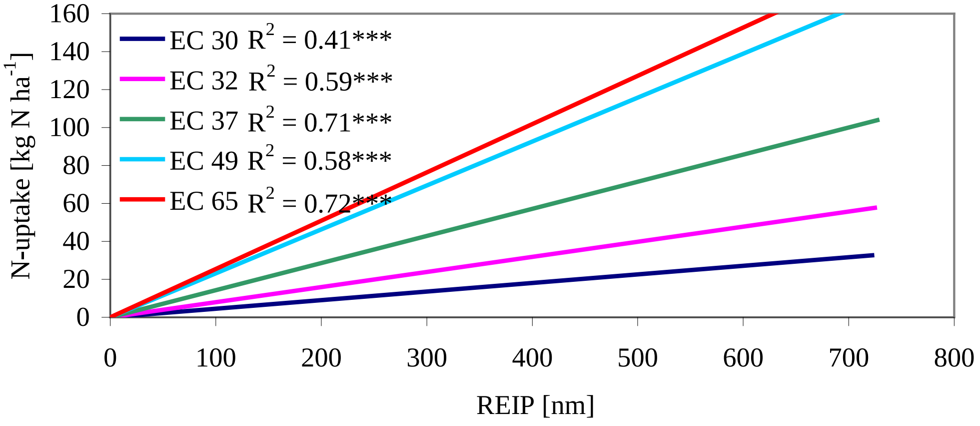

Figure 8: Linear regression analysis of REIP with N-uptake of the different growth stages (2007 to 2009)

In figures 9 and 10 the significance between the agronomic parameter N-uptake and gradients and constants of the regression lines of REIP with N-uptake becomes evident. The analysis of the gradient and the constant for the parameter N-uptake clarifies that an important factor on a VI, in this case of REIP, is the growth stage. The gradient increases during the vegetation period, while the constant decreases. All results were significant at p=0.000 (***).

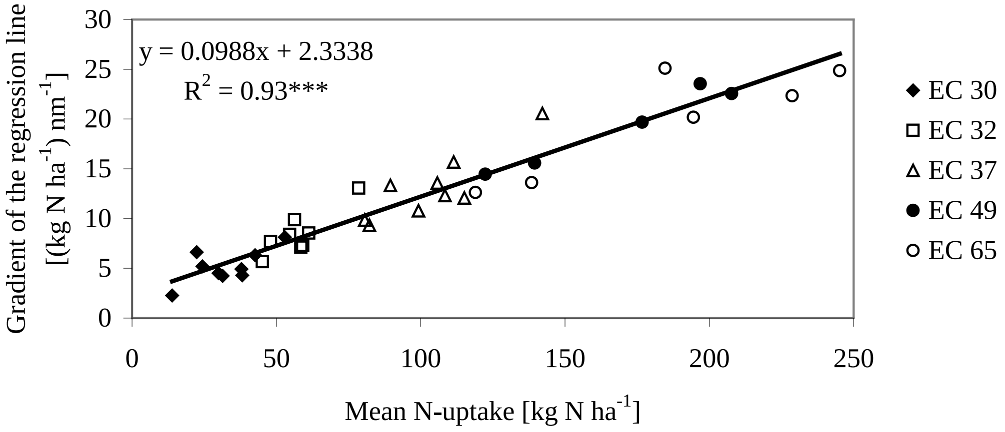

Figure 9: Regression analysis of mean N-uptake and gradient of the regression lines (2007 to 2009)

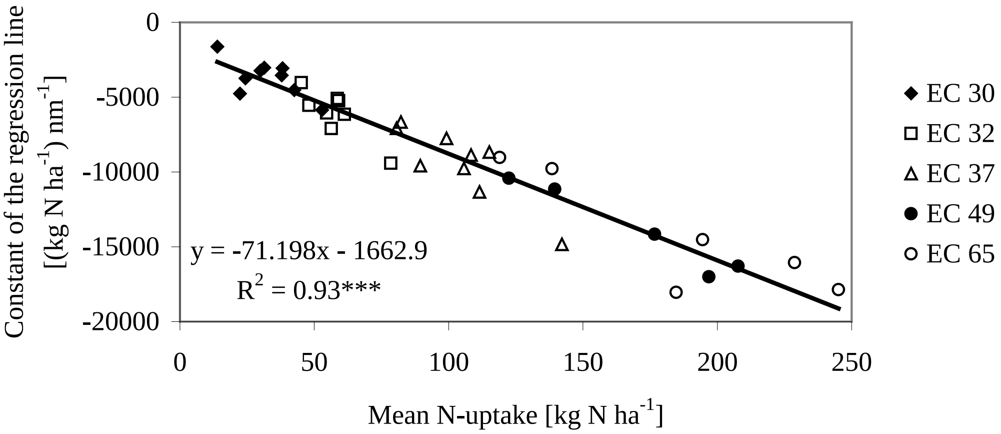

Figure 10: Regression analysis of mean N-uptake and constant of the regression lines (2007 to 2009)

The high and significant (p=0.000) coefficients of determination show that a predominant factor in the regression equations – and associated variables – is the N-uptake in the dry matter above ground. This fact is outstanding because the regression lines contain data from three trial years with seven different cultivars on nine test sites with twelve N-treatment levels overall.

DISCUSSION

The field trials showed that many different VIs can be used for precision farming and particularly for nitrogen fertilization. Especially the VIs REIP, NDI 1, NDI 2 and SR 2 (as shown in figure 3) displayed the best coefficients of determination over all N-treatment levels at all growth stages over the three trial years. The only VI that was low at all growth stages was SAVI. The VIs of spectra using higher wavelengths showed the best results (table 4). The VIs that uses higher wavelengths – more in the infrared region – have a better differentiation of the various N-treatment levels. It seems that the higher the wavelength used, the better the coefficient of determination. Another aspect for this assumption is that these VIs could better differentiate the N levels. The NDVI showed very weak results in the differentiation of the N levels, whereas the VIs NDI 1 and NDI 2 were significantly better, despite using the same formula as that for NDVI. The only difference was in their wavelengths.

Another aspect is that VIs other than NDVI and SAVI do not present the saturation effect relative to the N-treatment. As illustrated in figure 4 at growth stage EC 37, the REIP has a relatively high coefficient of determination, as well as a good differentiation of the N-uptake. The measurement points were evenly spread. In figure 5, NDVI shows another behavior. Only the low N-uptakes are differentiated from the higher ones. This fact, in combination with the saturation effect, becomes apparent because of the accumulation of measurement points at approximately NDVI 0.95. This saturation effect could be observed at all growth stages.

Reflectance measurements were able to detect a variable N supply of winter wheat canopies. With increasing mineral N doses, and therefore increasing N-uptake, the VI REIP shifted towards longer wavelengths, as shown in figure 4. This behavior was due to a reduced reflectance in the red region of the spectrum with higher chlorophyll concentration.

Besides the ability of the VIs to differentiate the N levels, another aspect is the influence of the cultivars on their results. In order to use VIs for fertilization purposes, the influence of the cultivars should be as low as possible to enable application to many different cultivars. This is a prerequisite for reflectance sensors and their VIs, respectively, if they are to be used by many farmers for precision farming purposes. This consideration is detailed in table 5. The influence from the various cultivars is irrelevant in nearly all VIs, with the exception of NDVI and IR/R at growth stages EC 30 and EC 32, and SAVI at EC 32. This context becomes apparent in the graphs for EC 32 over three years in figures 6 and 7. There, the influence of the cultivars on REIP is especially at low N-uptake levels up to a marginal REIP value of 728 nm. Above this value, a slight but non-significant influence could be observed. The curve progressions of the NDVI show a completely different behavior. Yet at low N-uptakes, the influence of the cultivars becomes evident and is minimized at higher N-uptakes. This fact reflects the saturation effect. At higher N-uptake levels it is impossible for the NDVI to differentiate N levels and therefore also the cultivars. This interrelationship becomes also evident by the fact that the coefficients of determination for REIP, which are significant at $p = 0.000$, are between $R^2 = 0.73$ and $R^2 = 0.83$ for all cultivars, whereas the range of coefficients of determination of the NDVI is only between $R^2 = 0.47$ and $R^2 = 0.64$, also with a significance at $p = 0.000$. This fact is again caused by the saturation effect. As a result of these trials, NDVI as well as SAVI are not qualified to be used for fertilization purposes.

As shown in figures 9 and 10, the significance in all three trial years between the agronomic parameter N-uptake and gradient, as well as the constant, becomes evident. As detailed above, the analysis of the gradient and the constant for the parameter N-uptake in the dry matter above ground suggests that the N-uptake is one of the most important factors on a VI. The cause of this is the local and variable growth and the differentiated N accommodation of the individual test sites. The gradient increases while the constant decreases during the vegetation period. Obviously the different N-uptake rates of the individual test sites and particular years, combined with the same upgrowth, do not have any effect on the gradient or on the constant of the regression line, respectively. This fact becomes evident with the high coefficients of determination at $p = 0.000$ and shows that the regression lines, and accordingly their variables, are mainly affected by N-uptake.

Regarding the results of this study, VIs can be a tool for farmers for fertilization purposes tailored to the plants' needs. Implementation of the actual N-status of the canopy, captured with reflectance measurements and in combination with yield maps, can be considered in a sensor-based N fertilization.

CONCLUSION

An optimal application of mineral N fertilizer to winter wheat is dependent on soil and weather conditions. In order to avoid an over-fertilization, which can cause various negative effects on plants health and hazards to the environment, mineral N doses should be applied according to the plants' needs. Besides a basis fertilization regarding the soil and its N mineralization ability, as well as a safety factor, the dose of mineral N given at the essential growth stages can be based on reflectance measurements. However, an important aspect is to avoid a high amount of mineral N fertilizer. Thus timing as well as the soil are important factors in a system of sensor-based N fertilization.

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