Crop imaging and soil adjusted variable rate nitrogen application in winter wheat

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Abstract

Site-specific nitrogen (N) management in precision agriculture is used to improve nitrogen use efficiency (NUE) at field scale. The aim of this study has been to contribute to improvements in decision support for application of N fertilizer. Specifically, image-based methods were applied and improved to better target the application of N fertilizer via variable rate application (VRA) for small fields, as typical in Swiss agriculture. Multi-spectral images acquired with an unmanned aerial vehicle (UAV) platform and soil N data at reference locations were used to explore the in-field variability of crop in a plot-based field experiment that compared uniform standard (ST) rate to variable rate (VR) application. The VR final yield resulted in the same range as the ST but showed an average 10% reduction in fertilizer use.

Keyword: nitrogen management, winter wheat, UAV, variable rate application.

Introduction

The spatial and temporal distribution of N available for agricultural crops in the field varies greatly according to a multitude of factors including soil properties, climate and management (Kindred et al, 2015). In Swiss agriculture, farm size is considered medium to small scale as average farm extension is around 20 ha (Swiss FSO, 2018). It follows that the monitoring and management of in-field variability presents additional obstacles compared to large-scale precision farming operations (e.g. Farmstar-conseil, France). Nonetheless, N fertilizers are widely used and their application represents both an environmental issue and a cost factor that are being actively tackled. The implementation of a precision farming framework may be beneficial to further improve NUE at medium to small scale and an example for other countries with similar issues.

Aim and Hypothesis

The study presented in this paper is part of a project that aims to develop methods for the implementation of site-specific N fertilization in Switzerland. The focus is on main crops such as winter wheat (*T. aestivum*) and maize (*Z. mays*). With the aid of low-altitude remote sensing technology and based on monitoring of various soil parameters (e.g. soil type and nitrate content), the project objectives are to map heterogeneity in fields and to provide data-based recommendations for variable rate N fertilization in fields of the size of a few ha. At the same time the economic and environmental costs and benefits are evaluated. This first experiment was designed to test the functionality of the sensors and materials involved, to validate principles from in the literature (Gabriel et al, 2017; Heege, 2013; Nawar et al, 2017) and to get first insights in to the practical implementation. The main hypothesis for this preliminary study was that the implementation of site-specific N management via VRA would reduce average N application compared to the standard fertilization strategy without affecting yield and thus increasing NUE.

Material and methods

Experimental site and design

The experimental site is located at the Agroscope research centre in Tänikon, Canton Thurgau, Switzerland (47.4790021°N, 8.9059287°E) and managed by the Swiss Future Farm. The climate in this region is characterized by 1170 mm annual rainfall and an average annual temperature of 8.6°C recorded by a local weather station (data range 1970-2017) from the federal office of meteorology (MeteoSwiss). The field covered an area of 2.5 ha on which winter wheat (cultivar Arnold) was sown on the 19th of October 2017. The soil in this field is characterized as a Gleysol based on a soil survey map provided by the national soil monitoring network (NABO). The soil type was not homogenous across the field, in fact the central part was characterized by a more stagnating Gleysol.

A randomized block design with three treatments replicated in six blocks (n = 6) covering 1.35 ha of the field was chosen to study in-field variability. The dimension of a single plot was 15x50 m, to match the operational range of the pneumatic fertilizer spreader (Rauch, Sinzheim, Germany) used. N fertilizer was applied in the form of mineral ammonium nitrate (24% N content), divided in three split applications (Table 1). The fertilization strategy is based on the mineral N (N_{min}) method provided in the "Principles of fertilization of agricultural crops in Switzerland" (PRIF) (Sinaj & Richner, 2017). The treatments consisted of a standard (ST) and of a variable rate (VR) treatment, for which each plot was managed individually by evaluating the initial N_{min} (e.g. Plot 1 with N_{min} = 30 kg N/ha received 80-30 = 50 kg N/ha fertilizer in the first application) and the in-season spectral indices (e.g. Plot 10 with mean index value of 0.25, 25% higher than the field average received 25% less fertilizer i.e. 40 kg N/ha in the second application). Finally, a non-fertilized (NF) treatment was used as a measure of soil N supply.

Table 1. Fertilization strategy adapted from Swiss reference (Sinaj & Richner, 2017) and Levy & Brabant (2016). N_{min} and rates of N fertilizer per treatment in kg N/ha are reported per growth stage in BBCH decimal units (Meier et al., 2009). For VR, the range is shown.

	N_{min} BBCH 20	Split 1 BBCH 23	Split 2 BBCH 32	Split 3 BBCH 45	Total
Reference	-	80 - N_{min}	60	20	160 - N_{min}
ST	44	36	60	20	116
VR	30-85	0-50	40-70	0-20	50-132
NF	43	-	-	-	0

Soil and plant analysis

To obtain a measure of N_{min} available in the soil at the end of the winter season, mixed samples of 6-8 soil cores from each plot were collected on 27th February 2018 at three different depths 0-30 cm, 30-60 cm and 60-90 cm and the concentration of NH_4 and NO_3 was measured. The mean 0-90 cm N_{min} per plot were used as reference for the calculation of the first split application to apply as shown in Table 1.

Biomass samples were collected at BBCH 32 and few days before harvest (8th July 2018) in two locations per plot. The BBCH 32 samples were dried at 60°C for 48 h to quantify dry matter and afterwards N concentration was measured in the laboratory. The samples at harvest were air dried for two weeks and threshed to separate the grain from the straw which together make up the plant dry weight. N concentration was measured in both the milled grains and straw material and then used to calculate N uptake (dry matter x N concentration).

Acquisition of aerial data

The low-altitude remote sensing UAV platform was composed of a multispectral camera (Parrot Sequoia, Paris, France) mounted on a Quadcopter (DJI P4P, Shenzhen, China) and flown over the field on a weekly to bi-weekly basis. Spectral information of the growing crop was recorded in four bands of the light spectrum, namely Green (G) centred at 550 nm, Red (R) at 660 nm, Red Edge (RE) at 735 nm and Near-Infrared (NIR) at 790 nm. The bandwidth was 40 nm for G, R and NIR and 10 nm for the RE. The output of the camera consisted of one separate image for each band. The images were captured while the camera was being flown over the field in a single grid automatic flight plan (Pix4D Capture, Lausanne, Switzerland) by the drone at 5 m/s speed and 1.9 s time interval at 50 m height. The ground sampling distance (GSD) of the single band images was 4.5 cm/pixel. The raw images were processed in the photogrammetry software Pix4D Mapper: first a radiometric correction was applied by using a Airinov reflectance target, then they were stitched together to create a reflectance map and finally they were georeferenced with ground control points (GCP) before generating final index maps of the field. The spectral index selected for this study, the Normalized Difference Red Edge index (NDRE = (NIR - RE) / (NIR + RE)), is known for its sensitivity to chlorophyll and N content of the crop (Basso et al, 2016). The data were extracted per each plot with the zonal statistics package in the GIS software QGIS (2.18) and further analysed with RStudio (R version 3.4.1).

Results

Spectral measurements

There was a high correlation ($R^2 = 0.53$) between N uptake, analysed from mid-season destructive samples and NDRE measurements (Fig. 1). This result was a good indication of the possibility of using the selected spectral index to make a qualitative assessment of the crop's N status. The changes in NDRE through the growing season showed an interesting temporal pattern (Fig. 2) and increases in the index curve corresponded with the time points of the three split fertilizer applications. Differences between the NF treatment and the VR/ST became significant after the second split N-application, which also coincided with the end of the prolonged drought period in this region in 2018. After flowering and beginning of senescence, the NDRE reflectance signal changed and started to decrease.

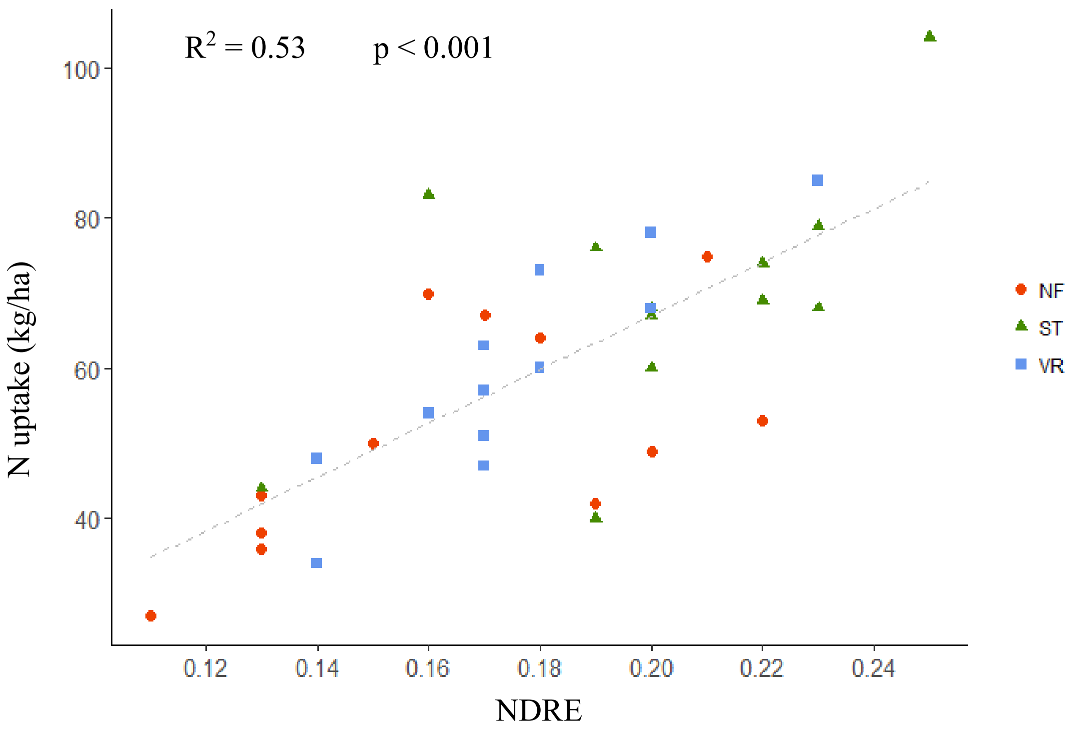

Figure 1. Linear regression between the NDRE and the N uptake at BBCH 32. Samples were collected from the same area of 1 m2, twice per each plot.

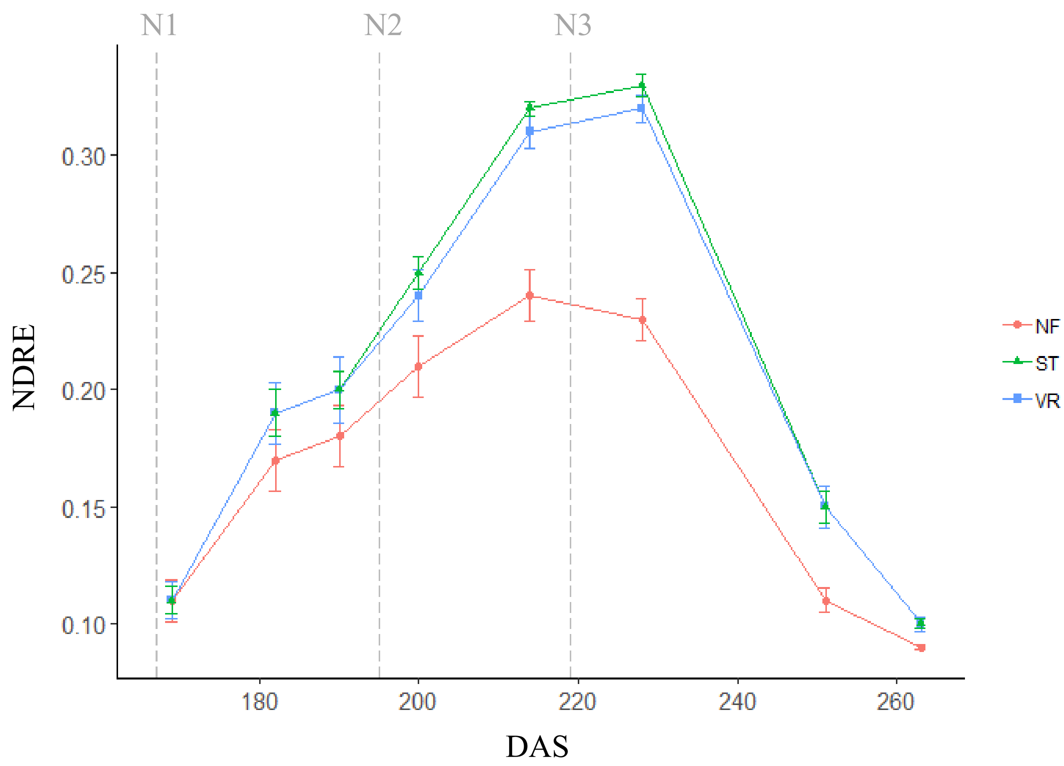

Figure 2. Seasonal patterns of NDRE measurements in 2018. Each measurement point represents average values per treatment with standard error (n = 6). Time is represented on the x axis as days after sowing (DAS). N1, N2 and N3 denotes the first, second and third split application, respectively.

Grain yield

The grain yield obtained via manual sampling (Fig. 3) showed no significant difference between the VR treatment and the ST treatment (6.34 ± 0.27 t/ha and 6.23 ± 0.23 t/ha, respectively) while both were above the yield achieved by non-fertilized plots (3.81 ± 0.21 t/ha). Thus, the changes in management did not affect the yield of the VR treatment, in which the N fertilizer was redistributed and on average was reduced by 11 kg N/ha (Table 2) compared to the ST treatment.

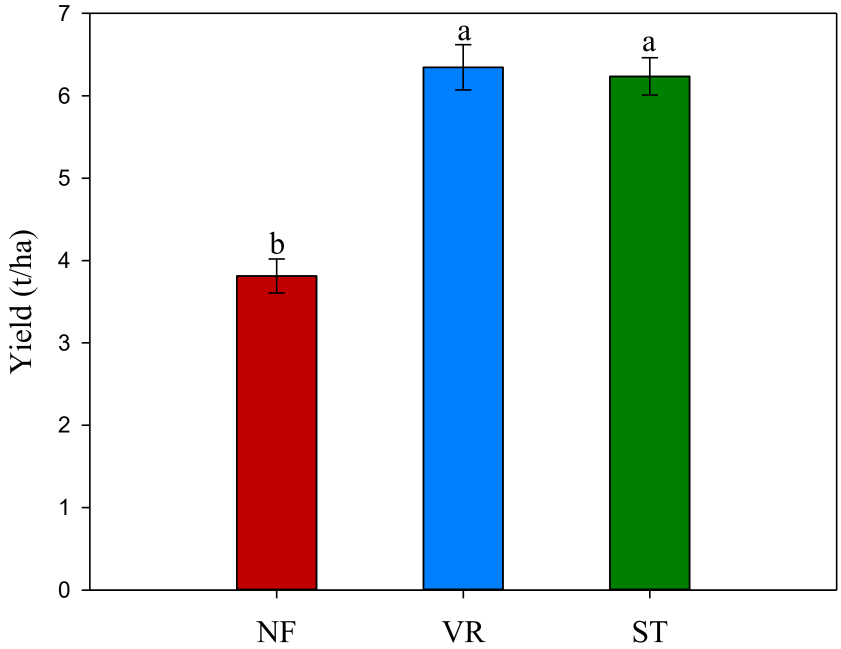

Figure 3. Grain yield of winter wheat at harvest in t/ha. Bars represent the average values per treatment with standard error (n = 6). Letters denote the level of significance.

Nitrogen use efficiency

The apparent fertilizer recovery (AFR) (Kindred et al., 2015) as reported in Eq. (1) was used as a measure of the quantity of N fertilizer recovered by the crop. In this equation, the value of N uptake from the NF plot (as a quantification of the soil N supply) was subtracted from the N uptake (where x = ST or VR) of a treatment and divided for the N fertilizer applied.

$$AFR = \frac{\text{N uptake (x) - N uptake NF}}{\text{N applied}} \qquad (1)$$

Total N uptake in both the VR and ST treatments resulted in an uptake of 179 kg N/ha (Table 2). The reduction in average applied N seemed to indicate a total higher use efficiency (AFR) in the VR (93.8%) compared to ST (83.1%). The difference was however not significant ($p = 0.26$). The same pattern was true for the grain only (AFRg) with 72.3% for VR and 67.2% for ST. The average soil N supply estimated from the non-fertilized plot was 84 kg N/ha.

Table 2. N balance including N applied with the fertilizer and N uptake from the crop at harvest. Letters denote the level of significance.

	N application (kg N/ha)	N uptake grain (kg N/ha)	N uptake straw (kg N/ha)	N uptake total (kg N/ha)	AFRg %	AFR %
NF	-	68b	15b	84b	-	-
VR	105a	144a	35a	179a	72.3a	93.8a
ST	116a	146a	32a	179a	67.2a	83.1a

Discussion

Spectral indices can be reliable to follow vegetation development but a robust quantification needs further calibration data or even reference plots such as N rich strips and/or a non-fertilized plot (Raun et al, 2005; Samborski et al, 2009). Following the temporal evolution of NDRE differences across the six VR plots was the base of the rationale to adjust the fertilization strategy in-season in the different plots which seemed to result in a higher NUE due to a reduction in average N applied. This is in line with several experiments testing remote sensing based variable rate fertilization in wheat as reviewed by Diacono et al. (2013). Compared to other studies, in this experiment, tools such as management zones and an N rich strip were not directly delineated and used for the decision because, as mentioned in the beginning, the main aim of this preliminary study was to test the drone camera system and to gain first-hand field experience. The advantage of such tools is that in theory they provide a more objective means of comparison for the remote sensing technology and they facilitate the direct conversion to N recommendations via algorithms (Franzen et al, 2016; Holland & Schepers, 2010). Furthermore, in this study, the fertilizer was reduced (up to 50%) in single plots showing better growth during the season and increased (up to 15%) in the plots that showed reduced growth. The benefits of this approach are that fertilizer is redistributed across the field in greater quantity to the areas in which plant growth stimulation is wanted and in reduced quantities to areas showing a prominent SNS. A possible negative consequence could be that in areas in which plant density or biomass is lower due to the combination of factors other than N (e.g. water limitation or compaction), the supplementary N applied could not be properly used (Ebertseder et al, 2003) and could increase the environmental risk. Excessive N could also result in lodging. Another common approach is therefore to adapt fertilizer quantity to the yield potential of a certain plot or management zone (Bushong et al, 2016). In this case, the benefit comes from targeting areas of high potential where more fertilizer will be provided to allow the crop to reach its full potential.

The last winter wheat growing season (2017/2018) was characterized by an intense and prolonged drought, especially in the month of April and beginning of May with only 14 ml summed precipitation during this time compared to the average 90 ml (source: MeteoSwiss). Normally, yield expectation for winter wheat in this region is around 7 t/ha of grains. As expected, the drought affected the final yield and probably also the N supply in this period. Despite this drought, the yield achieved was still in a good range and was comparable to that of other winter wheat fields in the same area. The tendency of the Gleysol to retain more water and the soil heterogeneity in the field played a distinct role in this year. The central area of the field characterized by a more organic soil was visible from early in the season and in the UAV images (Fig. 4) where the vegetation developed better than in the surrounding plots.

Figure 4. NDRE map produced from images taken on 6th April 2018 (BBCH 24) with the UAV system. The variability is visible across the trial design.

Conclusion

The experiment described in this paper was a first experience into the implementation of site-specific N management in Switzerland supported by low-altitude remote sensing and information about soil heterogeneity. The knowledge gained was important to better understand the relation between the digital data and the actual processes in the field through the growing season. It provided positive indication that by managing in-field variability, even on a small scale, it is possible to influence the efficiency of N uptake from the crop, thus reducing the residual N that can accumulate after the season and the risk of loss by emissions. The environmental conditions, especially the soil and the dry weather played a crucial role for N management. Deciding on the most appropriate site-specific fertilisation strategy is crucial to improve the efficiency of nitrogen uptake in wheat. In the future studies of this project, the delineation of management zones and the estimation of zone-specific yield potential will be taken into account as factors to develop the basic strategy. UAV images provided a base for supporting the decision regarding the amount and spatial distribution of the second and third application of N fertilizer. This can be further improved by the use of data driven algorithms but it requires ultimately an expert evaluation before the information is transferred to the variable rate machinery. Potential improvements for the in-season management may be made through the integration of data from the continuous monitoring of the soil-nitrate content.

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