68. N balance and satellite-based monitoring of selected winter wheat fields in a nitrate vulnerable zone in Switzerland

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Abstract

The study was carried out in a nitrate vulnerable zone in central Switzerland. The focus was set on fertilizer application methods and the use of satellite-based remote sensing to monitor crop growth and nitrogen (N) balance in winter wheat over three years. Sentinel-2 satellite imagery was collected for 27 selected winter wheat site-years. Soil mineral N data, along with crop yield and N uptake measurements, were collected to calculate field-specific N surplus. Preliminary results showed a consistent relationship between satellite-based information and crop growth across the monitored site-years, which reflects the variations in N application rates and N uptake by the crop.

Keywords: N balance, nitrogen management, satellites, winter wheat

Introduction

The ground-water reservoir below the central plains of Switzerland provides around 80% of the regional drinking water supply. At the same time, this region is a key area for arable and vegetables production. Due to intensive agricultural use and unfavourable hydrogeological conditions, in many parts of the region, the nitrate concentration in groundwater exceeds the quality target of the Swiss Federal Water Protection Ordinance for groundwater of 25 mg nitrate/l (FOEN, 2019).
The influence of excessive and imprecise fertilizer application on nitrate leaching has been shown to be consistent under intensively cropped regions, typically over winter in Central Europe (Vigliotti *et al.*, 2020). Other factors such as crop cover and type made clear that certain crop rotations and the effect of mineralization of organic N are more prone to cause leaching (Frick *et al.*, 2022). Satellite images application has proven useful for monitoring of N status in wheat as well as N balances (Fan *et al.*, 2022). Integrating satellite data with crop and soil information, can support estimation of N inputs and crop N uptake throughout the growing season (Curk and Glavan, 2023; Lake *et al.*, 2003). These approaches help optimize fertilization by adjusting application rates according to crop needs, reducing the risk of over-fertilization and minimizing environmental impacts like nitrate leaching (Basso *et al.*, 2016; Delgado *et al.*, 2005). At the regional scale, remote sensing of crops and N uptake enables the spatial integration of in-field measurements to generate maps and, ultimately, to aggregate values for specific crops and crop rotations, as well as for the region as a whole. Such spatially explicit and cumulative information facilitates informed decision-making and the monitoring of management outcomes.

Objective and hypothesis
The objective of this study was to assess the N balance in selected winter wheat fields based on different fertilization practices and to explore how satellite data can be used to remotely identify differences in seasonal trends of crop growth at regional level and differences related to fertilizer application at field level.

Material and methods

Experimental site and fertilizer methods

The study region comprises approximately 1300 ha of agricultural land and is situated in central Switzerland in the cantons of Solothurn and Bern (Figure 1). The 30-years average annual precipitation sum and air temperature are 1100 mm and 11°C, respectively (MeteoSuisse). Different soils characterize the region, mostly Cambisols and calcaric Cambisols. Inside the perimeter of the project, data were collected form 26 selected winter wheat (*T. aestivum*) fields over three years (2022–2024) for a total of 27 site-years (Figure 1).

Different N fertilizer methods were tested including field-specific N recommendation as described in the Swiss principles of fertilization (Sinaj and Richner, 2017). The standard "Norm" recommendation for winter wheat is 140 kg N/ha to be divided into three split applications at the end of tillering, beginning of stem elongation and emergence of the flag leaf. The other methods used were the soil mineral N content (SMN) method and the adjusted N fertilizer norm (ANFN). The SMN method uses a correction of a yield-based reference N demand value for a crop based on SMN (nitrate-N and ammonium-N) measured over 90 cm with additional correction factors related to soil properties, organic fertilizer application, and previous crop. The ANFN is a model-based recommendation which corrects the norm fertilizer for a crop by considering soil properties, weather, previous crop and organic fertilization as well as management (Maltas *et al.*, 2015). Additionally, in selected fields, strips with no fertilizer (0N) applied or according to the farm's standard (ST) were used as control. The fertilization schemes are grouped in three categories: (1) one method (ANFN or SMN) at whole field level and (2) direct comparison, in which one or both methods were compared to ST and 0N.

Soil and crop analysis

The soil mineral N (SMN; nitrate-N and ammonium-N) was measured in mixed samples of 10–15 soil cores from each field and plot at three 30 cm layers over 90 cm. The 0–90 cm SMN per plot were used as reference for the calculation of the fertilizer recommendation. The samples at harvest were collected in one m^2 subplots with three replicates in each plot/treatment. N concentration was measured in both the milled grains and straw material to calculate the total N uptake (grain dry weight * grain N concentration + straw dry weight * straw N concentration). Additionally, an indicator for N surplus that includes also the estimated soil N supply (SNS) from the total N uptake of the crop in the 0N plots was calculated.

Acquisition of satellite data

Sentinel-2 (S2) satellite time-series from the region were selected for different dates within the winter wheat growing season of each site-year. The images were pre-processed and filtered for cloud-cover over 10% and mean blue reflectance over 0.1 to account for residual cirrus clouds. The reflectance

Figure 1. Study area comprising the project's borders in the canton of Solothurn (blue line) and Bern (red line) and the fields' borders (yellow lines). Base image source: GoogleMaps®.

data were used to calculate the normalized difference red edge (NDRE = NIR + Red / NIR – Red = S2 Band 8 – S2 Band 6) (Barnes *et al*., 2000) as well as a model-based leaf area index (LAI). This was obtained through the inversion of the PROSAIL radiative transfer model (Jacquemoud *et al*., 2009) parametrised for winter wheat, where a neural network was trained to retrieve LAI from S2 pixels. The model outputs predictions ranging from 0 to 8, and any pixels indicated as cloud, snow, shadow or water by the S2 Scene Classification Layer was set to N/A.

Results

Fertilization and N balance

The N fertilizer recommendations (N fert) for winter wheat were limited at the Norm value of 140 kg N/ha for nitrate vulnerable zones (Figure 2a). The range was between 100 and 140 kg N/ha with a median of 135 kg N/ha for the Standard and the SMN treatment and the median of the adjusted N fertilizer norm (ANFN) was 140 kg N/ha. The median for the years 2022 and 2023 was lower (110–120 kg N/ha for SMN and ANFN), however the recommendations for the year 2024 were higher with a median of 140 kg N/ha. The reported recommendations for all 27 site-years, were not equally distributed among treatments, due to trials with different design. The total N uptake was the in the range of 90 to 310 kg N/ha (Figure 2b). The 0N treatment showed the lowest levels of N uptake with 110 kg N/ha. The fertilized treatments Standard, SMN and ANFN were in the same median range between 200 and 230 kg N/ha. The differences between years were substantial, with 2023 being in general the year with highest N uptake (median range: 151 to 228 kg N/ha) and 2024 the year with the lowest N uptake (median range: 97 to 200 kg N/ha). The N surplus (data not shown) did not show significant differences among the treatments with a median of 32 kg N/ha for the ANFN, 41 kg N/ha for the SMN treatment and 55 kg N/ha for the ST treatment and range between –55 and 125 kg N/ha.

Satellite-based monitoring

The mean values for the normalized difference red-edge (NDRE), and the leaf area index (LAI, m^2/m^2) across all site-years are reported for the three growing seasons (2022–2024) (Figure 3). All indices showed a trend of higher cumulated biomass production in 2023 as compared to 2022 and 2024. However, the maximum values were in a similar range with 0.19–0.28 for NDRE and 3.5–5.5 m^2/m^2 for LAI.

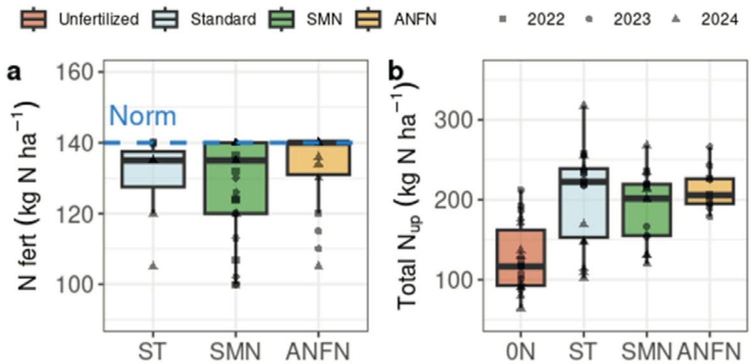

Figure 2. Distribution of fertilizer recommendation (a; kg N/ha) over three years (2022–2024) and three treatments: farmer's standard (ST; *n*=7), based on soil mineral N (SMN; *n*=25) based on the model adjusted N fertilizer norm (ANFN; *n*=18). The recommendations were limited at the norm value for wheat of 140 kg N/ha (blue dashed line). Total N uptake (b; N_{up}, kg N/ha) for different treatments plus control with no fertilizer (0N).

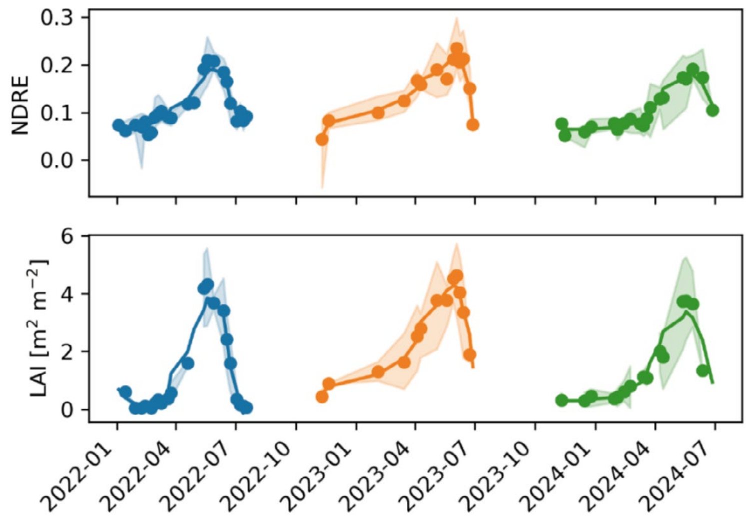

Figure 3. Satellite-based temporal dynamics of the mean (with range) normalized difference red-edge (NDRE) and leaf area index (LAI m^2/m^2) for all winter wheat site-years (n=27) shown over three growing seasons 2022 (blue), 2023 (orange) and 2024 (green).

In an example site-year (P1, 2023), the mean NDRE and LAI extracted through the season were in the same range for the fertilized treatments with no differences, while the unfertilized control showed a lower development of biomass after March (time of the first fertilizer application), as shown by the time-series in Figure 4a,c. The SMN and the ANFN treatment received respectively 29% and 18% less fertilizer than the norm and the standard at 140 kg N/ha (Table 1). All fertilized treatments had yield and N uptake values in a similar range (lower in SMN but not significant). Additionally, the NDRE and LAI maximum values were extracted for each treatment (n=5) and the linear regression with crop total N uptake (kg N/ha) reported correlations of R^2=0.88 for NDRE and R^2=0.84 for LAI (Figure 4b,d).

Discussion

Influence of N supply on N balances

This study evaluated nitrogen (N) fertilization recommendations for winter wheat in nitrate vulnerable zones (NVZs), with the recommendations generally constrained by a norm of 140 kg N/ha

Table 1. Parameters for comparison of fertilizer treatments in the site-year P1 (2023).

Year	Site	Treatment	N fert (kg N/ha)	Grain yield (t/ha)	N uptake (kg N/ha)
2023	P1	0N	0^c	4.77^b	101^b
		ANFN	115^b	7.27^a	229^a
		SMN	100^b	6.80^a	180^a
		Norm	140^a	7.12^a	224^a
		ST	140^a	7.04^a	239^a

The N fertilizer application (N fert), the grain yield, and the N uptake are reported.

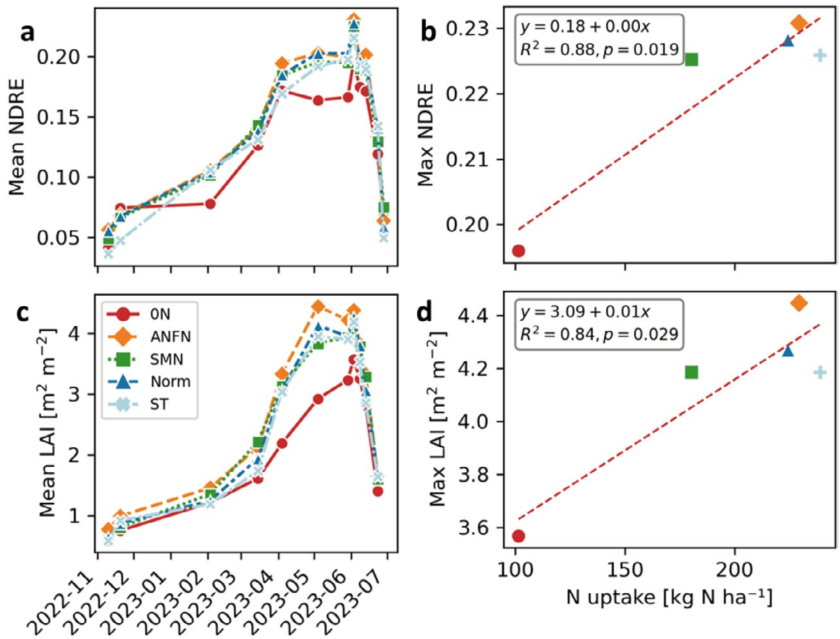

Figure 4. Time series of the mean (with range) NDRE (a) and LAI in m^2/m^2 (c) for one site-year (P1, 2023) for the five treatments: unfertilized (0N), adjusted N fertilizer norm (ANFN), mineral N based (SMN), norm value and farmer's standard. Linear regression between the maximum NDRE (b) and LAI (d) values against N uptake (kg N/ha) for the five treatments.

(Sinaj and Richner, 2017). The results show that the median fertilizer recommendations over the three-years period for the farmer's standard and soil mineral N (SMN) treatments were similar, while the adjusted N fertilizer norm (ANFN) aligned with the upper limit. The lower recommendations in 2022 and 2023 (110–120 kg N/ha for SMN and ANFN) were likely influenced by environmental factors and soil nutrient status. The increase in 2024 recommendations could be attributed to the intense precipitations during winter (around 500 mm from November 2023 to February 2024). which impacted soil mineral N levels, highlighting the dynamic nature of fertilizer management. Total N uptake ranged from 90 to 310 kg N/ha, with the 0N control treatment showing the lowest uptake as expected (median: 110 kg N/ha). The fertilized treatments (ST, SMN and ANFN) had similar uptake values (200–230 kg N/ha). Again, year-to-year differences in N uptake were significant, with 2023 showing the highest uptake and 2024 the lowest. These variations underscores the need for precise fertilizer application and a better understanding of the mineral and organic N pool dynamics to minimize risk of nitrate leaching (Frick *et al.*, 2022). These results support the growing pool of evidence that optimized, site-specific N fertilization strategies are important especially for NVZs (Basso *et al.*, 2016).

Potential and limitation of satellite-based monitoring

The analysis of normalized difference red-edge (NDRE) and leaf area index (LAI) across the 2022–2024 growing seasons revealed clear patterns of biomass production, with 2023 showing the highest cumulative growth. Despite this variability, maximum values for NDRE (0.19–0.28), and LAI (3.5–5.5 m^2/m^2) were similar across years, suggesting a consistent peak in vegetation biomass at the height of the growing season. These findings align with other studies indicating that satellite-based indicators are reliable to monitor biomass development (Scharf *et al.*, 2002) and N status (Perich *et al.*, 2021). In the example field shown, the fertilized treatments exhibited similar growth trends for NDRE and LAI, with no significant differences across treatments, in contrast to the unfertilized control showed lower biomass development starting around mid of march(time of the first and second split applications of fertilizer). The correlation analysis between maximum NDRE, and LAI values and total crop N uptake (kg N/ha) revealed strong relationships and appear promising for using remote sensing indices as valuable proxies for monitoring crop N uptake and assessing fertilizer efficiency. In the presented study the information from the satellite was used mostly for monitoring purposes, i.e., to observe the impact of different N application treatments on vegetation development and N uptake. However, the observed relationship with N uptake could be used for steering in-season recommendation of N fertilizer by adapting the recommended amounts as a function of the observed cumulated N uptake. This type of satellite-based fertilizer recommendation has been shown to improve N use efficiency and reducing N surplus which in turns would reduce the risk of N leaching to groundwater (Berger *et al.*, 2020; Delgado *et al.*, 2005). The concept should be broadly tested with other fields in the region.

Conclusion

By integrating satellite monitoring with field data, this study provided valuable insights into the relationship between fertilization practices, crop growth, and N cycling in nitrate-sensitive areas. The findings encourage the use of remote sensing to facilitate precision N management and monitoring in regions with high crop production and need for environmental protection. Furthermore, the study points in the direction of using satellite-based information for N fertilizer recommendations.

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