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Investigating two solutions to balance revenues and N surplus in Swiss winter wheat

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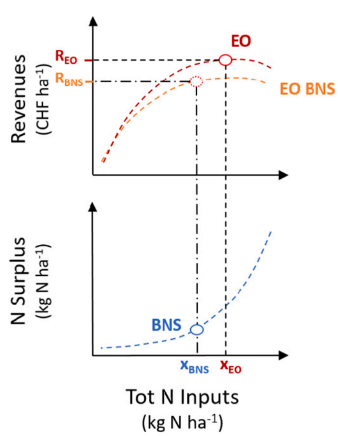
HIGHLIGHTS

- A combined economic and ecological assessment of N fertilization showed possible solutions to reduce N surplus
- The technical solution, variable rate application, reduced N surplus by 32% without affecting revenues in 5 out of 7 fields
- The market-based solution, as tax on N price, was not viable to shift economic optimum toward a more balanced N supply

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Reducing N surplus from agriculture without compromising yield and quality requires economically and ecologically viable solutions.
OBJECTIVE: Based on field data, we investigated a technical and market-based solution to balance the economic and environmental performance of nitrogen (N) fertilizer application in winter wheat in Switzerland.
METHODS: The technical solution, i.e. variable rate (VR) technology, was compared to the standard uniform fertilizer application (ST) in terms of revenues and N balance over seven site-years between 2018 and 2020. The potential of a market-based solution to align revenues and N surplus was investigated based on the relationship between two indicators: the economic optimum (EO) of the revenues and the balanced N supply (BNS). The EO

Abbreviations: AFR, Apparent fertilizer recovery; BNS, Balance nitrogen supply; CHF, Swiss Francs; C_N, Cost of nitrogen fertilizer; EO, Economic Optimum; N, Nitrogen; N_{app}, Nitrogen fertilizer application; NF, No fertilizer control; NR, Nitrogen rich control; N_{up}, Nitrogen uptake; P_y, Yield price; R_{G-CN}, Revenues (Gross – nitrogen fertilizer costs); SNS, Soil nitrogen supply; ST, Standard treatment; VR, Variable rate treatment; Y, Yield.

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was estimated using a production function approach. The BNS was empirically defined as the point at which the N surplus estimated from total N input (N fertilizer + soil N supply) reaches a limit value of 30 kg N ha^{-1}.
RESULTS AND CONCLUSIONS: On average, the revenues of VR were about 4% higher than in ST. The N surplus was, on average, 32% (21 kg N ha^{-1}) lower in VR compared with ST due to a 13% reduction in N inputs with no significant differences in yield. Despite the differences across years and fields, VR appeared to be reducing N surplus without losses in revenues in 5 out of 7 site-years. The revenue curve reached an EO at total N input of 205, 249 and 246 kg N ha^{-1}, in the years 2018, 2019, and 2020, respectively. The BNS was calculated at 220, 195, and 178 kg N ha^{-1} N inputs for the years 2018, 2019, and 2020, respectively. The results show that a price increase of up to 5.4 times the current fertilizer price through taxes would be necessary in order to reduce the N surplus to an environmentally friendly level. Such an increase would hardly be politically feasible.
SIGNIFICANCE: The reported data showed that VR technology appears as a viable solution for producing lower N surplus at comparable revenue levels, thereby making it an option for small- to medium-scale winter wheat production in Switzerland. The environmental benefit could encourage the financial support of technologies for precise N management, which are often too expensive for these systems. Future research should verify or extend the numeric values found in this study.

1. Introduction

As in many other European countries, the nitrogen (N) surplus levels from agriculture in Switzerland have remained high at around 90.000 t per year since 1995 (FOEN, 2020; Spiess and Liebisch, 2020). Reducing N surplus from agricultural production without compromising yield and quality requires practicable solutions that are economically and ecologically viable. Site-specific management of N fertilizer by means of variable rate (VR) application has shown the potential to decrease N surplus while maintaining the quality of the yield and economic return when compared with standard uniform application (Basso et al., 2016b; Ebertseder et al., 2003; Finger et al., 2019; Zebarth et al., 2009). Several studies evaluating the potential of site-specific N management have focused on either the economic or environmental aspects (Meyer-Aurich et al., 2021; Meyer-Aurich et al., 2010; Murray and Yule, 2007; Ngatia et al., 2019). However, integrated assessments of economic and environmental performance are so far only available to a limited extent (Nasielski et al., 2020), but are necessary for the design and implementation of possible N surplus reduction measures.

Previous research has shown that site-specific N management can benefit both the profitability and environmental performance of crop production (Dumont et al., 2016; Wang et al., 2003). For instance, sensor-based data combined with VR technology can provide precise information on crop growth and nutrient availability to spatially and temporally adjust fertilizer applications (Bushong et al., 2016; Hunt and Daughtry, 2018). Several field studies comparing sensor-based N management with common farmers' practices indicated significant increases in N use efficiency (Cohan et al., 2018; Raun et al., 2002; Samborski et al., 2016; Stamatiadis et al., 2018). In addition, soil N release from mineralization is also fundamental for a precise N balance (Clivot et al., 2017; Córdova et al., 2018; Yin et al., 2020), but it is still complex to correctly estimate. These management systems have saved N fertilizers (from 10% to about 80% less N) and reduced residual N in the soil (by 30–50% less N), and, thus, the risk of loss, without compromising yields or grain quality (Basso et al., 2016a; Diacono et al., 2012; Koch et al., 2004; Wang et al., 2020).

In order to achieve positive environmental effects with VR technology, farmers need to adopt these technologies on a wide scale. This will only happen if the use of the technologies is economically viable. The economic viability of a new technology is determined by both variable and fixed costs (Bachmaier and Gandorfer, 2009). The variable costs are relevant for short-term decisions, such as the economically optimal use of N fertilizer. More precisely, a farmer will only reduce the use of N fertilizers if the prices for fertilizers rise. On the one hand, this can happen due to price increases on the market, as is currently the case (Baffes and Koh, 2021), or through the government levying taxes with the aim of reducing the economically optimal input use (Finger, 2012; Meyer-Aurich et al., 2020). Existing studies show that, to estimate the economically optimal use of N fertilizer, yields and grain quality must both be considered (Colaço and Bramley, 2018; Gandorfer and Rajsic, 2008; Taulealea et al., 2007). This is because reducing the amount of fertilizer can lead to a lower protein content, i.e. lower grain quality, thereby affecting the EO of N fertilization due to a lower selling price. Research on the economic and ecological effects of adapted N fertilization should also take into account the effects on grain quality. In this context, solutions that balance economic and environmental problems are needed.

This study investigates two possible solutions to the N surplus problem. The first is a technical management solution: site-specific N management as compared to standard uniform management. The second one is a market-based solution: increasing the price of N fertilizer by implementing a tax. The assessment is based on experimental data from seven winter wheat field trials over three years (2018–2020) in Switzerland. The specific objectives were to: (i) determine the revenues and N balance of the two management strategies, and ii) define two indicators that can be used to assess the economic and environmental performance: the EO measured in terms of revenues and the balanced N supply (BNS) of N inputs, respectively, and estimate the increase in N price necessary to shift the EO at a value that corresponds to a BNS.

2. Materials and methods

2.1. Experimental design and data collection

The dataset used in this study consists of ground truth data collected over seven experimental fields between 2018 and 2020 and managed by the Swiss Future Farm in northeast Switzerland. During the growing season of 2017–2018, the first experiment was carried out in one field (F1); during the growing season of 2018–2019, it was carried out on three fields (F2–F4); and during the growing season of 2019–2020, it was carried out on three fields (F5–F7). The fields were divided in non-randomized blocks containing individual plots and were managed with different treatments in order to study the effects of the in-field variability. The treatments consisted of a standard (ST) uniform rate of fertilizer (154–155 kg N ha^{-1}) and adjusted site-specific application with a VR technology application of a fertilizer (80–155 kg N ha^{-1}) based on multispectral images and soil data. In this treatment, the first split application in spring is corrected by using mineral N values from soil samples. The second and third split of the season were then adjusted by quantifying in-field variability by means of multispectral images and relating it to the N uptake in the field (Argento, 2021; Argento et al., 2020). Two controls were used: one control with no fertilizer (NF) and one with additional fertilizer in the first part of the season (NR). The treatment rationale reflects typical fertilization strategies used in Switzerland (Sinaj and Richner, 2017). Ammonium nitrate fertilizer was applied in three split applications at the wheat's crucial growth stages. Field F1 was divided into 18 plots of 15 × 50 m (six blocks of two treatments + one control NF). Fields F2–F4 were divided into eight to 12 plots 30 × 80 m (two to three blocks of two treatments + two controls) and fields F5–F7 were divided into 12 to 16 plots 30 × 50 m (three to four blocks of two treatments + two controls). The number of replications differed per site-year (n = 2–6). Additional details on the experimental setting and treatments can be found in Argento et al. (2020, 2021). The trials' design is reported in the supplementary information (Supplementary Figs. S1–3).

Plant protection was kept at the minimum necessary to avoid damages that would influence the experiment's outcome. The experiments focused on winter wheat (*T. aestivum*) of the cultivar Arnold (Saatzucht Donau, Austria) in the first two growing seasons and the cultivar Montalbano (Agroscope/DSP Delley, Switzerland) in the third growing season. Fields F4 and F7 were sown later compared with the other two site-years F2 + F3 and F5 + F6, respectively. For F4, this negatively affected the growth during the season, as reflected by a largely heterogeneous canopy and reduced final yield. In contrast, no adverse effects were observed for F7. A detailed description of the sampling methods and experimental setup can be found in Argento et al. (2020). Dry biomass (t ha^{-1}) and N concentration (%) of wheat grain and straw were measured in the plant samples collected from each experimental plot before harvest for a total of ca. 330 data points over the seven site-years (F1–F7). The N uptake (N_{up}, kg N ha^{-1}) was calculated by multiplying the dry biomass by the N concentration of the corresponding plant sample.

2.2. Economic and environmental assessment

For the economic assessment, we focused on the revenues from winter wheat production in CHF ha^{-1}, here defined as the difference between gross revenues (R_G) minus N fertilizer costs (CN), i.e. $R_{G\text{-}CN}$:

$$RG - \mathrm{CN} = Y^*P_y - N\mathrm{app}^*P_N \quad (1)$$

where Y is the grain yield (kg ha^{-1}), P_Y is the grain price (CHF kg^{-1}), N_{app} is the amount of fertilizer applied (kg N ha^{-1}), and P_N is the price of N fertilizer applied (CHF kg^{-1}). Other than the fertilization regime, the two treatments were managed in the same way. Therefore, the fertilizer cost was the only variable cost considered. For our study, we set a grain price at 0.52 CHF kg^{-1}, corresponding to the average price of conventional top-quality wheat grain in Switzerland during the study period of 2018/2020 (Agridea, 2019). The price, i.e. the cost of N fertilizer, was set at 0.38 and 0.46 CHF kg^{-1} for 24% N and 27% N, respectively (Agridea, 2019). Currency exchange values are 1 CHF = 1.05 USD = 0.93 EUR (UBS, 2021). The economic comparison between the variable rate application of N and standard N application was based on the calculation of the differences in revenues, N costs, and grain yields between VR and ST. A one-way ANOVA in the "R" software (R Core Team, 2021) based on the single factors 'treatment', 'year', and 'field' was applied to test whether the differences existing between VR and ST were significant. The interaction between the factors 'treatment' and 'year' was also tested with a two-way ANOVA to assess which variable had a significant effect on the observed differences between the VR and ST treatments.

To determine the economically optimal N inputs, we applied a revenue maximization approach based on a quadratic production function using all of the data from the seven field trials (F1–F7) grouped per year (2018–2020). As depicted in Fig. 1a), the EO is defined at the level of N inputs where the marginal value of the product (i.e. the additional wheat quantity produced by one additional kg of N used is multiplied by the wheat price) is equal to the marginal costs (i.e. the price of an additional kg of N). In other words, the marginal value is defined as a one-unit change in revenues (ΔNR_v) because of a one-unit change in N fertilizer (ΔC_N), and if this first derivative equals zero, the optimum of the revenues curve is reached (EO shown with the point Fig. 1a)). We calculated the EO using the function "optimize" implemented in the "R" software (R Core Team, 2021).

For the environmental assessment, we calculated the N balance (N input – N output, kg N ha^{-1}), which is defined as the difference between the crop's total N input and N uptake (Eq. 2). The total N input (kg N ha^{-1}) was calculated as the sum of N inputs from the fertilizer (N_{app}, kg N ha^{-1}) and the N supply from the soil and atmosphere (soil N supply (SNS), kg N ha^{-1}). The SNS was calculated based on the total N uptake of the NF treatments, as Kindred et al. (2015) described, per each field and used as a measure of the N provided from the soil system by means of all environmental processes, such as N mineralization and atmospheric deposition. When the N inputs exceeded the plant N uptake (N_{up}, kg N ha^{-1}), the N balance resulted in an N surplus (kg N ha^{-1}), i.e. the amount of inorganic N that remains in the soil at the end of the growing season, which can be stored in the soil and is at risk of being lost to the environment.

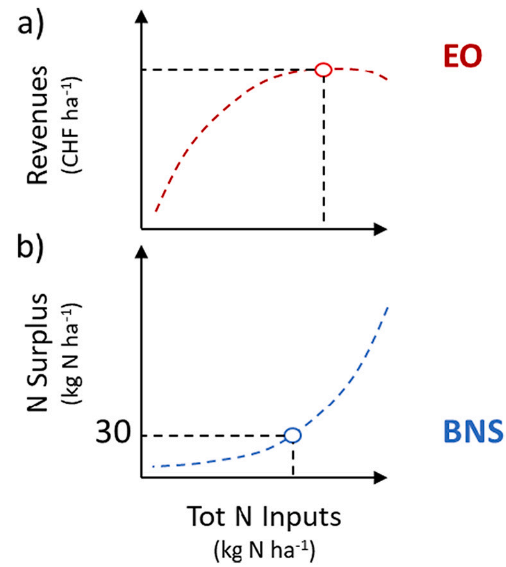

Fig. 1. Concept figure for the two indicators chosen in the study: a) the economic optimum (EO) of revenues and b) the balanced N supply (BNS) based on N surplus, as a function of the total N inputs (N fertilizer + soil N supply).

$$N\ balance = (SNS + N\mathrm{app}) - N\mathrm{up} \quad (2)$$

We calculated the apparent fertilizer recovery (AFR, eq. 4.3) as a measure of N use efficiency (Kindred et al., 2015). The N uptake from the NF plot (SNS) was subtracted from the N uptake of a treatment plot (VR, ST, or NR) and divided for the N fertilizer applied:

$$AFR(\%) = \frac{N_{up} - N_{up}\ (NF)}{N_{app}} * 100 \quad (3)$$

For a BNS, we assume a total N input (kg N ha^{-1}) for the current study which leads to an N surplus of 30 kg N ha^{-1}. This value was empirically set for this study, being an accepted critical value in Switzerland in the context of the political agenda aiming to reduce N losses of 20% by 2030 (Swiss Parliament, 2019). As depicted in Fig. 1b), the BNS point can be found on the quadratic curve between the N input and N surplus based on the data from the seven field trials (F1–F7) grouped per year (2018–2020). We estimated the BNS by using the complete dataset in the "R" software package (R Core Team, 2021) by i) fitting a quadratic response curve of N surplus to the total N input and ii) finding the point where N surplus = 30 kg N ha^{-1} on the curve (Fig. 1b). To ensure that the environmentally preferable N input X_{BNS} is also the economically best solution R_{EO}, the costs for fertilizer were increased to such an extent that the economically optimal N input corresponded to the input at BNS (Fig. 2). We calculated for the full model, for each year, and for each field the increase in fertilizer price that was necessary to shift the R_{EO} so that it matched to the same N input of the corresponding BNS point, thus generating a new EO at BNS (R_{BNS}). The increase was

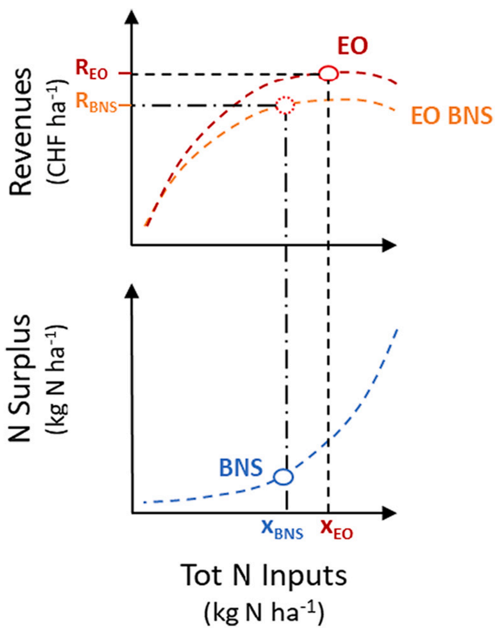

Fig. 2. Concept figure for the calculation of the theoretical increase in N price (orange curve), which would be necessary to drive the economically optimal value (EO) to the new optimum (EO BNS) causing only a surplus of 30 kg N/ ha (BNS) based on the total N inputs. The lower EO BNS would correspond to a reduction in N surplus (X_{EO} ➔ X_{BNS}) and in revenues (R_{EO} ➔ R_{BNS}).

calculated in the software "R" by testing a range of increase in price up to six times the initial price (0.42 CHF ha^{-1}) in the profit maximization function, until the resulting maximum of the optimised function matched the BNS.

3. Results

3.1. Differences in yields, fertilizer costs, and revenues between the treatments

The N costs, grain yields, and revenues for each field are reported in Table 1 as averages across all years of the study period (2018–2020), here distinguishing between the VR and ST applications. On average, across all seven site-years (F1–F7), the N costs in the VR treatment were 23% lower than in the ST treatment. However, the variability between years was high, ranging from an average N cost savings of 15 CHF ha^{-1} in 2018/2019 (except for F4) to 90 CHF ha^{-1} in 2020. A significant difference in N costs between the VR and ST treatments was only found for the year 2020. The grain yield did not show significant differences between the two treatments of the same site-year and was between 6.23 and 7.38 t ha^{-1} among the six site-years. In field F4, the yield was lower (3.7 t ha^{-1}). The large variability between years had a higher impact than between fields of the same year. The yields were significantly lower in 2018 than in 2020, while in 2019, the values were in-between that of years 2018 and 2020.

The calculated revenues showed higher values for VR than ST in five out of the seven site-years (F1-–F5). The values ranged from 1.9%, corresponding to 69 CHF ha^{-1}, to 11.5%, corresponding to 352 CHF ha^{-1}. In two site-years (F6 and F7), the revenues were higher in the ST treatment than VR of 0.5%, corresponding to 16 CHF ha^{-1} and 8% corresponding to 260 CHF ha^{-1}, respectively. On average, the revenues of the VR treatment were 4% (94 CHF ha^{-1}) higher than in the ST treatment among the seven site-years. The differences were not statistically significant between the two treatments.

Even though there are significant differences in N costs in all fields (except F1) and no differences in grain yields between the VR and ST treatments, the results suggest that the cost savings, together with the unchanged yields, allow higher revenues, on average. This observation can be attributed to the relationship between N uptake and grain yields,

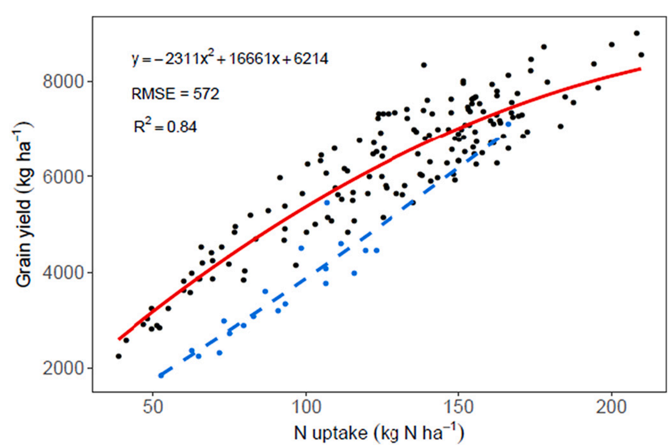

Fig. 3. Relationship between grain yield and N uptake (red trend line) over six site-years (F1–F3, F5–F7, black dots). F4 is shown separately (blue dots and dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Nitrogen fertilizer costs, revenues, and differences between the revenues of the two treatments —standard uniform (ST) and variable rate (VR)—applications for the seven site-years (F1–F7).

Year	Field	Treatment	N fertilizer costs	Grain yield	Revenues (gross revenues- fertilizer costs)	Difference in revenues (VR - ST)	
			(CHF ha^{-1})	(t ha^{-1})	(CHF ha^{-1})	(CHF ha^{-1})	%
2018	F1	ST	193 ± 0a	6.23 ± 0.1a	3050 ± 54a	76	2
		VR	173 ± 12a	6.34 ± 0.12a	3126 ± 61a		
	F2	ST	266 ± 0a	6.38 ± 0.03a	3053 ± 18a	352	12
		VR	243 ± 1b	7.02 ± 0.17a	3405 ± 89a		
2019	F3	ST	264 ± 0a	6.25 ± 0.18a	2988 ± 96a	327	11
		VR	256 ± 2b	6.87 ± 0.21a	3315 ± 109a		
	F4	ST	268 ± 0a	3.69 ± 0.97a	1652 ± 501a	109	7
		VR	164 ± 9b	3.7 ± 0.18a	1761 ± 99a		
	F5	ST	268 ± 0a	7.18 ± 0.1a	3466 ± 53a	−16	0
		VR	200 ± 5b	7.02 ± 0.04a	3450 ± 26a		
2020	F6	ST	268 ± 0a	6.98 ± 0.31a	3364 ± 161a	−260	−8
		VR	175 ± 5b	6.31 ± 0.24a	3104 ± 127a		
	F7	ST	268 ± 0a	7.38 ± 0.25a	3570 ± 132a	69	2
		VR	157 ± 3b	7.3 ± 0.7a	3639 ± 363a		

The letters a, b, c, indicate significance levels.
The values are reported as average with standard error (n = 2–6).

namely decreasing grain yields with increasing N uptake, as shown in Fig. 3. For all treatments over the seven site-years, the increase in the yield diminished at N uptake levels that were higher than 150–200 kg N ha^{-1}. In this range of N uptake, any additional N input has a lower probability of contributing to the yield, thereby representing a greater risk of economic loss. F4 was the only field that did not follow this trend.

3.2. Differences in the N balance between the treatments

The N balance generally showed an N surplus for all fertilized treatments (Table 2, Fig. 4). The inputs of N fertilizer ranged between 0 and 160 kg N ha^{-1} among the different treatments and site-years (F1–F7), with an average reduction of 25% in VR (mean = 114 kg N ha^{-1}) compared with ST (mean = 149 kg N ha^{-1}). The N uptake ranged between 127 and 258 kg N ha^{-1} in the fertilized treatments over the seven site-years (mean = 189 kg N ha^{-1}). The N uptake in the VR treatments did not show statistically significant differences from the N uptake in the other fertilized treatments—ST and NR—except for F5 in 2020 (Table 2). The N uptake from the control with NF was considered in order to measure the SNS. The values showed high variability (mean = 108 kg N ha^{-1}, Fig. 5, red dots) with higher values in 2019 (F2–F4;

Table 2
Nitrogen balance of the seven site-years (F1–F7), including N fertilizer application (N_{app}), total N uptake (N_{up}), the total N input in the system (N_{app} + SNS), N surplus [(SNS + N_{app}) – N_{up})], and apparent fertilizer recovery [AFR = (N_{up} – $N_{up\ NF}$)/N_{app} * 100].

Year	Field	Treatment	N_{app} (kg N ha^{-1})	Total N_{up} (kg N ha^{-1})	N input (kg N ha^{-1})	N surplus (kg N ha^{-1})	AFR (%)
2018	F1	NF	0b	84 ± 19b			–
		ST	116 ± 0a	179 ± 15a	199 ± 26a	20 ± 24a	83 ± 21a
		VR	105 ± 39a	179 ± 30a	189 ± 39a	9 ± 32a	94 ± 35a
	F2	NF	0d	143 ± 33b			–
		ST	154 ± 0b	221 ± 16a	293 ± 39a	72 ± 27a	51 ± 10a
		VR	142 ± 2c	228 ± 20a	281 ± 26a	53 ± 38a	60 ± 14a
	F3	NF	0d	127 ± 3b			–
		ST	153 ± 0b	185 ± 23a	281 ± 0a	96 ± 23a	37b ± 17a
		VR	148 ± 2c	192 ± 18a	276 ± 2b	85 ± 16a	43 ± 15a
2019	F4	NF	0c	138 ± 10a			–
		ST	154 ± 0a	191 ± 85a	290 ± 0a	98 ± 85a	35 ± 55a
		VR	96 ± 10b	183 ± 23a	231 ± 10b	48 ± 31a	48 ± 27a
	F5	NF	0c	66 ± 13c			–
		ST	155 ± 0a	178 ± 11a	222 ± 17a	43 ± 10a	78 ± 7a
		VR	116 ± 12b	148 ± 8b	182 ± 10b	34 ± 17a	78 ± 13a
	F6	NF	0c	74 ± 25b			–
		ST	155 ± 0a	164 ± 38a	230 ± 21a	65 ± 37a	58 ± 25a
		VR	104 ± 9b	127 ± 19a	179 ± 41b	52 ± 41a	50 ± 18a
2020	F7	NF	0c	122 ± 16b			–
		ST	155 ± 0a	219 ± 53a	278 ± 11a	59 ± 57a	62 ± 34a
		VR	88 ± 6b	188 ± 65ab	211 ± 27b	22 ± 39a	72 ± 41a

The letters a, b, c, indicate significance levels.
The results are reported for the standard (ST) and variable rate (VR) treatments and the control with no fertilizer (NF). The values are reported as average with standard deviation of the average.

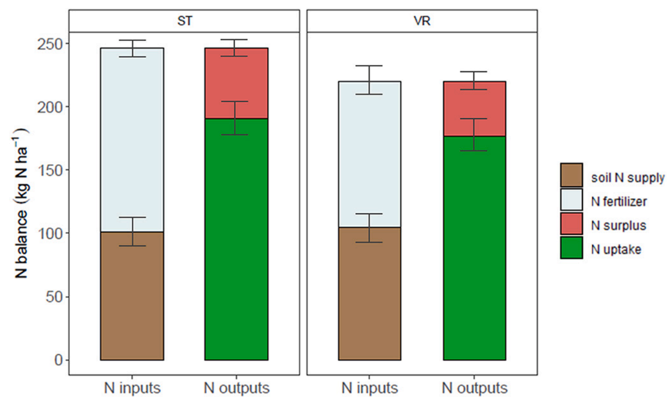

Fig. 4. Balance of N inputs (soil N supply + N fertilizer) and N outputs (N uptake + N surplus) for the standard (ST) and variable rate (VR) treatments, here shown as the average of all seven site-years (F1–F7). The error bars represent the standard error (n = 2–6).

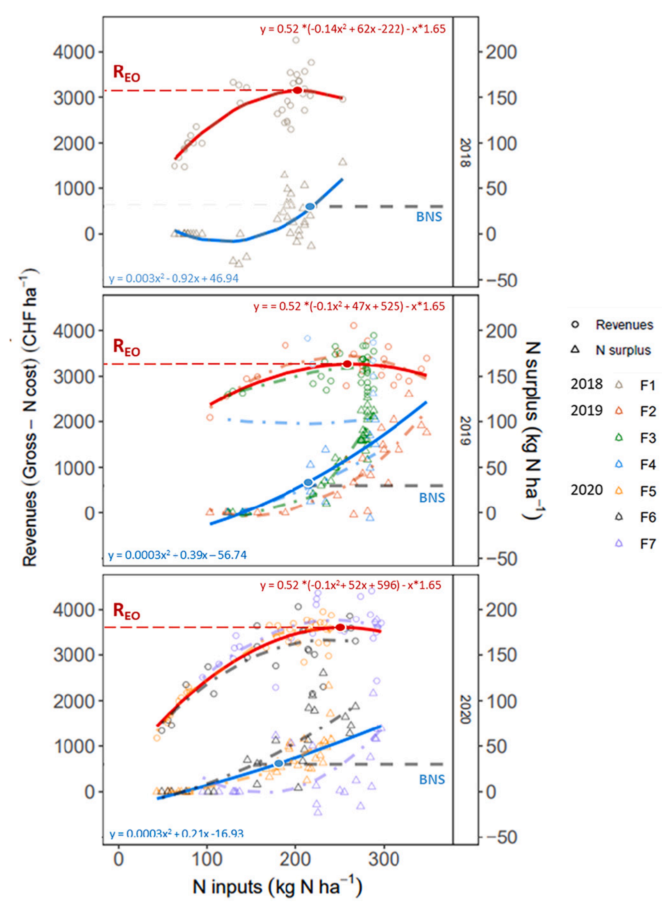

Fig. 5. Revenue response curve (left y-axis, red trend line; circles) and N surplus response curve (right y-axis, blue trend line; triangles) dependent on the total N inputs (fertilizer + soil N supply) for the seven site-years (F1–F7, colours) grouped by year (2018–2020). The economic optimum of revenues (R_{EO}, red dot) and the balanced N supply (BNS, blue dot) are shown on the corresponding trend line. The grey dashed line represents the BNS at 30 kg N ha^{-1} N surplus limit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

127–143 kg N ha^{-1}) compared with 2018 and 2020 (F1, F5–F7; 66–122 kg N ha^{-1}).

Over the three years of the study (2018–2020), the average N inputs of the ST treatment were 35 kg N ha^{-1} higher than the N inputs in the VR treatment. The plants' N uptake, on the other hand, were only slightly smaller in VR. This resulted in 32% lower N surplus in the VR treatments (21 kg N ha^{-1}) (Table 2, Fig. 4). The N surpluses showed a higher variation between the years than between the different sites. In 2018, the values were generally low, and the N surplus was about 50% lower for VR than ST (9 kg N ha^{-1} for VR and 20 kg N ha^{-1} for ST in F1). In 2019, the values were generally higher (55–100 kg N ha^{-1}). The N surplus in the VR treatments was 10–45 kg N ha^{-1} lower than the ST treatments in all three site-years (F2–F4). In 2020, the values were between the two previous years, and the N surplus in VR was around 10 kg N ha^{-1} lower than in ST in F5 and F6, whereas in F7, they were about 40 kg N ha^{-1} lower.

In terms of N use efficiency, the values varied significantly between years and fields (Table 4.2), but rarely among the fertilized treatments. The AFR of VR (42.8–93.8%) and ST treatments (37.2–83.15%) did not differ significantly. However, a trend of improved AFR of 13% was observed on average for site-specific management when compared with standard uniform application.

3.3. The relation between the economic optimum and the balanced N supply

The estimated curves of revenues and N surpluses as a function of total N inputs are used to assess the economic and environmental performance over the various years and different treatments (Fig. 5). For the overall model, including data across all years and fields, the fertilizer applied at the EO and the fertilizer applied at the BNS resulted in a total N input of 239 and 201 kg N ha^{-1}, respectively (Table 3). The corresponding revenues, R_{EO} and R_{BNS}, were 3276 and 2373 CHF ha^{-1}.

Based on these results and given current N fertilizer prices of 1.65 CHF kg N^{-1}, the hypothetical tax would have had to generate an increased price up to 5.76 CHF kg N^{-1}, corresponding to a 3.5-fold increase, in order to balance the fertilizer input from an economic and environmental perspective. However, the data from the seasonal models (2018–2020) showed variance over the three years of this study. In 2018, the fertilizer applied at the EO (205 kg N ha^{-1}) was lower than at the BNS (220 kg N ha^{-1}); therefore, an increase in fertilizer prices would not have improved the environmental performance. In 2019 and 2020, the fertilizer applied at the EO was 249 and 246 kg N ha^{-1}, respectively. The amount of fertilizer applied at the BNS for these two years was calculated at 195 and 178 kg N ha^{-1}, respectively. In these years, a 3.9- and 5.4-fold increase in N fertilizer's price would have balanced the fertilizer applied at the EO with the BNS.

In the models for the single site-years, the economically optimal N input varies between 112 and 285 kg N ha^{-1}, whereas the fertilizer input at the point of BNS varies between 153 and 257 kg N ha^{-1}. In order to align the EO with the BNS, the increase in N fertilizer prices via a tax should have been between 1 and 60% across fields F1, F2, F5, and F7.

The models' explanatory power is assessed by the coefficient of determination (R^2), which was 0.62 for the overall model with a root mean square error (RMSE) of 414 CHF ha^{-1} and a mean absolute error (MAE) of 323 CHF ha^{-1} (Table 4). The coefficients of determination for the seasonal models are in line with the overall model, except for during 2019. This year contains field F3 with an insignificant effect of N fertilizer input, and field F4 (late sown and damaged canopy), which shows the highest error (RMSE = 1338 and MAE = 1216).

For all three considered years and around the points of the EO and the BNS, the N surplus curve is steeper than the revenue response curve. This means that a reduction of one unit of N input has a higher impact on N surplus than on revenues, i.e. a reduction in N input leads to higher N surplus reductions than revenue losses.

Table 3
Calculations of economic optimum (EO) and balanced N supply (BNS) of the total N inputs, (fertilizer + soil N supply).

		EO	BNS	R_{EO}	R_{BNS}	N price initial	N price taxed
		kg N ha^{-1}	kg N ha^{-1}	CHF ha^{-1}	CHF ha^{-1}	CHF kg N^{-1}	CHF kg N^{-1}
Overall		239	201	3276	2373	1.65	5.76
	2018	205	220	2996	2683	1.65	-[a]
	2019	249	195	3113	2046	1.65	6.43
Year	2020	246	178	3445	1912	1.65	8.90
	F1	206	220	3137	3124	1.65	-[a]
	F2	246	257	3259	2882	1.65	-[a]
	F3	285	250	3267	2091	1.65	4.86
	F4	112	209	1856	1897	1.65	–
	F5	213	188	3444	2641	1.65	5.65
	F6	232	153	3196	1601	1.65	9.88
Field	F7	244	252	3571	3832	1.65	-[a]

R_{EO} is the optimised revenue at the initial fertilizer price level, R_{BNS} is the optimised revenue when fertilizer prices are increased to such an extent that the economically optimal N input corresponds to the N input at BNS. The results are reported for the overall model, for each year (2018–2020) and for the seven site-years (F1–F7).

[a] Symbol "-" indicates that BNS is higher or equal to EO and therefore an increase in fertilizer prices via tax would not improve the environmental performance.

4. Discussion

4.1. Economic and environmental assessment of the technical solution

The effects of the two N management technologies on grain yields, grain quality (affecting grain selling prices), and costs of fertilizer are important determinants when comparing the economic performance of VR application to the economic performance of a ST of N fertilizer.

With regard to grain yields, no significant differences were observed between VR and ST. An assessment of the protein content also showed no significant difference between the two treatments; however, a trend of reduced protein content with lower N application was observed (Argento, 2021). The costs for N fertilizer were, on average across all fields, lower in VR than in ST. In five out of seven of the site-years, the VR application of the fertilizer resulted in 1.9–11.3% higher revenues than the ST. In two site-years, the returns of ST were 0.5% and 8% higher than VR, respectively. These findings are in line with other studies (Diacono et al., 2012; Koch et al., 2004) and with the promised savings

Table 4
Calculations of the coefficient of determination (R^2), root mean standard error (RMSE), and mean absolute error (MAE) for the economic optimum (EO) and balanced N supply (BNS) models of the total N inputs (fertilizer + soil N supply).

		EO			BNS		
		R^2	RMSE	MAE	R^2	RMSE	MAE
			CHF ha^{-1}	CHF ha^{-1}		kg N ha^{-1}	kg N ha^{-1}
Overall		0.625	414	323	0.51	30	29
	2018	0.635	409	583	0.13	24	24
	2019	0.319	335	565	0.50	30	30
Year	2020	0.696	413	693	0.33	32	37
	F1	0.57	446	345	0.13	24	17
	F2	0.46	318	255	0.45	30	23
	F3	−0.001	374	299	0.51	27	21
	F4	–	1338	1216	0.42	27	20
	F5	0.86	279	247	0.53	18	12
	F6	0.62	474	360	0.33	33	23
Field	F7	0.11	548	453	0.14	44	33

The errors are reported for the overall model, for each year (2018–2020) and for the seven site-years (F1–F7).

of commercial enterprises that offer satellite-based fertilization support services (e.g. €40 ha^{-1}, Farmstar Conseil, France and €50 ha^{-1}, VISTA, Germany). Since the yields were not significantly different, the main reason for the observed differences was attributed to the lower N fertilizer costs in VR, which led to higher revenues compared to ST.

However, in order for site-specific management to be economically viable at the farm level, it must cover all of the additional costs from the technologies involved, as well as information gathering and processing (Murray and Yule, 2007). These costs include the information service, i.e. the prescription map, which is estimated to be around €15–80 ha^{-1} (Heege, 2013; Space-Tec, 2012). Furthermore, fixed costs are relevant in long-term decisions, such as the investment in new technologies. The investment cost for VR technologies depends largely on the type of technology. For instance, satellite images are freely available but require additional processing costs and purchasing N sensors or drones can be very costly (Bakker et al., 2005; Fabiani et al., 2020; Späti et al., 2021). The equipment of a tractor with a VR-compatible fertilizer spreader can be estimated at around €15,000. This study was limited in calculating these additional costs since the spreading and GPS technology were already available at the research farm and the project itself covered the main costs of information e.g. UAV and soil analysis. Moreover, the main author of the paper carried out the additional amount of work to produce the information and it could not be considered fully representative of an actual commercial system. Other than technology, information, and labour, the costs were not different between VR and ST. The focus of the study was to show, as a starting point for future research, if there are observable differences based only on fertilizer costs. Nonetheless, we provide an estimate of these costs in Supplementary Table S1. The costs of technology and information accounts for the risk of incurring higher expenses and therefore reducing the EO.

Furthermore, VR application benefits are only meaningful within fields that show a sufficient degree of variability in the soil and in crop growth (English et al., 2015; Kindred et al., 2015). The data in this study showed that the variation between the different years is higher than between the different fields of the same year. Therefore, taking the variation between the years into account is also crucial in order to optimize the N fertilization. Ultimately, depending on the size of the farm, the economic potential varies (Heege, 2013), and often, the observed higher revenues per ha with VR are not sufficient to sustain the required investments in small- to medium-scale farming (Fabiani et al., 2020; Meyer-Aurich et al., 2010). In such circumstances, sharing machinery or contractor services with another farm could be more appropriate and beneficial than purchasing them.

To assess the environmental effect of the two treatments, we used the N surplus approach. The calculation of N surplus in the N balance is an approach to evaluate the efficiency of crop fertilization systems, be it on the plot, field, or farm level. Of course, the surplus contains several fates for N in the agro-environmental system, such as N leaching, residual N and gaseous emission, or soil N stock changes that cannot be easily disentangled (De Notaris et al., 2018; Jan et al., 2017; Zhang et al., 2019). Nevertheless, it allows the evaluation of the N use efficiency and serves as a good and well-accepted indicator for N-related problems caused by suboptimal N fertilization (Van Beek et al., 2003; Velthof et al., 2009).

Over the three years considered in this study, the N surplus showed a very high variation. In all three years, N inputs consisting of the N fertilizer and Soil N Supply (SNS) between 200 and 300 kg N ha^{-1} caused N surpluses of about −20–150 kg N ha^{-1}, mainly attributed to the very heterogeneous soils' N supply, plant densities, and development within the single fields. These results show that VR technologies have not addressed this variability as is done in this study. In fact, even with the reduced fertilization of VR in all fertilized treatments, the N uptake was lower than the supplied total N inputs, implying that part of the applied fertilizer was either lost to the environment or immobilized in the soil (Supplementary Fig. S4). Ultimately, to optimize N fertilization the N supply of the soil, i.e. the N from mineralization of soil organic matter, previous crop residues, organic fertilizers, and atmospheric deposition during the winter wheat season must be included in the calculation.

The presented results of the seven site-years show that VR technology could reduce N surplus but that a significant variation of the apparent fertilizer recovery (AFR) was encountered. Over the seven site-years, the plants absorbed 24–94% of the applied N. There was no evidence that higher AFR values lead to significant differences in yield, as confirmed in other studies (Cohan et al., 2018; Diacono et al., 2012; Raun et al., 2002). In practice, achieving AFR values over 90% is complex and not ideal for soil health (Cohan et al., 2018). Therefore, the goal for maximizing efficiency should be 80–90%. To achieve this goal, the prediction of soil N mineralization and plant N uptake is necessary. As the results have confirmed, in addition to different soil parameters, the meteorological conditions (over different years) have a major influence on N release. Currently, the in-season estimation of the N supply from the soil and atmosphere represents a gap that can partially be bridged by soil sampling, although it is cost and labour intensive.

4.2. Indicators to assess economic and environmental performance

The indicators used to assess economic and environmental performance of the considered technical and market-based solutions were the economic optimum (EO) of the revenues curve and the point of balanced N supply (BNS) of the N inputs curve, respectively. The concept established in the current study can be used to optimize both environmental and economic performance. However, as the identified optima were specific to each year and for this dataset. Future studies should improve the data basis to reduce uncertainties related to large variations in yields across fields and years (Fig. 5).

To calculate the EO of the N input, we calculated the total N inputs by summing up SNS and N fertilizer. We included the SNS in the calculation because it is a fundamental parameter for determining the actual amount of the N fertilizer demand and must be considered for a BNS. In order to compare the values of N input across BNS and EO, we also considered SNS and N fertilizer when calculating the EO even though the N released from the soil would result in lower costs for N fertilizer. If the EO was calculated based only on additional N fertilizer input (i.e. not considering the soil N supply), the economically optimal N input levels would have been between 100 and 150 kg N ha^{-1} (Supplementary Fig. S5), which are lower compared to results from other studies (Meyer-Aurich et al., 2010; Nasielski et al., 2020). One reason might be the lower yields of the considered Swiss wheat varieties or because the mineralization potential of the soil is higher (Bean et al., 2018; Maltas et al., 2015).

The point of BNS is difficult to determine because the fate of residual N is not known precisely and there is no universal definition of a critical value for N surplus (EEA, 2019). As shown by recent political discussion in Switzerland on the context of a path to reduce N losses of 20% by 2030, values of N surplus up to 30–40 kg N ha^{-1} are generally considered acceptable (Swiss Parliament, 2019). The critical N surplus values are defined in relation to environmental problems, i.e. drinking water pollution or ecosystem eutrophication, and can vary for specific regions, climate, and geomorphology. In the current study, we chose an empirical value of 30 kg N ha^{-1} N surplus, which reflects the current goal of reduction in N losses at national level. Robust values need to be established at both the regional and national levels. Due to the variation of SNS (2018: 84 kg N ha^{-1}; 2019: 136 kg N ha^{-1}; 2020: 88 kg N ha^{-1}) and applied N fertilizer between treatments, the BNS was determined to be different for each of the three years of the study. In all three years, the decline in revenue compared to the declines in N surpluses was very small. Hence, the results suggest that relatively large positive effects on environmental performance are possible with comparably small revenue losses.

One main outcome from the analysis with the two indicators is that, because of the high variation across fields and years, it is difficult to establish a generalized model, even within a season. This is particularly true for fields like F3 and F4 because the additional impact of external factors like management and experimental design affected plant growth. Furthermore, the low number of data points for each site-year causes interpretation difficulties for the outcome of such models. One solution to this problem would be to have a higher spatial resolution of yield (e.g. yield maps based on combine harvest) as well as N surplus or, even better, directly measured losses in order to have a highly spatially resolved N balance (Klement et al., 2017; Liu et al., 2010; Mittermayer et al., 2021).

4.3. Assessment of the market-based solution

A market-based solution, such as taxes on N fertilizer, could promote a more precise use of N fertilizer, minimizing the risk of environmental emissions (Berntsen et al., 2003; Blottnitz et al., 2006; Finger, 2012; Good and Beatty, 2011). An increase in N price would contribute to the shift of the EO closer to the environmentally preferable N input by encouraging a more precise use of fertilizers. Our results show a large gap between the optimal N inputs that are dependent on whether the EO or the BNS is considered. The question on how to balance fertilizers is addressed in the recent ongoing discussion on reducing the N surplus from fertilizer applications in Switzerland, Europe, and worldwide (Berntsen et al., 2003; Drury et al., 2007; Jan et al., 2017; Liang et al., 2019). The concept developed in our study to assess the environmental and economic performance of N management application technologies was used in a subsequent empirical assessment based on field trial data in order to address this question.

According to our results, current N fertilizer prices of 1.65 CHF kg N^{-1} would have to be increased between 3.5 and 5.4 times so that the economically optimal N fertilizer input corresponds to a balanced N supply. However, from a political perspective, it is hard to imagine that such a price increase would be feasible. One way to justify price increases would be to reinvest the tax revenues in agriculture, for instance, by supporting farmers' investments in VR or other technologies and measures that increase N use efficiency (Schläpfer, 2016; Schmidt et al., 2017; Shaviv, 2005; Späti et al., 2021).

5. Conclusion

Combining information of economic and environmental performance of N fertilization allows for identifying possible solutions to reduce N surplus without affecting revenues. The results of this study showed that technical solutions, such as VR technology, have the potential to reduce N fertilizer input without compromising yields and revenues as compared to standard application. Given that all costs can be covered and significant variability is detected in the field, VR application is thus a possible technical option to reduce N surplus for small- to medium-scale winter wheat production in Switzerland. However, the high variation across the fields, and especially years, makes it difficult to accurately estimate the environmentally optimal N fertilizer input at the field level. One solution to solve this problem could be to have a higher spatial resolution of yield information (e.g. yield maps based on combined harvest) as well as N surplus or direct measurements of losses in order to have a highly spatially resolved N balance. To further improve on-farm N use efficiency, a better understanding of in-season variability is crucial. For this, advances in plant and soil sensing technologies and related models are needed.

A concept combining economic and environmental performance indicators allowed for identifying the potential of market-based solutions to align the economically optimal N input with the fertilizer input at the balanced N supply that would be favourable from an environmental perspective. The concept of linking the two indicators is well suited to characterize the economic and environmental performance of N fertilization. However, the fertilizer taxes calculated in this study would have to be many times the current fertilizer prices in order to align the indicators, which makes the implementation of such a measure hardly feasible from a political point of view. Moreover, this approach can only be applied after the harvest, requiring plant analyses of fertilized and non-fertilized plots; this is not necessarily applicable or possible in practice. Future research should focus on expanding the database to verify the numeric values found in the present study. Furthermore, additional cost parameters, such as labour and technology, could be considered.

Data availability

The data associated with this manuscript are available on Mendeley Data: Argento, Francesco (2022), "Investigating two solutions to balance revenues and N surplus in Swiss winter wheat", Mendeley Data, V1. DOI: doi:10.17632/ydmnx6dm3b.1

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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