HYPERSPECTRAL DATA ANALYSIS OF N-FERTILISATION EFFECTS ON WINTER WHEAT: A CASE STUDY OF HUIMIN COUNTY, NORTH CHINA PLAIN

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ABSTRACT:

High nitrogen fertiliser applications are very common in many densely populated areas as in the North China Plain (NCP). A still growing population and an ongoing economic progress enforce that process. Remote sensing methods can help to optimize the N-management for diagnosing crop N status on a field and regional level. For that purpose, spectral and agronomic data were collected during the vegetation period of winter wheat (*Triticum aestivum L.)* in 2006 and in 2007 in the study area of Huimin County. In a post-processing step, a hyperspectral and agronomic data library was established which enables the analysis of spectra in dependence of agronomic data. The investigated parameters include biomass, N-uptake, LAI (Leaf Area Index), plant height and others. Finally, a model was developed which could be applied for extrapolation of the regional knowledge by using hyperspectral air or satellite borne remote sensing data.

This paper shows that the collection and postprocessing of spectral and agronomic data of winter wheat in combination with GIS (Geographic Information Systems) and RS (Remote Sensing) analysis help to identify over-fertilised and undersupplied managements for different phenological stages from shooting to heading.

1. INTRODUCTION

The agricultural area in China declines in many densely populated areas due to a fast urbanization, an ongoing growth of population and continuing economic progress. Further negative effects are caused by desertification and erosion in sparsely populated areas. In order to compensate these losses of agricultural land, high fertiliser, pesticide, fungicide and other measures are applied to increase yields. As a result of the green revolution the fertiliser input increased and quintupled from 6 bn. t in 1977 to 32 bn. t. in 2006 in China (FAO, 2004). Consequently, the environmental pollution from agricultural use is a severe issue in China and especially in the North China Plain (NCP), which is one of the most important areas for crop production in the country. Traditionally, the yearly N-input per ha amounts to approximately 600 kg to 800 kg by conventional methods in the NCP (Böning-Zilkens, 2004; Jia et al., 2004) for usually 2 harvests of a winter wheat/ summer maize rotation. An optimal N-fertilisation is very important for a profitable harvest. Chen et al. (2006) show that N_{min}-based fertilisation management results in moderate harvest. Time-consuming N-soil and N-crop analyses are required for evaluation during and after the growth stage (GS). Remote sensing methods have been used in order to estimate crop N-status in wheat (Flowers et al., 2001; Serrano et al., 2000; Wright et al., 2004). The analysis helps to derive significant parameters which can be used to fulfil the requirements for environmental problems in large areas (Haboudane et al., 2002). The combination of spectral reflectance and agronomic parameters show linear correlations for winter wheat crops at the shooting and heading stage. Based on a spectral and agronomic library many combinations can be tested and adequate models can be developed.

Different N-treatments were detected by spectral measurements during a field campaign as the N-status affects the chlorophyll content in the plants. Deficient N-supply causes earlier chlorophyll degradation in winter wheat crops compared to an optimal supply (Büker, 1992; Schellberg, 1990). The economic situation on the world market and the doubling of nutritional needs in the forthcoming decades (Meng and Chang, 2004) illustrate this problem. Hence, recent research projects in precision agriculture are focusing on the relationship between N application rate, yield and environmental pollution (Serrano et al., 2000), the workflow of this study is based on three steps: (1) spectral and agronomic data collection, (2) establishment of a hyperspectral and agronomic data library and (3) model development for knowledge extrapolation.

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2. MATERIALS AND METHODS

2.1 Study Area

The study area is located in Huimin County (PR China), close to the Yellow River (Huang He), in the northeast of Shandong province, which is part of the NCP (Fig.1). The climate could be distinguished as a warm-temperature sub humid continental monsoon climate with a mean temperature of 12.5°C and an average yearly precipitation of approximately 600 mm.

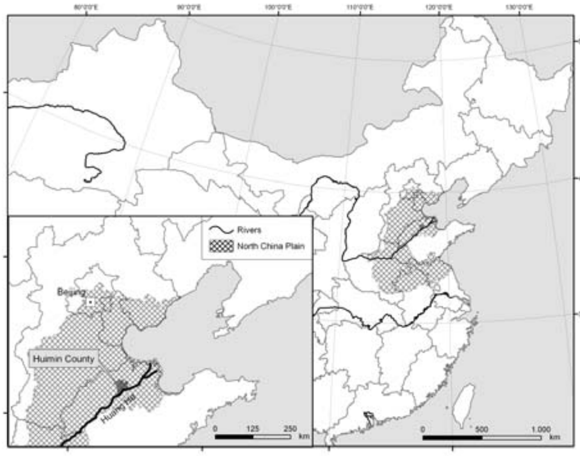

Figure 1. Map of study area.

Predominantly precipitations occur in summer. The farmers in this region operate a traditional cropping system with a summer maize and winter wheat rotation. Winter wheat is sown after harvest of summer-maize in autumn (in late September) and is harvested in early June. Winter wheat is irrigated during the drought in spring.

2.2 Experiments

The field studies consisted of three small size experiments with varying N-application and different regional winter wheat cultivars. The plot size within the experiment field's ranges from 28 m² to 170 m².Fields of experiment 1-3 were located at Xizhangliu village in Huimin County for the years 2006 and 2007.

Experiment 1
In this experiment the influence of manuring with five nitrogen treatments (0, 5, 25, 75, 100 kg N/ha) and four replications on *Weimai8* winter wheat cultivar was investigated. Each plot (10 m by 15 m) has been fertilised before planting. During growth stage 6 (Large, 1954) half of the plots received topdressing with nitrogen fertiliser again.

Experiment 2
In experiment 2 the amount of N-fertilisation was surveyed on two varieties of winter wheat (*Kenong9204* and *Lumai23*). Each plot was divided in six smaller plots. Each small plot (4.5 m by 7 m in 2006 and 4 m by 9 m in 2007) has been manured with a different rate:

- No N (control)
- 40% of optimum N rate (Opt)
- 70% of Opt
- Opt
- 130% of Opt
- Conventional N rate (con).

Experiment 3
The fields of this experiment represent the common cultivation method for this region. All fields belong to different farmers using different varieties of winter wheat and varying rate of N-fertiliser. The planting date differs according to the practice of the individual farmer.

In 2006 three farmers' fields (Expt4) and four in 2007 with an area between 2.5 ha and 4.5 ha have been additionally examined for satellite image analysis. Six different cultivars *Jimai20*, *Jimai21*, *Lumai8*, *Lumai23*, *Weimai8* and *Zimai12* were planted on these fields. All fields were managed by farmer's common practice. Image acquisition of multispectral data with IKONOS, EO-1 ALI and ASTER, hyperspectral data with Hyperion and radar data with RADARSAT and Envisat, has been performed simultaneous to the field data collection.

2.3 Field measurements and data collection

2.3.1 Spectral reflectance measurements: High resolution spectrometers from Analytical Spectral Devices Inc. (ASD) were used for taking spectral measurements, a Handheld FieldSpec (range 325 nm to 1075 nm) in 2006 and a QualitySpec (range 350 nm to 1800 nm) in 2007. The hyperspectral devices detect the electromagnetic spectrum from visible (VIS) to the near/shortwave infrared (NIR/SWIR) with 512 channels for FieldSpec and one TE cooled channel for QualitySpec by using optical fibre cable. The default FOV (Field Of View) of the devices with an angle of 25° was used for the measurements. The sensor was fixed by an orthogonal construction 1 m above the crop. It consists of three brass-poles, which were combined with moveable joins to a triangle (Laudien, 2005). A mounted sprit-level allowed reliable vertical spectra acquisition. The acquisition geometry is specified by the apex angle and measuring height (see Eq. 1). Consequently the acquisition radius amounted to 22.2 cm for the measurement and the acquisition area to 15 square centimetres (see Eq. 2). Continuous calibration measurements of optimisation by a white reference panel ($BaSO_4$) and of dark current were taken depending on illumination changes. The measurements were taken at noon from 10 am to 2 pm under cloudless conditions. For each plot three measurements were done in order to reduce the influence of atmosphere (clouds, wind, etc.) and field conditions. The spectra were collected at feekes growth stage 3-11 (10 measurements for Expt1-Expt3, 8 readings for Expt4 in 2006 and 6 measurements for all experiments plots in 2007). Approximately 14'000 spectra have been acquired for 2006 and 2007.

$$r\,[m] = h * \tan(\alpha/2) \quad (1)$$

$$A\,[m^2] = \pi * r^2 \quad (2)$$

with r = radius, h = measuring height [m],
α = apex angle [°],
A = acquisition area

2.3.2 Agronomic parameter's measurements: Agronomic measurements, including soil moisture, chlorophyll content, LAI (leaf area index), plant height, row distance, biomass and soil samples were combined with spectra measurements in 2006 and 2007. Soil moisture was measured by moisture meter (Delta-T Devices) in 2006 and with Aquaterr T-300 in 2007. Chlorophyll content readings using SPAD 502 (Minolta) were taken at mid-length of the uppermost fully expanded leaf from 30 randomly selected plants and averaged to one value for each plot. LAI was measured by SunScan Canopy Analysis System (Delta-T Devices) in 2006. Plant height and row distance were measured before taking biomass. Biomass samples were selected randomly in each plot by cutting 2 neighbouring rows of vegetation (1 m by 0.3 m). The samples were weighed before and after drying at 70°C. Dried biomass was milled and N concentration was determined by Kjeldahl-N method (Li et al., 2008). Biomass samples were collected during the GS 4, 6, 7 and 9 in 2006 and during the GS 4, 5, 7, 9 and 10 in 2007. Nitrate concentration from the stem base was measured by a reflect meter at the shooting (3) and heading (4) stage.

Soil samples were collected during the GS (2006 and 2007) and after harvest in 2005, 2006 and 2007. More details for the soil N min analysis are in Li et al. (2008). Approximately 54’000 agronomic data are available for 2006 and 2007.

2.4 Data pre-processing and statistical analysis

Data pre-processing includes average determination and elimination of outlier. The pre-processed data were tested by regression analysis using Excel and SPSS. A t-distributed test statistic using Eq. 3 was selected for this analysis.

$$\hat{t} = \frac{R * \sqrt{n-2}}{\sqrt{1-R^2}} \qquad (3)$$

with $\hat{t} > t_{n-2,\alpha/2}$, t is t- distributed

Data of Expt1, Expt2 and Expt3 are the basic for observed data. Farmer’s field data (Expt4) were tested for model prediction. The performance of the model was examined by the statistical parameter R² (coefficient of determination), RMSE (root mean square error) and RE (relative error).

3. RESULTS

3.1 Hyperspectral and agronomic data library

The averaged spectral data and the agronomic data were organised and stored in a Microsoft Excel spreadsheet. The agronomic data for each plot were added. For data analysis, several vegetation indices (VI) including NDVI, HNDVI (Hyperspectral Normalized Difference Vegetation Index), HVI (Hyperspectral Vegetation Index), RVI (Ratio Vegetation Index), OSAVI (Optimized Soil-Adjusted Vegetation Index),

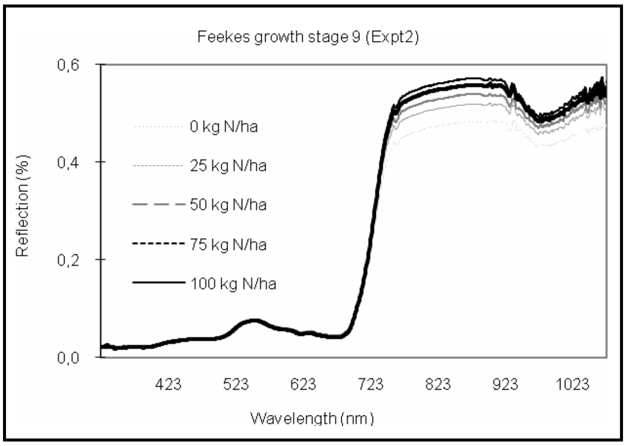

Figure 2. Influence on reflection by N-treatments

MCARI2 (Modified Chlorophyll Absorption Ratio Index), RE (Reflection in Red Edge), REP (Red Edge Position), MCARI (Modified Chlorophyll Absorption Ratio Index), GI (Greenness Index), TVI (Triangular Vegetation Index), CAI (Chlorophyll Absorption Integral) and TCI (Triangle Chlorophyll Index) were calculated.

VI	Formulation	Reference
NDVI	$R_{NIR} - R_{RED})/(R_{NIR} + R_{RED})$	ROUSE et al. (1974)
HNDVI	$(R_{827} - R_{668})/(R_{827} + R_{668})$	Oppelt & Mauser (2004)
RVI	R_{680} / R_{800}	Daughtry et al. (2000)
HVI	$(R_{750} - R_{700})$	GITELSON et al. (1996)
OSAVI	$(1+0.16)*(R_{800} - R_{670})/(R_{800} + R_{670} + 0.16)$	Oppelt & Mauser (2004)
MCARI2	$\frac{1.5 * [2.5 * (R800 - R670) - 1.3 * (R800 - R550)]}{\sqrt{(2 * R800 + 1) - (6 * R800 - 5 * \sqrt{R670})}}$	HABOUDANE et al. (2004)

Table 1. Formulation of selected VIs

Table 1 shows the formulations for some VIs which will be discussed later. In addition, correlations between the agronomic parameters and the vegetation indices were determined. Other vegetation indices can be integrated if necessary. The data library allows analysis for each phenological stage and each cultivar of winter wheat.

3.2 Influence of N treatments and cultivar

The data analysis shows, that winter wheat cultivars and N-treatments affect the results. Between the local cultivars *Kenong9204* and *Lumai23* exist huge spectral differences (approximately 10% point reflection difference in NIR) were recognised. In the field the plant leaves appear in dark and clear green colour. The correlations coefficients for *Kenon9204* cultivar are stronger significant at the same probability level. Schellberg (1990) obtained the same results for local winter wheat cultivars in Germany. Furthermore, different N applications can be recognised in the spectra: The higher the N-rate the higher is the reflection (Fig. 2). Sole exception is the 75 kg N/ha rate. Spectra of these plants appear to be slightly higher in their reflection. With this method over-fertilised fields can be detected in an early feekes GS. Depending on the spectra, the progress of the VI during all feekes GS (see Fig. 3) and the harvest the 50 kg N/ha rate can be regarded as the optimum N-rate. As Fig. 3 shows, the crops showing this N-rate has a relative high vitality using HNDVI time series. OSAVI and HVI show equal course. Jia et al. (2008) get similar results because of SPAD reading and nitrate content analysis.

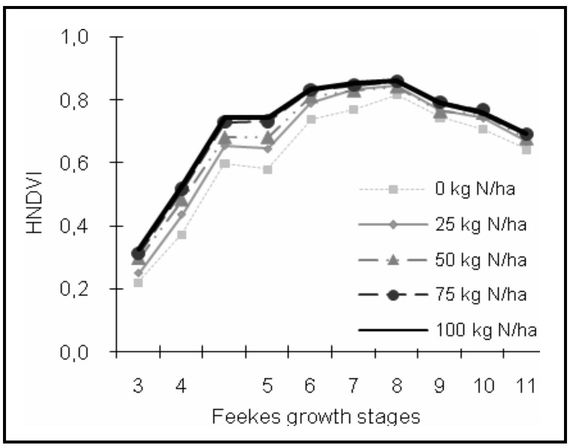

Figure 3. Time series HNDVI

3.3 Establishment of a regression model

For the establishment of a regression model the correlation between the VI and agronomic parameter from the experiment field data from 2006 have been tested by coefficient of determination (R^2). Generally the correlations are dependent on the winter wheat variety and GS. For the analysis four different feekes GS (4, 5, 7 and 9) were used. The analysis show that correlations between hyperspectral VIs and agronomic parameters are higher as for multispectral VIs. Significant correlations could be made for biomass, N-content, N-uptake, SPAD and measured LAI for the experiment fields. N-uptake was calculated as the product from dry biomass and N-content. Biomass and plant N-uptake show the highest R^2 values for HNDVI, HVI, OSAVI and MCARI2 for the experiments fields. SPAD readings were only significant for the GS 4, but not for other GS or across all stages. The chlorophyll content decreases during the stages 4 to 9, so that this parameter is disregarded for the use in a model. The R^2 for LAI and the VI also show different significant and not significant correlations for the tree experiments. An establishment of a model for LAI is not possible with the 2006 data.

Results for multispectral VIs like the NDVI in this study are evaluated in Li et al. (2008). Analysis from Koppe et al. (2008) show that Normalized Ratio Indices (NRI) derived from a large number of two-bands combinations of EO-1 ALI and Hyperion satellite images offer good results

3.4 Model evaluation

In this step the data are analysed for model evaluation. Thereby the data of the farmer´s field from the two years 2006 and 2007 are validated. For 2006 the GS 4, 5, 7 and 9 have been considered and for 2007 GS 4, 5 and 7. Table 2 shows the coefficient of determination (R^2) for the agronomic parameters like biomass, plant N-uptake and LAI and selected VI. Plant-uptake and biomass show the highest R^2 values for all VIs. HNDVI and OSAVI are more significant as NDVI and other VI for the four stages and across the stages in 2006. Correlations for LAI can be stated only for two feekes GS. Regarding the analysis of 2007, the performance of the regression models is less reliable than in the 2006 analysis as the R^2 values are lower. Especially the R^2 values for OSAVI at the feek GS 4 and 5 are lower as for RVI or NDVI. So in 2007 the models for RVI show the best performance for the feekes GS 4 and 5, OSAVI for the GS 7 and across all stages calculations of OSAVI and HNDVI provide best results

		NDVI	RVI	HNDVI	HVI	OSAVI	MCARI2
2006	*Feekes growth stage 4, n = 74*						
	biomass (kg/ha)	0.629***	0.603***	0.665***	0.518***	0.656***	0.567***
	Plant N-uptake (kg/ha)	0.710***	0.707***	0.752***	0.716***	0.727***	0.532***
	Feekes growth stage 5, n = 43						
	biomass (kg/ha)	0.323*	0.323*	0.318*	0.160	0.313*	0.239*
	plant N-uptake (kg/ha)	0.390**	0.391**	0.330*	0.305*	0.445**	0.393**
	Feekes growth stage 7, n = 43						
	biomass (kg/ha)	0.107	0.101	0.123	0.034	0.115	0.086
	plant N-uptake (kg/ha)	0.294*	0.290*	0.308*	0.176	0.357*	0.304*
	LAI	0.077	0.081	0.088	0.193	0.182	0.222
	Feekes growth stage 9, n = 43						
	biomass (kg/ha)	0.104	0.101	0.126	0.099	0.156	0.119
	plant N-uptake (kg/ha)	0.130	0.124	0.129	0.149	0.202	0.181
	LAI	0.148	0.152	0.296*	0.300**	0.389**	0.357**
	***All growth stages** n= 203, n = 86 for LAI*						
	biomass (kg/ha)	0.583**	0.603**	0.609**	0.441**	0.620**	0.525**
	plant N-uptake (kg/ha)	0.593**	0.618**	0.618**	0.449**	0.631**	0.532**
	LAI	0.114	0.112	0.149	0.115	0.239*	0.203*
2007	*Feekes growth stage 4, n = 95*						
	biomass (kg/ha)	0.407***	0.443***	0.410***	0.054	0.229**	0.289**
	plant N-uptake (kg/ha)	0.351***	0.333**	0.349**	0.082	0.241**	0.299**
	Feekes growth stage 5, n = 52						
	biomass (kg/ha)	0.323*	0.358**	0.342*	0.151	0.302*	0.379**
	plant N-uptake (kg/ha)	0.390**	0.301*	0.292*	0.111	0.270**	0.454**
	Feekes growth stage 7, n = 50						
	biomass (kg/ha)	0.044	0.037	0.051	0.101	0.114	0.131
	plant N-uptake (kg/ha)	0.023	0.013	0.022	0.031	0.049	0.138
	***All growth stages**, n = 197*						
	biomass (kg/ha)	0.583**	0.603**	0.609**	0.441**	0.620**	0.525**
	plant N-uptake (kg/ha)	0.593**	0.618**	0.618**	0.449**	0.631**	0.532**

* significant at 0.05 level; ** significant at 0.01 level; *** significant at 0.001 level

Table 2. Correlations coefficients for relationships between agronomic parameters and VIs for farmer’s field

4. DISCUSSION

The agronomic parameters and the spectral reflectance are influenced by the farmer´s management during the growth stages. It has to be considered, that, this study was made under normal conditions on fields managed by usual famers, so that fields, cultivars, plant date, N-management, harvest date and irrigation have not been modified for the study. Schellberg (1990) and Bücker (1992) analyse fields in specially adapted case studies with similar results. Oppelt and Mauser (2004) show, that the models are influenced by winter wheat cultivar and growth stage. Here the OSAVI correlates for many winter wheat cultivars. LAI measurements were not taken frequently and only in 2006. Therefore it is not possible to evaluate the data and take it into consideration here as well.

Additionally, the spectral and agronomic data can be stored in a Web–based spectral database. That ensures easy management of a very voluminous data (Laudien, 2006).

The research in Huimin County in 2006 and 2007 shows, that some promising models can be developed for hyperspectral VIs. The experimental data of these two years result in more similarities as differences in their results. By means of the spectral and agronomic library the influence of N-fertilisation and cultivars can be analysed for every feekes GS and across all stages in a time series, assuming that data has been collected for that stage.

5. CONCLUSION

The collected and post processed spectral and agronomic data of winter wheat in combination with GIS and RS analysis help to identify over-fertilised and undersupplied managements for different phenological stages from shooting to heading. Some VIs like OSAVI, HNDVI and MCARI2 show significant correlation between biomass and N-uptake. In the early development stage (shooting), the different N-applications for the treatments could be detected in the spectra as well as in agronomic parameters such as chlorophyll content and biomass. Consequently, the vitality of the crop can be detected on a local scale. The extrapolation of the derived experimental plots on a regional scale is realised by analysing Hyperion imagery in a comparable manner (Koppe et al., 2008). Here, it can be stated that some of the VIs like HNDVI, which performs well on plot scale, cannot be used for Hyperion imagery. Others, such as MCARI, come up with reliable results, so that the chosen VI has to be rated very carefully while being adapted to the analysis.
The method of knowledge extrapolation, as presented in this contribution, offers the possibility to facilitate the development of a decision support tool for winter wheat production and to secure an adequate nutrition management in such densely populated areas as the NCP. These steps of precision agriculture, as described by Rösch et al. (2007) are very important for a sustainable agricultural production.

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