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Within-field variation of actual and maximum winter wheat yield in relation to crop management

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ABSTRACT

Context: The potential magnitude of agronomic yield gain through management is rarely explored at the field scale. Increasing yield through greater use of inputs without considering local potential yield may pose environmental and economic risks.
Study objectives: i) examine yield gain through increased management intensity, including irrigation, and how it varies within and between fields, ii) evaluate the environmental and economic risks of uniform N-rates within fields.
Methods: Field experiments were performed at three sites, with varying yield potential, in each of 12 fields with winter wheat (*Triticum aestivum* L.) in Sweden over three years. Irrigated and rainfed maximum yield under non-limiting cropping inputs (Yim and Ym), actual yield under conventional management (Ya), and yield gains (Yim-Ym and Ym-Ya) were determined.
Results: More frequent pest control was most effective to increase yields, followed by higher fertilizer rates. However, within-field yield variation, relative to the lowest yield recorded in the field, was, on average, similar for Ya and Ym but reduced by irrigation (Yim). Thus, water limitation was the main reason for within-field yield variations, possibly related to soil texture.
Conclusions: Actual and maximum yields vary between and within fields. This variation cannot be entirely compensated for by intensified management. Therefore uniform yield levels within fields should not be strived for, instead site-specific optimal levels should be the goal.
Implications: The within-field variation in yield needs to be considered as N rates based on site-specific yield levels within fields were found to be more profitable than uniform N rates.

1. Introduction

Stagnating winter wheat (*Triticum aestivum* L.) yields in Europe, and the difference between actual and potential yield (the yield gap), has been a major concern over the years (Boogaard et al., 2013; Brisson et al., 2010; Elmquist et al., 2014; Knight et al., 2012; Schils et al., 2018). Research attempting to explain the difference between actual and potential yield is typically performed at a national or regional scale, but precision agriculture studies have shown that yields and input requirements can vary substantially within fields (Blackmore et al., 2003; Robertson et al., 2008; Gebbers and Adamchuk, 2010; Bölenius et al., 2017), meaning that the potential yield gain may also be expected to vary at a field scale. For greater utilization of the potential yield, yield limiting factors need to be known at an operative farm or field scale. Simply increasing, for example, nitrogen (N) inputs without any knowledge of potential yield and within-field variations poses increased environmental and economic risks (Gebbers and Adamchuk, 2010; Engström et al., 2011; Delin and Stenberg, 2014).

Yield limitations caused by suboptimal micro- and macronutrient levels in soil, with the exception of highly dynamic N, can probably be minimized using up-to-date soil nutrient maps and general fertilization recommendations (Swedish Board of Agriculture, 2023). Appropriate

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pest control and water supply are also important to address yield limitations. For the accurate calculation of economically optimal N (EON) rates, soil N availability and expected yield level must be estimated as accurately as possible (Bushong et al., 2016; Delin, 2005; Engström and Lindén, 2009; Ratjen and Kage, 2015; Øvergaard et al., 2013).

There are now easy-to-use tools to visualize within-field variation in crop vigor and yield in each unique field. For example, remote-sensing image-based vegetation index maps showing variation patterns in crop biomass and nutrient status are now freely available in near-real time in decision support systems for precision agriculture (Söderström et al., 2017), while yield maps for individual fields are provided by most modern combine harvesters. In addition, field trials demonstrating within-field variations in, for example, soil properties, yield, and yield limiting factors can be valuable in encouraging farmers to adopt variable rate application (VRA), i.e., site-specific adaptation of cropping inputs to increase yield in high-potential areas and reduce environmental effects in low-potential areas.

The aims of this study were to estimate:

i) agronomic yield gains by non-limiting cropping inputs with and without irrigation as compared to general recommendations, and thereby identify major yield-limiting factors and how they vary within and between fields.

ii) economic and environmental risks arising when using field-average data instead of site-specific N-rates.

2. Material and methods

2.1. Experimental set-up and statistics

In each of the four major wheat-growing regions in Sweden (Västra Götaland, Skåne, Östergötland, and Uppsala(Fig. 1), field experiments were carried out in four fields per year (2015–2017), with a total of 12 fields. Field sizes were 30–45 ha in Västra Götaland, 35–40 ha in Skåne, 10–15 ha in Östergötland and 30–50 ha in Uppsala. Three experimental sites were established in each field, in areas expected to represent low-, high- and intermediate-yielding areas according to historical yield maps, remotely sensed vegetation index maps, farm soil maps and farmer experience. The selected fields were seeded in early autumn with a high-yielding cultivar of winter wheat (Västra Götaland: Julius 12/9, Norin 11/9, Brons 15/9; Skåne: Ellvis 17/9, Ellvis 26/9, Ellvis 26/9; Östergötland: Mariboss, 11/9, Mariboss 13/9, Mariboss 13/9; Uppsala: Olivin 13/9, Olivin 13/9, Julius 16/9). Within each region, a different field on the same farm (Bjertorp, Krageholm, Hyttringe, and Lövsta) was used in each of the three years. Daily precipitation and temperature data was collected from weather stations placed in each field. These are all well managed farms with low weed pressures and monitored soil nutrient status. At the three experimental sites in each field, irrigated maximum yield (Yim), rainfed maximum yield (Ym) and rainfed actual yield under conventional management (Ya) were measured. The average yield differences (Ym-Ya and Yim-Ym) were calculated for each field and at the three sites within each field. The possibility of reducing the yield differences through management, such as through N-fertilization, PKSmicro-nutrient fertilization, pest control and irrigation, was explored.

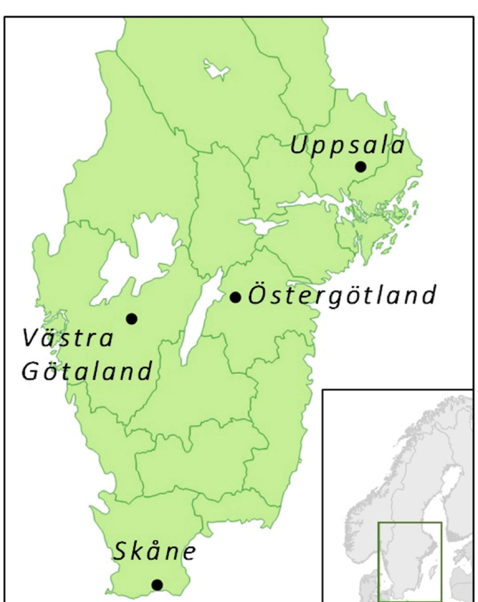

Fig. 1. Locations of the study farms in south Sweden. County boundaries: SCB, Statistics Sweden. European boundaries: Sevdari and Marmullaku (2023).

For this, there was one experiment with 19 fully randomized plots at each field site with various combined treatments (Table 1). Each plot measured 3 or 6 m x 12–15 m (36–90 m^2; only in Uppsala the plots were 6 m wide, due to machinery limitations), and a 20–25 m^2 sub-area within each plot was combine-harvested to determine yield. To account for the border effect the harvested area had 2 m width inside the plots. Yield was calculated in kg per hectare at a 15 % moisture content, and protein content (% of dry matter) was analysed from a grain sample of 1000 g. The treatments in the experiment were a combination of N fertilization (three levels: 0 = no N fertilization, 1 = general recommendations, 2 = 100 kg N ha^{-1} above recommendations), phosphorus-potassium-sulfur-micronutrient (PKS-micro) fertilization (two levels: A = recommended level, B = 2x recommended level) and pest control, mainly fungicides (two levels: a = 0–2 applications, in accordance with recommendations to adapt to the cropping season/requirement, b = 2–3 application of pesticides that follow what was used in cultivar trials in the area). A high nutrient input and high pest control treatment (2Bb) was included to ensure growing conditions with as little growth limiting factors as possible, supporting potential yield at the site under the given weather conditions (Ym). A treatment with the recommended inputs of nutrients and pest control (1Aa) was included to estimate actual yield obtained through conventional management (Ya). Other treatment combinations were included to isolate the effect of each treatment (1Ab, 1Aaw, 1Ba, 1Bb, 2Aa, 2Ab, 2Ba, one replicate of each). The main treatments (0Aa (unfertilized), 1Aa (Ya), 2Bb (Ym), 2Bbw (Yim)) were performed in triplicate at each field site (Table 1).

Supplementary drip irrigation was provided in two of the three years (not 2015 due to high precipitation), in two treatments: 1) 1Aa (one replicate per field site), to determine irrigated actual yield (Yia); and 2) 2Bb (three replicates), to determine irrigated maximum yield (Yim). A total of 30 mm of water was provided on each irrigation occasion and there were 1–4 irrigation occasions per growing season, depending on the amount of natural precipitation.

2.2. Soil sampling

Soil texture and chemical soil properties were determined at all three sites per field. Samples were taken from three soil layers (0–20, 30–60, and 60–90 cm) and analyzed for clay, silt, and sand content. Soil texture was determined through the sedimentation method (Gee and Bauder, 1986). Total carbon content was measured through dry combustion at 1250°C on a CNS-2000 analyser (LECO Corporation, St. Joseph, MI, USA). Soil pH was determined using dry soil samples mixed with distilled water at a ratio (w/v) of 1:5. Ammonium lactate–extractable P (P-AL), K (K-AL) and Mg (Mg-AL) were determined (Egnèr et al., 1960). Ammonium lactate-extractable P and K (P-AL and K-AL) concentrations in the soil were determined by adding 60 mL of ammonium lactate solution (AL + acetic acid) to 3 g of soil (dried at 35–40 °C, sieved <2 mm mesh). To determine hydrogen chloride-extractable P and K (P-HCl and K-HCl), 50 mL of 2 M HCl solution were added to 2 g of soil (dried at 35–40 °C, sieved <2 mm) and boiled for 2 hours (modified from Egner et al., 1960). The final concentrations in the soil samples were

Table 1
Treatments used in a three-factorial experiment investigating different levels of nitrogen (N) and phosphorus-potassium-sulfur-micronutrient (PKS-micro) fertilization, and pest control in farmers' fields and in experiments at three sites within each field. Four treatments had three replicates (0Aa, 1Aa, 2Bb, 2Bbw). The remaining treatments had one replicate (1Ab, 1Ba, 1Bb, 2Aa, 2Ab, 2Ba and 1Aaw). The experiments at each site contained 19 totally randomized plots.

0Aa	0Aa	0Aa	1Aa	1Aa	1Aa	2Bb	2Bb	2Bb	2Bbw
2Bbw	2Bbw	1Aaw	1Ab	1Ba	1Bb	2Aa	2Ab	2Ba	
Factors*	Treatments								
Nitrogen fertilization:									
0	Unfertilized, 0 kg N ha^{-1}								
1	Recommended N-rate (on average 190 kg N ha^{-1})								
2	High N-rate for potential yield (on average 340 kg N ha^{-1})								
PKS-micro:									
A	Recommended PKS fertilization								
B	High rates of P, K, S, and micronutrients (2 x recommendation)								
Pest control:									
a	Recommended application (0–2 times per season)								
b	High frequency pesticide application (2–3 times per season)								

* With *irrigation* (w) in 1Aa and 2Bb. Irrigation was not performed 2015.

determined using ICP/OES (Avio200, Perkin Elmer, Waltham, MA, USA). Total carbon (C) concentration in soil was determined through dry combustion using an elemental analyzer on macro samples (Trumac CN, Leco Corp, S:t Joseph, MI, USA).

2.3. Grain sampling

One grain sample per plot of 1000 g was analyzed for total N content and water content using near infrared transmission (NIT) spectroscopy (FOSS Infratec1241 NIT equipment, Hillerød, Denmark).

2.4. N-uptake in unfertilized plots

At growth stage (GS) 31–32 and 45–47 (Zadoks et al., 1974), crop samples were cut in each unfertilized plot in an area of 0.5 m^2, dried at a maximum 60 °C (48–70 hours), and then analyzed for nitrogen content (% N of dry matter). The N-content of the crop samples was calculated for kg N ha^{-1}.

2.5. Volumetric soil water content

In all replicates of the three treatments (1Aa, 2Bb, 2Bbw) at each of the three within-field sites, access tubes were installed to monitor changes in volumetric soil water content (VSC) in the soil profile using a moisture meter (Profile probe, type PR2, Delta-T Devices Ltd, Cambridge, UK). Moisture was measured at 10, 20, 30, 40, 60, and 100 cm depths every second week in the period April-July.

2.6. Calculations and statistics

Statistically significant differences ($p < 0.05$) between field sites in terms of yield, grain protein content and yield gaps at within-field sites were analyzed using ANOVA (general linearized model, Fisher's comparison test) in the software Minitab®18. A three-factorial analysis was performed to determine the impact of N fertilization (Nfert), PKS-micro fertilization (PKSfert), pest control (Pestc), and their interactions on yield for each field and each within-field site.

The factors (fixed) in the model were Nfert (1, 2), PKSfert (A, B), Pestc (a,b), blocks/field sites (1,2,3) and interactions. To investigate if and how the effect of the three factors varied within each field, a three factorial analysis was also performed for each of the three field sites, with the same eight treatments. The factors (fixed) in this model were Nfert (1, 2), PKSfert (A, B) and Pestc (a,b). When analyzing all three years together, field ($n = 12$) was also included as a factor in the model, and site ($n = 36$) was nested within field. Statistically significant differences between Yim and Ym (i.e., irrigation effects) were explored using one-factorial analysis/ANOVA/GLM field-wise and site-wise.

Economical optimal N-rate (EON) was calculated using N-fertilization recommendations from Yara AB (Oslo, Norway), based on expected yield and sensor-measured N-uptake in an unfertilized 3 m x 4 m plot (zero-plot) at growth stage GS32–45 (as a measure of soil mineral N availability). The Yara AB N-fertilization calculation model for winter wheat is based on data from 63 field trials performed from 2015 to 2020 and available for farm advisors.

For each within-field site, three cases (C1, C2 and C3) were compared with a reference case (C0), where C0 is general farmers' practice, to calculate EON based on field-average yield (Ya) and N-uptake in one (in this case randomly selected) zero-plot per field. In C1, field-average yield and the zero-plot at each site were used to calculate EON. In C2, site-specific Ya and N uptake in the randomly selected zero-plot from the same field were used, and in C3, site-specific yield and zero-plot N uptake at each site were used. It was assumed N-rates with the better decision supports (C1-C3) were more correct compared to common practice (i.e., any difference compared to C0 is interpreted as an improvement).

The financial gain of the three cases (C1-C3) compared with general practice (C0) were estimated assuming values of 1 SEK kg^{-1} wheat grain and 10 SEK kg^{-1} fertilizer-N. At field sites with EON > 10 kg above general practice (i.e., sites which were under-fertilized in C0), it was assumed that increased fertilization of 20 kg N ha^{-1} would lead to a possible yield increase of 1000 kg ha^{-1} (based on Yara AB recommendations).

For each case, the financial gain was calculated and summarized for: *i*) the part of the field that would have been under-fertilized by common practice and could give a higher yield through increased fertilization, and *ii*) the part of the field that was over-fertilized by common practice and the N rate could be reduced without yield loss.

3. Results

3.1. Weather conditions 2015–2017

In Fig. 2 the cumulative precipitation from the start of the growing season until harvest is plotted as a function of degree days, that is from April to August. In all fields, total precipitation from drilling in September 2014 to harvest in August 2015 was higher (600–711 mm) than in the other years studied (370–660 mm). Also during the growing season in 2015 the precipitation was higher apart from Skåne 2017 (Fig. 2). Specifically, during the beginning of stem elongation (DC31–37). All regions had the lowest rainfall during stem elongation 2016.

3.2. Average yields and yield differences

The highest yields were obtained in the maximum treatments under irrigation (Yim), on average 11460 kg ha^{-1} for all years and field sites.

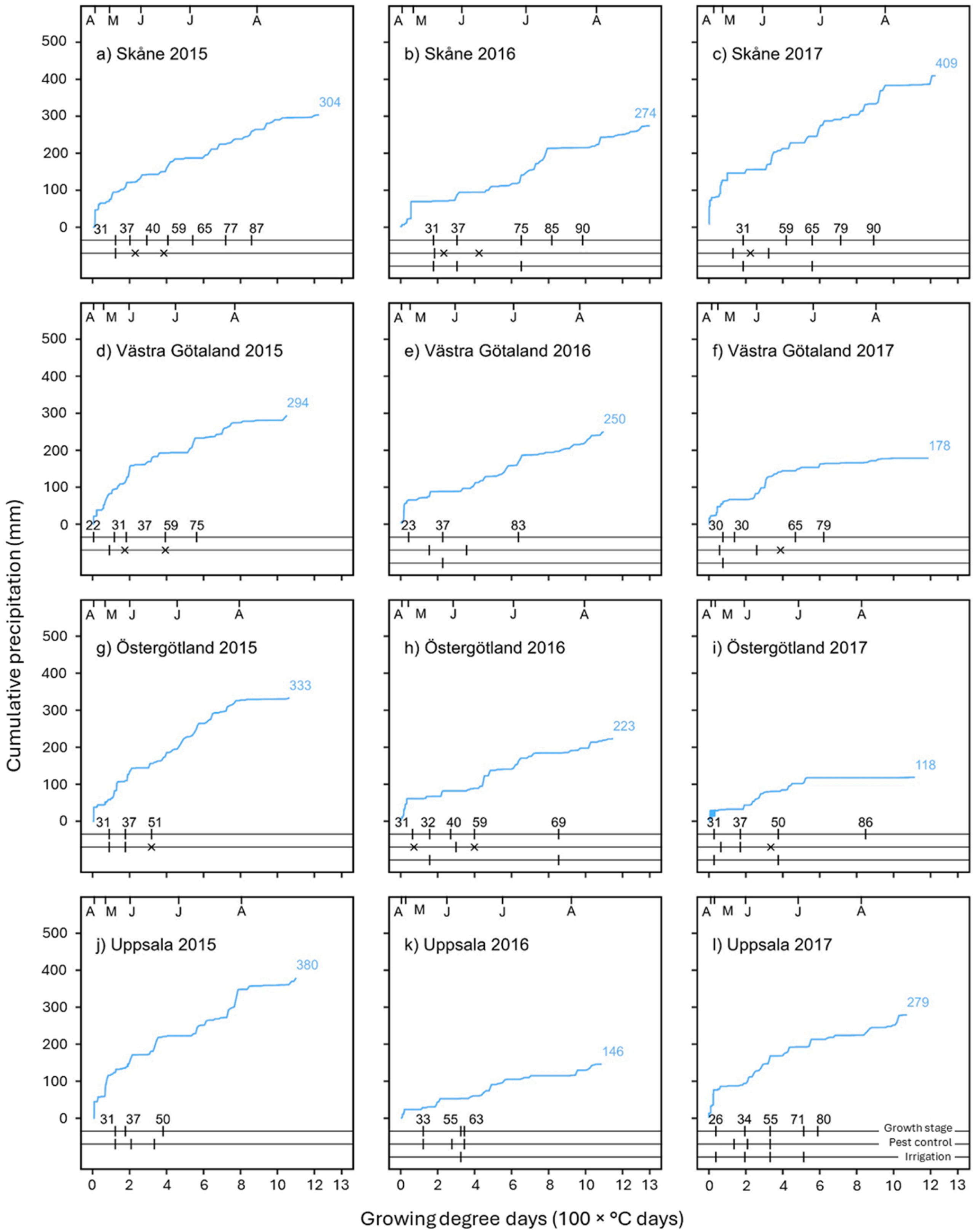

Fig. 2. Cumulative precipitation in relation to growing degree days (base temperature 5°C). Data are shown from the start of growth in the spring until harvest. Secondary x-axis indicate with tick marks the first day in each month, April to August. Growth stages are according to Zadoks et al. (1974). Fungicide applications are marked with tick marks when applied 2–3 times (Ym) and with crosses, when also applied 0–2 times (Ya). Treatment Ym = the rainfed maximum yield with maximum inputs of makro/micronutrients and pesticides and Ya = the actual yield obtained under conventional management.

This was 1479 kg ha^{-1} (14.8 %) higher than the actual yield (Ya) and 620 kg ha^{-1} (5.7 %) higher than the rainfed maximum yield (Ym), representing the irrigation effect (Yim-Ym). The second highest average yield was a rainfed maximum yield (Ym) of 10951 kg ha^{-1} for all years and within-field sites, which was 791 kg ha^{-1} (8.6 %) higher than Ya, representing the yield difference (Ym-Ya). However, the yield differences between treatments varied substantially, both between and within fields (Tables A1-A3 in the Appendix). The standard deviation (SD) for Ym-Ya was 529 kg ha^{-1} (ranging between −3 and 2060 kg), while for Yim-Ym it was 782 kg ha^{-1} (ranging between −760 and 2 225 kg).

The N-rate applied for Ya was 157–229 kg N ha^{-1} (an average of 190) and agreed with recommendations based on estimated yield and soil N supply (Swedish Board of Agriculture, 2023). The protein content in Ya was on average 11.9 %, confirming that N-rates were close to EON (Tables A1-A3). The N-rate applied for Ym was 293–396 kg N ha^{-1} (an average of 340) and protein was 13.3 %, which indicates rates well above recommendations and EON.

3.3. Yield limiting factors

Between fields, the yield differences between rainfed maximum yield and actual yield (Ym-Ya) varied substantially. The three-factorial ANOVA (data not shown) of all 12 fields in the four regions over three years showed that the yield difference Ym-Ya was mostly explained by different levels of pest control ($p < 0.001$) and N fertilization rates (N-effect; $p = 0.04$). Strong interactions ($p < 0.001$) were found between field and N-effect and between field and PKS-micro (data for each field and for each within-field site is presented in Tables A1-A3).

Field-wise, only the three highest positive yield differences (Ym-Ya) were statistically significant, 1346 kg ha^{-1} in Västra Götaland in 2016, 1660 kg ha^{-1} in Östergötland in 2016, and 1454 kg ha^{-1} in Östergötland in 2017 (Tables A1-A3). In 2015, there was a significant negative yield difference (Ym-Ya) in Västra Götaland, which was likely the combined effect of high N-rates in Ym causing lodging and yield reductions and a pest control effect causing increased yields in Ym. In 2016, the yield difference (Ym–Ya) in Västra Götaland was mainly the result of higher N fertilization, but may also be affected by increased pest control, while in Östergötland it was caused equally by higher N fertilization and pest control. In Uppsala, increased pest control was the only explaining factor in 2016 and in Skåne there was only a tendency for an N-effect on yield. In 2017, the yield gains in Östergötland and Skåne were explained by increased pest control, while the yield gains in the other two regions were not significant. Over the three-year study period, PKS-micro did not explain the yield gains significantly for any field, but still coincided with major yield increases at two within-field sites (see below).

Within-field analysis indicated that the magnitude of the yield gains (Ym-Ya) and their causes varied greatly between sites. Yields in the unfertilized plots (Y0N) also varied greatly, as did grain protein content. A significantly posiN-effect on yield (Ym-Ya) was detected at seven of the 36 individual within-field sites (Tables A1-A3). For all sites there was a significant, but week, negativ relationship between the N-effect on yield and unfertilized yield, indicating a higher effect at sites with lower Y0N (i.e., less plant-available soil N) (Fig. 3a). The sites with a significant N-effect on yield had on average, 389 kg ha^{-1} higher yield increase and Y0N yields were 260 kg ha^{-1} lower compared with the other sites with no significant yield effects (Fig. 3a). A strong correlation between Y0N yields and N uptake in later growth stages (GS45) confirmed the relationship between Y0N yield and soil mineral N (Fig. 3b). N-uptake at GS45 in the Ya and Ym treatments also correlated well with the Y0N yields.

Yield increases caused by higher input of PKS-micro were not statistically significant, although there was a tendency in one site in Västra Götaland in 2017 and in one in Uppsala in 2016. These two sites were characterized by lower soil P-HCl (and one by lower K-HCl, K-AL and pH) than the other two sites in the same field (Fig. 3c).

There were significantly higher yields caused by increased pest control at 12 of the 36 sites (Tables A1-A3). At these sites, the yield increase could be related to higher N uptake at GS45 ($r^2 = 0.58$, $p = 0.00$), indicating greater biomass and a denser crop (Fig. 3d). Looking at all sites, this relationship was significant but weaker as it included sites that had no need for increased pest control. The sites with significant yield increases had on average 667 kg ha^{-1} higher yield and 23 kg N ha^{-1} higher N-uptake compared with the sites with no significant yield increases. Precipitation during the cropping season could not explain the higher yields caused by extra pest control (Fig. 3e).

3.4. Impact of irrigation on rainfed maximum yield and actual yield

No irrigation was performed in 2015 as rainfall was high and frequent during the growing season (Fig. 2). Four of the eight fields achieved significant yield increases for irrigation (Yim-Ym) in 2016 and 2017 (Table 2). In 2016, yield increased significantly due to irrigation in three of the four regions, with the irrigation effect (Yim-Ym) being on average 930 kg ha^{-1} in Västra Götaland, 1010 kg ha^{-1} in Skåne, and 400 kg ha^{-1} in Uppsala. In 2017, winter wheat yield increased due to irrigation (Yim-Ym) by 1590 kg ha^{-1} in Uppsala. Three of the eight fields achieved significant yield increases due to irrigation (Yia-Ya) in 2016 and 2017. The irrigation effect (Yia-Ya) in 2016 was 650 kg ha^{-1} in Västra Götaland and 524 kg ha^{-1} in Östergötland, was 1280 kg ha^{-1} in Uppsala in 2017. As expected, the greater irrigation effects coincided with less rainfall. The yield effect of irrigation varied substantially between the three sites within each field (Table 2). Irrigation effects exceeding 1 metric tonne ha^{-1} (up to 2 tonnes) were obtained at one field site in Västra Götaland in 2016 and 2017, one field site in Skåne in 2016, and three field sites in Uppsala in 2017, although these were not always statistically significant. Larger irrigation effects typically coincided with lower VSC values in the 20 and 30 cm soil layer (mean VSC 13 % in May and 10 % in June). At VSC values of 20 % and 19 %, the effects of irrigation were never strong (Fig. 4). The major differences in irrigation effect observed for within-field sites in Västra Götaland in 2017 and Skåne in 2016 may be explained by a lower clay content and higher sand content in the soil profile (Fig. 5) in combination with a higher elevation, indicating the lower potential water storage capacity of the soil. In Skåne in 2016, the field site gaining least from irrigation was also sandy, this was at a low elevation in the field close to a lake (data not shown).

3.5. Yield variation at within-field sites

The yields inYa and Ym differed significantly between the three field sites, in seven (Ya) and eight (Ym) out of the twelve fields (Tables A1-A3). The variation between within-field sites in terms of Ya was also reflected in Ym in the same field, despite higher inputs of N, PKS-micro, and pest control in Ym. The average relative yield differences (RYD) between sites within a field, here calculated as the relative difference in yield compared with the lowest value in the same field, was 18 % for Ya (1 330 kg ha^{-1}, SD 816 kg ha^{-1}) and 17 % (1 250 kg ha^{-1}, SD 940 kg ha^{-1}) for Ym. However, with irrigation (Yim), the within-field variation was reduced to 11 % (852 kg ha^{-1}, SD 481 kg ha^{-1}).

The comparison of the within-field yield variation in Ya (three sites) against the field-average value for each field showed that it was similar at 31 % of all within-field sites (+/- 300 kg ha^{-1}), lower at 31 % of all sites (737 kg ha^{-1} on average), and above the field-average value at 40 % of all sites (952 kg ha^{-1} on average) (Fig. 6a and A1).

The results from the scenario analysis are presented in Fig. 6 and Table 3. We assumed that common practice is to determine the N rate based on a uniform target yield and a uniform soil N supply (Case 0). It was assessed that about 190 SEK ha^{-1} would be gained using a site-specific soil N supply (Case 1, target yield still uniform), about 230 SEK ha^{-1} using a site-specific yield (Case 2; soil N supply still uniform), and about 300 SEK ha^{-1} using both a site-specific yield and a site-

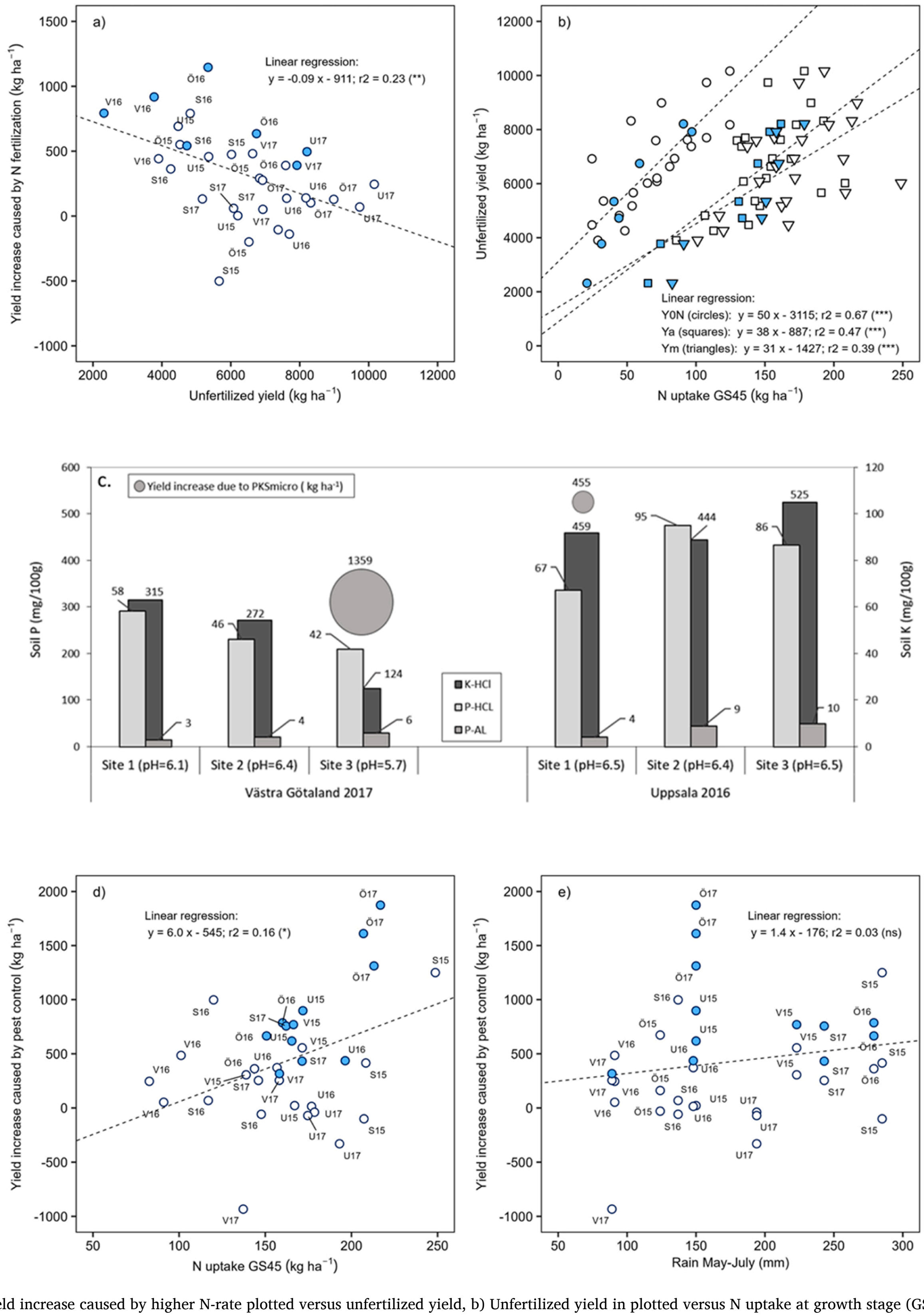

Fig. 3. a) Yield increase caused by higher N-rate plotted versus unfertilized yield, b) Unfertilized yield in plotted versus N uptake at growth stage (GS) 45; c) yield increase caused by increased PKS-micro fertilization and its relationship to soil properties at two sites ($p = 0.22$ and 0.12, respectively), d) yield increase caused by more frequent pest control plotted versus crop N uptake in GS45 and e) yield increase caused by more frequent pest control plotted versus cumulated total precipitation in May-July. Filled symbols: p-value of yield increase ≤ 0.05. Labels: Ö= Östergötland, S=Skåne, U=Uppsala and V=Västra Götaland, numbers denote year. Ym=rainfed yield with maximum inputs, Ya=actual yield under conventional management, Y0N=yield in unfertilized plots.

Table 2

Irrigated maximum yield (Yim: high inputs for optimal growing conditions including irrigation), irrigated actual yield (Yia) and irrigation effects (Yim-Ym and Yia-Ya) (15 % moisture content, kg ha^{-1}, Ym: rainfed maximum yield and Ya: actual yield with conventional input levels) for fields and for three sites within each field at four experimental sites in 2016 and 2017. Statistical significances ($p < 0.05$) are marked as *, $p < 0.01$** and 0.001***).

	2016				2017			
	Yim	Yim-Ym	Yia†	Yia-Ya	Yim	Yim-Ym	Yia†	Yia-Ya
Västra Götaland, irrigation date: 26/5 (GS37)					10/5 (GS30)			
Site 1	8372b	1160***	6690	701	12405ab	208	12409	830
Site 2	8608b	795	6753	212	13189a	597	12245	531
Site 3	9932a	823	8609	1045	11506b	2223	10067	1238
p-value:	*0.004*				*0.04*			
Field average:	8971	926	7351	653	12367	1009	11573	867
p-value:		*0.000*		*0.014*		*0.06*		*0.24*
Skåne, irrigation date: 17/5, 30/5, 29/6 (GS31, 37, 75)					22/5, 26/6 (GS31, 65)			
Site 1	10849	608*	9870	521	10886	−575	10864	63
Site 2	10505	2225	7873	994	10335	415	8921	−161
Site 3	11947	202	11647	522	10437	−203	9936	−349
p-value:	*0.17*				*0.39*			
Field average:	11100	1011	9797	679	10553	−121	9907	−149
p-value:		*0.04*		*0.47*		*n.s.*		*0.31*
Uppsala, irrigation date: 10/6 (GS55)					4/5, 31/5, 16/6, 4/7 (GS26, 33, 50, 71)			
Site 1	9425	471	7959	−95	11253b	1063	10980	950
Site 2	10537	677	9807	75	12700a	2023	11640	1027
Site 3	10428	50	10056	142	12747a	1683*	12840	1870
p-value:	*0.01*				*0.000*			
Field average:	10130	399	9274	41	12233	1590	11820	1282
p-value:		*0.04*		*n.s.*		*0.000*		*0.005*
Östergötland, irrigation date: 19/5, 22/7, (GS32, 69)					16/5, 20/6 (GS31, 50)			
Site 1	12985	82	11369	297	13890	77	13270	437
Site 2	12931	112	11605	582	13147	−760	11680	−167
Site 3	12449	497	11289	691	13550	133	11940	−153
p-value:	*0.21*				*0.21*			
Field average:	12788	230	11421	524	13529	−183	12297	39
p-value:		*0.14*		*0.01*		*0.33*		*n.s.*

† Irrigated actual yield had only one replicate at each site.

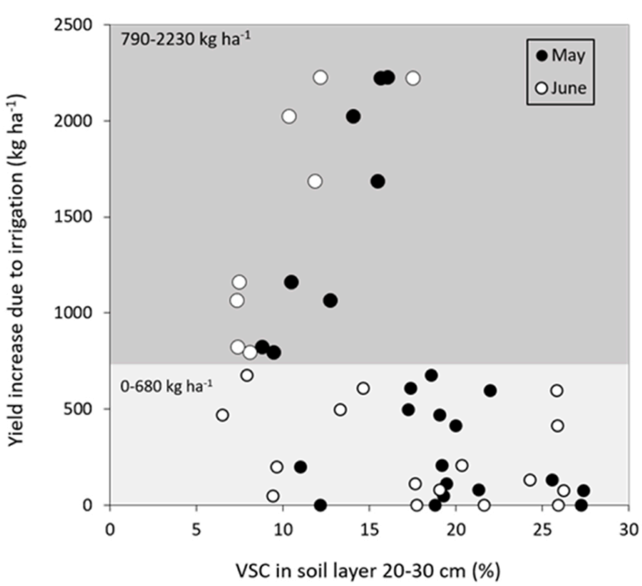

Fig. 4. Yield increase caused by irrigation (Yim-Ym) at field sites in 2016 and 2017 (n = 24) as a function of volumetric soil water content (VSC) measured in May (black circles) and June (white circles) in soil layer 20–30 cm. The mean VSC for sites with higher yield increases (dark grey area; VSC_{may} = 13 (+/- 3) and VSC_{jun} = 10 (+/- 4)) and sites with lower yield increases (light grey area; VSC_{may} = 20 (+/- 5) and VSC_{jun} = 19 (+/- 7) differed significantly ($p < 0.05$).

specific soil N supply (Case 3). The net economic benefit from improved yields was larger than the economic benefit avoidance of spreading more fertilizer N than is needed by the crop. It was deemed important to take both the within-field variation in soil N supply, and the variation in yield potential into account when determining N-rates.

4. Discussion

4.1. Explaining the yield differences between rainfed maximum yield and actual yield

This study showed that yields could often be improved by increased fertilizer rates and pest management compared to common practice. It should be stated that yields from common practice in this study are considered to be good or very good and are well above regional averages (6,3–8,4 tons in included regions and years; SCB, 2016, 2017, 2018). However, yields were not always significantly higher in Ym, and there were major differences between fields, sites and years in terms of what type of yield limiting factors would be reduced through management. Increasing the frequency of pest control and higher N fertilization reduced the yield difference (Ym-Ya) in 20 of the 36 within-field sites. The tendency for a high yield created by PKS-micro fertilization at two field sites with low P-AL and/or low pH indicates that P-fertilization and liming should also be considered.

The N-effect obtained was generally seen at field sites with less plant-available soil N during the growing season, confirming the importance of predicting plant-available soil N accurately when calculating EON (Engström and Lindén, 2009). Predicting plant-available soil N during the season using zero-plots (positioned at a representative site for the field) and expected yield for a field is the general recommendation when calculating N-rate in Sweden (Swedish Board of Agriculture, 2023).

In this study we found a relationship between effects of intensified pest management and N uptake, which relate to crop biomass (Fig. 3d). The relationship was weak, but significant. Especially Uppsala 2016 and 2017 and Skåne 2015 show non, or small yield increases despite relatively high N uptake. This is not surprising as a yield increase caused by intensified pesticide use requires also an infection pressure, and that the

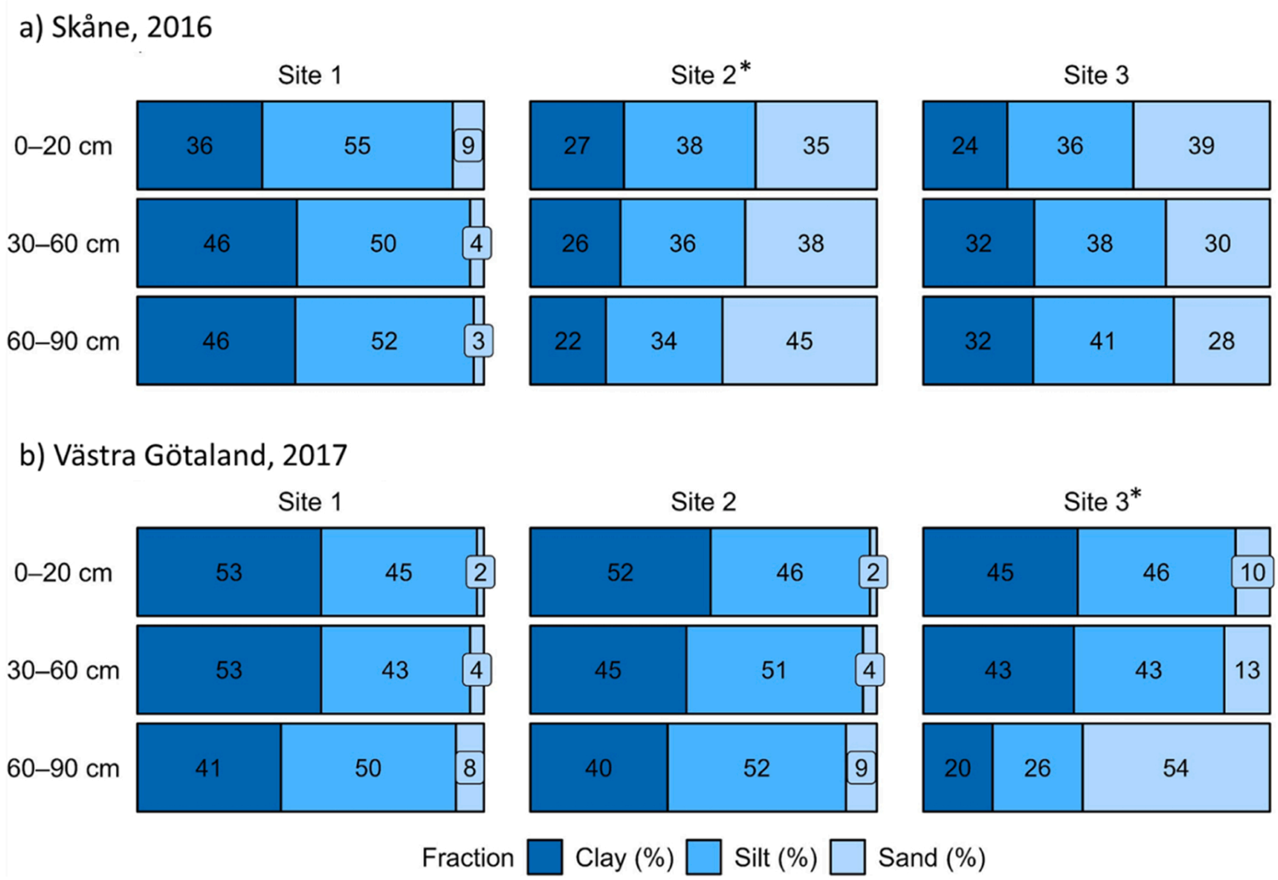

Fig. 5. Soil texture (% clay, silt, and sand) in three distinct layers of the soil profile (0–90 cm depth) at three sites in each of two fields. *The two sites with significant yield increases caused by irrigation.

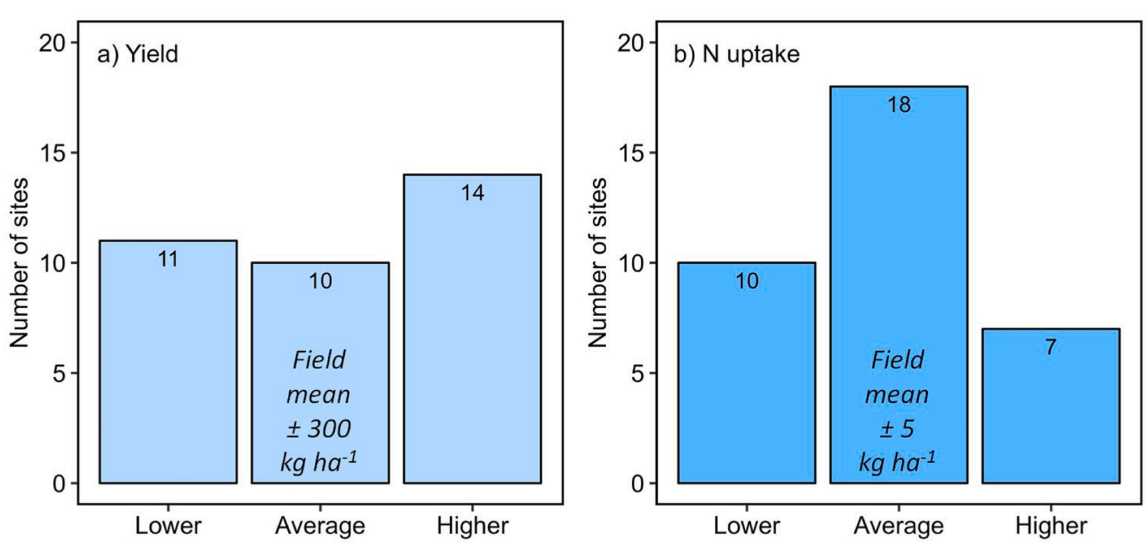

Fig. 6. Grouping of in-field sites when a) comparing actual yield (Ya) at three sites with field-average Ya, and b) comparing N uptake in zero-plots (GS32) at the three sites with field-average zero-plot N uptake.

recommended pest management is insufficient. Precipitation during the cropping season on the other hand, did not explain yield increase at all (Fig. 3e). The subordinate influence of the yearly weather situation on pest control effects was further highlighted by the strongest effect occurring in Östergötland 2017 (Fig. 3d). This location had one of the dryest cropping seasons (Fig. 2) and the highest yields of all years and locations (table A2). In addition, effects otherwise varied within fields and larger pest control effects were achieved at sites with higher N uptake and biomass (Fig. 3d), supporting previous findings that higher crop density is correlated with a higher degree of fungal infection (Jensen and Jørgensen, 2016). Based on their findings the authors suggested site-specific dose adaptation based on crop density or biomass.

Table 3
Results from the scenario analysis. The reference case ('practice') is to determine the N rate based on a uniform target yield and zero-plot N uptake (i.e. a uniform N rate). SEK = Swedish Krona (~ 0.1 Euro).

Scenario analyses	Case 1	Case 2	Case3
Basis for N-rate assessment			
Target yield	*Uniform*	*Site-specific*	*Site-specific*
N uptake in zero-plot	*Site-specific*	*Uniform*	*Site-specific*
For within-field sites where common practice N rate is too low			
Percent of within-field sites	11 %	29 %	20 %
Increase in N rate with the improved decision support (kg ha^{-1})	22	16	24
Yield increase (kg ha^{-1})	1080	807	1 187
For within-field sites where common practice N rate is too high			
Percent of within-field sites	*37 %*	*23 %*	*43 %*
Reduction in N rate with the improved decision support (kg ha^{-1})	26	22	25
For all within-field sites			
Average net financial gain (SEK ha^{-1})	194	234	299

Tackenberg et al. (2017) demonstrated up to 45 % fungicide reduction without yield losses based on on-the-go sensor estimated crop density. Within-field variation in biomass correlates well with yield (e.g., Raun et al., 2005), and a high yield potential may also be a prerequisite for larger yield effects of pest control in areas with denser biomass (Jensen and Jørgensen, 2016). Surface covering sensor systems on tractor, unmanned aerial vehicles (UAVs) and satellite platforms for crop density and biomass estimation with high spatial resolution is under strong development (Scotford and Miller, 2005; Li et al., 2010: Wang et al., 2021). There are also commercially available digital support systems that are in use for this purpose (e.g. Yara International ASA, Oslo, Norway and Dataväxt AB, Grästorp, Sweden).

The cost of pest control was approximately 1000 SEK ha^{-1} for the three applications in Ym and 0–600 SEK ha^{-1} for the up to two applications in Ya. A yield increase of 670 and 1000 kg ha^{-1}, at a wheat grain price of 1.50 SEK and 1 SEK per kg ha^{-1} respectively, would be required to cover the cost of three applications instead of two, and was obtained at 9 of the 12 sites at the higher grain price (Fig. 3d).

The PKS-micro effect on yield (tendency for significant differences) at two of the sites was most likely due to limited P availability. Using data from long-term field experiments, Kirchmann et al. (2020) showed that yield correlates positively with P-AL in soils with P-AL values between 3.3 and 9.7 mg 100 g^{-1} soil. This means that high yield increases can be expected at the two field sites that had 4.1 and 5.7 mg P-AL 100 g^{-1} soil. Kirchmann et al. (2020) also found a great effect of soil pH (5.4–7.5) on winter wheat yield, which increased by 1620 kg ha^{-1} per pH unit. This may explain the yield increases of 450 and 1 450 kg ha^{-1} observed for the higher PKS-micro dose at two of the sites, the latter of which had P-AL = 5.7 and pH = 5.7. The double dose of P (30–40 kg ha^{-1}) applied in Ym compared with Ya required a yield increase of at least 300 kg ha^{-1} to cover the cost (SEK 20 kg^{-1} P), and this was obtained at both sites.

4.2. *Impact of irrigation compared to rainfed maximum yield and actual yield*

A further increase in yield, from Ym to Yim, was obtained due to irrigation. The positive irrigation effect on yield varied substantially between and within fields, and the degree of this effect was mainly related to lower rainfall and sites with coarser soil texture (more sand and less clay). At these sites, greater yield increases could likely have been achieved with more frequent irrigation, as the results for Uppsala 2017 indicated. There was no significant evidence that irrigation affected grain protein content in Yim, probably as it was already high without irrigation in Ym. Water stress always results in reduced crop demand for N (Gonzalez-Dugo, 2010) and can lead to excessive N and N losses at individual within-field sites. Whether irrigation is cost-effective or not has to be evaluated for each situation. However, it is still interesting to identify areas in a field where water is a yield limiting factor in order to save water or adapt inputs. The substantial within-field differences in water requirement observed in this study occurred in situations when water stress was not obvious. At sites with significant, and sometimes substantial, yield increases under irrigation, actual yield (Ya) was still between 6 and 12 tonnes ha^{-1}, which represents normal to very high yields for Sweden. At least two interesting conclusions can be drawn from this: (i) there is a potential to save water by directing irrigation to where it is needed, and (ii) there is potential to increase yield and obtain benefits from an irrigation system even in years when irrigation would not normally be considered. To utilize this, a decision support system is needed to adapt irrigation events, frequency and intensity.

4.3. *Within-field variation in yield and field-average yield*

It has been suggested that it is unprofitable for farmers to exceed 80–85 % of water-limited potential yield (Ym) (Boogaard et al., 2013). In this study, the field average according to common practice (Ya) was 92 % of field-average Ym, and the N-rate in Ya was close to EON, indicating that yield gaps were not necessarily an issue on these farms, which were characterized by good management, when looking at whole fields.

The variations in Ya between sites within fields were not levelled out with higher inputs of nutrients or pest control in Ym. For irrigation (Yim), differences were, however, reduced by an average of over one third. Consequently, the major reasons for observed variations in within-field yield at these sites were soil texture and sub-optimal availability of water. Similarly, Bölenius et al. (2017) found that soil texture was the main factor explaining overall variations in yield within a 28-ha field over five years. Those authors also found a positive relationship between water-holding capacity in the subsoil (30–90 cm) and yield in dry years. The relationship between soil texture and yield depends largely on weather conditions, so the yield pattern under dry conditions may be altered when the water supply is sufficient (Delin et al., 2015). Without irrigation (Ya, Ym) and when N-rates are adjusted field average yields, the yield variations observed within fields could pose a risk of excessive N fertilization at field sites with lower yields than the field average, or yield losses at sites with higher yields than the average. Therefore, variable N-rates within fields are required to level out the protein content, reduce the lodging risk, and lower the risk of N losses (Pettersson et al., 2006).

As shown in this study, where fields with possible yield variations were chosen, it was more profitable to use within-field variations in yield and N-uptake in zero-plots (GS32) to calculate N-rates rather than following general practice based on field-average yield and a single zero-plot. This information may be helpful to farmers and advisors considering whether their within-field variations are great enough to adopt VRA. It was somewhat more important to use site-specific yield compared to using site-specific zero-plot N uptake. The best results were, however, obtained when using both site-specific yield and site-specific zero-plot N uptake. One should bear in mind that the reference case (general practice) in this case was based on correct target yield estimation. This is likely not accurate, as the yield will need to be predicted at the time of fertilization. This may lead to an overestimation of the financial gains in cases 1–3. On the other hand, using a zero-plot in the reference case (which not all farmers do) may lead to an underestimation of the financial gains; Getting the field average N-rate right is a first step (Karlsson-Potter et al., 2022). In practice, site-specific N-fertilization can be done in different ways. For example, it would be useful to split the field into management zones using yield stability maps (Blackmore, 2000, Blasch et al., 2020, Maestrini and Basso, 2021) based on multiple years of yield mapping from combine harvesters. With increasing availability of satellite imagery, satellite-based yield mapping has emerged as an efficient option to create yield maps (Alshihabi et al., 2024; Perich et al., 2023). For each zone, the achievable yield in the present year can then be assessed in the same way one would for the entire field (assessment based on experience and tacit knowledge), and soil N supply can be assessed by zero-plots (i.e. plots without N fertilization; Engström and Lindén, 2009).

If split-application is practiced (which is recommended; Swedish Board of Agriculture, 2023), the supplemental N rates can be varied according to within-field variations in crop N status by tractor-borne sensors or remote-sensing-based decision support systems (Söderström et al., 2017; Piikki et al., 2022). The latter are also useful for visual interpretation of within-field variation in crop status, something that should not be underestimated in crop producer's work to identify potential yield gains and to adapt management to remaining variation in fertility that cannot be influenced.

5. Conclusions

Actual and maximum yields vary between, but also within, fields due to spatial variation in biotic and abiotic environmental conditions. Furthermore, the biotic or abiotic condition that is yield limiting in a specific case also varies between and within fields. An important result of the present study was to show how this variation cannot be entirely compensated for through regular management (irrigation, pest control and fertilization), especially not in rain fed systems. This clearly shows that uniform yield levels within fields should not be strived for, instead site-specific optimal levels should be the goal. This was corroborated by a scenario analysis, in which N fertilization was found to be more profitable when adapted to site-specific yield levels and/or site-specific soil N supply. Overall, irrigation was the most important management practice for narrowing yield differences. In rainfed systems, extensive pest control was most important, followed by adequate fertilization with N and PKS-micro.

An equally important finding was that management efforts that did reduce variation and reduced yield differences varied both between and within fields and years. As long as this cannot be fully controlled, it is often best, both from an environmental and an economical point of view, not to strive for the maximum attainable yield at each site but to aim for a somewhat lower –optimized– production level.

CRediT authorship contribution statement

L. Engström: Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing original draft, Writing, review & editing. **Å. Myrbeck**: Data curation, Writing, review & editing. **A. Larsolle**: Data curation, Writing, review & editing. **E. Coucheney**: Visualization, Writing, review & editing. **K. Blombäck**: Writing, review & editing. **E. Lewan**: Writing, review & editing. **K. Persson**: Methodology, Formal analysis, Visualization, Writing, review & editing. **B. Stenberg**: Funding acquisition, Conceptualization, Investigation, Supervision, Project administration, Methodology, Writing, review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Bo Stenberg reports financial support was provided by Swedish Research Council Formas. If there are other authors, they 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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.109965.

Data availability

Data will be made available on request.

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