



Crop yield levels and nutrient requirements in field edge zones—is precision management motivated?

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Abstract

Purpose Around a quarter of Sweden’s arable land is located within 20 m of a field boundary, yet little is known about crop growth conditions and optimal fertilization in field margins. Therefore, the present study aimed to investigate this, and assess whether there is reason to adjust fertilization in field edge zones.

Methods The yield and grain quality of winter wheat (*Triticum aestivum* L.) were determined at three distances from field edges (8 m, 26 m and 45 m) in eight transects bordering forests and eight transects bordering open land. Topsoil properties were determined in the same locations and differences between groups were statistically evaluated.

Results The yield and thousand kernel weight were lower, and protein content was higher, close to field edges compared to yields in field interiors. The topsoil content of plant-available phosphorous (P) and potassium (K) was higher near the borders. Edge effects were greater towards forests than towards open land. The observed differences suggest lower rates of N, P and K by 22, 5 and 6 kg ha⁻¹ by field edges towards open land and 28, 13 and 19 kg ha⁻¹ by field edges towards forests, although the difference in K-rate by open land was not statistically demonstrated ($p > 0.05$).

Conclusion Reducing fertilizer rates in field margins can be a simple method of reducing redundant nutrient use without losing yield. More efficient nutrient use in crop production is necessary for the work towards environmental objectives, such as the 50% reduction of nutrient losses of the EU Farm to Fork Strategy.

Keywords Fertilization · Field edge · Field margin · Precision agriculture · Soil · Yield

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Introduction

Field edge zones are vast

Field edge zones (FEZs)¹ make up a substantial portion of arable land. In Sweden, around one quarter of cropland is within 20 m of a field edge (Persson et al., 2025). In individual fields, the exact area-percentage constituted by a FEZ of a certain width depends on the size and shape of the field. Smaller fields and fields of a more complex shape have a larger portion of their area in the FEZ. In landscapes with less intense crop production, where fields tend to be smaller and more irregular, the FEZs constitute a larger portion of the cropland than in major crop growing regions (ibid.).

Growth conditions in field margins are special

Studies have demonstrated that conditions near field edges often differ from conditions further into the field. For example, the **soil** type may be different, as may the **microclimate**, including shade and shelter effects from neighbouring vegetation (Kuemmel, 2003). There may also be **ecological edge effects**, including more weeds (Marshall, 1989; Romero et al., 2008; Wilcox et al., 2000) of a greater species richness (Yvoz et al., 2021) and greater pressure from pests and diseases. There may also be grazing wildlife as well as more pest predators and pollinators (Marshall, 2004). There is often more soil compaction close to field edges (Etana et al., 2020; Sunoj et al., 2021; Wilcox et al., 2000), and more sowing gaps and overlaps (Kharel et al., 2020). There are diverse types of FEZs, with outside land use and the cardinal direction of the field border influencing edge effects.

Crop yields are often lower close to field edges

As a result of the special growing conditions, crop yields are often lower in the FEZ. For example:

- Fincham et al. (2023) reported yield reductions of 10% in wheat (*Triticum aestivum* L.) and 18% in oilseed caused by field edge effects in 1174 fields in the UK.
- Pywell et al. (2015) reported yield reductions of 10%, 26% and 38%, respectively, in wheat, beans (*Vicia faba* L.) and oilseed rape (*Brassica napus* L.) within 9 m of the field edge on one 900 ha farm in the UK.
- Raatz et al. (2019) reported a 11–38% yield reduction in wheat, within 11–18 m of the field edge in two locations in Germany.
- Ward et al. (2020) reported a 2–30% yield reduction closer to borders compared to in field interiors (FI) in wheat and barley (*Hordeum vulgare* L.) in diverse types of border zones in 40 fields in Ireland.
- Sparkes et al. (1998) reported yield reductions of 26% in sugar beets (*Beta vulgaris* L.) and 7% in cereals in headlands compared FIs on one farm in the UK.

¹ In the present text, the term field edge zone (FEZ) is used to denote a zone of a certain width along the border of a field where conditions are, or are expected to be, different from field interiors (FI), because of the proximity to the field boundary. The width of FEZs may differ from case to case (in cited literature). Regarding the present study, the use of the term is clarified in Sect. 2.3.

The two first-mentioned studies were based on combine harvester yield monitoring, which may be unreliable close to field borders, while the third and the fourth study were based on manual harvesting. The last-mentioned study also used a combine harvester with a monitoring system but applied specially designed procedures to avoid common data quality problems associated with starts, stops, turns, etc.

Studies on fertilizer needs in FEZs are scarce

The crop requirements of the primary macronutrients, i.e., nitrogen (N), phosphorus (P) and potassium (K), are determined from estimates of crop nutrient demand governed by the yield level and soil nutrient supply estimated from soil sample analyses (or, in the case of N, unfertilized reference plots called zero-plots) (see the recommendations for fertilization by the Swedish Board of Agriculture, 2024). Although it is known, from the above cited literature, that both yield levels and soil conditions differ in FEZs compared to in the rest of the field, studies on crop nutrient requirements in this vast part of the fields are scarce, and we have been unable to find any.

We lack decision support precision management of FEZs

Precision agriculture is a production strategy which aims to adapt management (e.g. fertilizer rates) to within-field variation in crop growth conditions. The goal is to improve the resource use efficiency, sustainability, and profitability of production, but also to increase overall production and to ensure that quality targets for produce are met (International Society of Precision Agriculture, 2019). In many parts of the world, it is now relatively common to vary P and K rates based on topsoil sampling and analysis (one sample per hectare), and to vary N-rates based on current crop N status, sensed from tractors, drones, or satellites (McFadden et al., 2024).

However, in neither case, FEZs are treated separately. Unless any manual adjustments to the prescription files (the digital fertilizer-rate map) are done, FEZs are fertilized at the same rate as in FIs. The reason for this is presumably that the required decision support is missing in the FEZs. It is difficult to know the yield level. Yield monitoring on combine harvesters does not work well near field edges because of the multiple starts, stops, turns and non-full cutting-boards (Nissen & Söderström, 1999; Sudduth & Drummond, 2007; Lyle et al., 2014). Satellite-based mapping of in-season crop status and yield performs poorly due to the mixed pixel effect close to borders. We also often lack measurements on soil nutrient supply in the border zones. Soil samples are not taken near field edges; on the contrary, we avoid taking samples near the edge when mapping soils as they are not representative of the field as a whole, and for the same reason, we avoid placing zero-plots in the FEZs.

There are, however, some regulated restrictions. For example, in Sweden, fertilization must be avoided within two meters of watercourses or lakes, or on slopes greater than 10% facing water (SJVFS 2004:62).

Thus, border zones tend to be fertilized blindly, using the same rates as those used further into the field – rates are set at the discretion of the farmer, not based on data and knowledge.

Aim and scope

In this pilot study, crop grain yields, soil properties and resulting crop nutrient requirements were determined near two types of field edges, and compared with those further into the same field. The results from soil and crop sampling from sixteen sampling transects in winter wheat are presented and options for consideration of the special growing conditions along field edges are discussed. The results from the grain sampling have been partially published in a conference proceeding by Persson et al. (2025).

Materials and methods

Study area

The study was conducted in southwest Sweden on landscape formed by the Weichselian glaciation, which in this area lasted until approximately 11,500 years ago (Engdahl, 1997). The soils here are commonly classified as Eutric Cambisols according to the IUSS Working Group WRB (2022). The area is dominated by arable land and forests. The most common crops are ley, winter wheat, spring barley oats (*Avena sativa* L.), oilseed rape and potatoes (*Solanum tuberosum* L.).

Crop management

All sampled fields were managed by the same estate. Soil pH had recently been corrected using precision liming. In some years, phosphorus (P) was applied site-specifically based on soil analyses, while in other years it was applied at a uniform rate. Potassium (K) is given at the uniform rate of an NPK-fertilizer to spring crops. In the season of the present project (harvest 2024), no K was applied, and all observation plots received an N-rate of 254 kg ha⁻¹ and a P-rate of 39 kg ha⁻¹.

Sampling design

Sixteen transects consisting of three sample points each were laid out, eight bordering open land use (another field with or without a small dirt road in between) and eight bordering forests (Fig. 1). There were four transects in each of the four fields, two of each type. The distances from field borders were approximately 8 m, 26 m and 45 m, respectively. Tramlines were avoided. The 8 m observations are considered to represent FEZs, while the 45 m observations are considered to represent FIs. At 26 m from the edge, intermediate observations are made with no prior assumption of whether they represent FEZs or FIs (it is not known how wide a FEZ is in the studied agricultural landscape).

Crop sampling

Crop samples were collected on July 31st and August 1st, 2024, shortly before combine harvesting of the fields. At each sample location, two crop subsamples were collected within 3–5 m of the sample centre point (Fig. 1b). Each subsample consisted of two crop rows

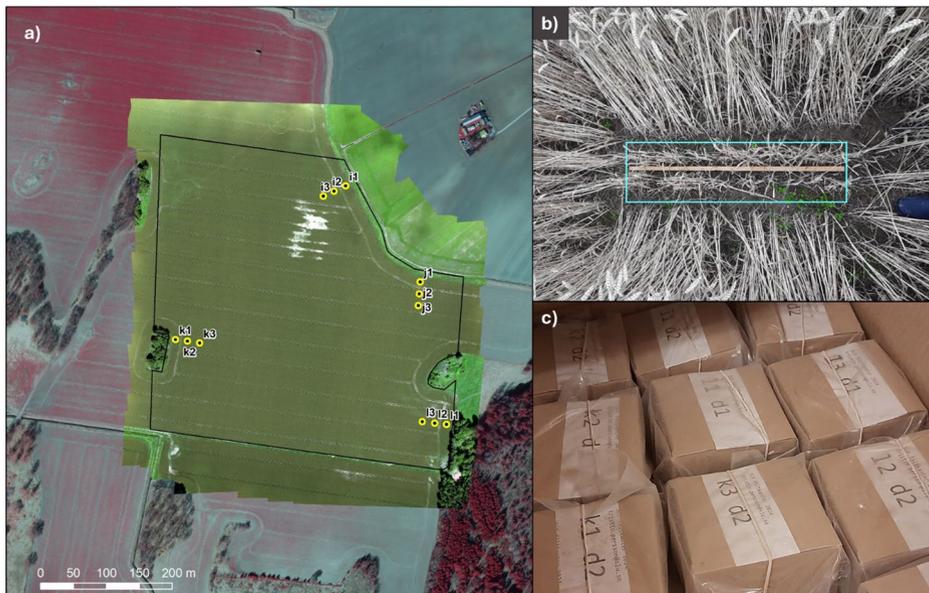


Fig. 1 Placement of observation transects in one of the fields (a). Each transect (i, j, k, l) consists of three observation plots placed at three distances from the border: 8 m (field edge zone; FEZ), 26 m (intermediate), and 45 m (field interior; FI). In each of these, the crop was cut at harvest (b) and composite soil samples (c) were taken from 0–20 cm and 40–60 cm. The RGB mosaic in (a) is from the drone-borne camera and the background orthophoto behind the mosaic is provided by Lantmäteriet (Gävle, Sweden)

of 1 m length, which corresponded to c. 0.33 m² per subsample and 0.67 m² in total. The predetermined sample locations were retrieved using a real-time kinematic global navigation satellite system (RTK-GNSS) of model DataGrid Mk3 Chameleon (DataGrid Inc., Gainesville, Florida, USA) with a horizontal positional error of 1–2 cm.

Soil sampling

The soil sampling was conducted within three months of harvest. The crop sampling locations were retrieved using the RTK-GNSS described above. At each sample location, one topsoil sample (0–20 cm depth) was collected. The samples consisted of eight subsamples taken at a distance of 3–5 m from the sample centre point, using an auger with an inside diameter of 3 cm.

Lab analyses

All crop and soil analyses, including sample preparation, were conducted by Hushållningssällskapet's laboratory in Grästorps, Sweden, which is accredited (no: 10508) by Swedac (Borås, Sweden).

Grain analyses

The grain samples were threshed and weighed using a Zürn z150 thresher (Zurn, WI, USA) and an EK-2000i balance (A&D Medical, Tokyo, Japan). A grain yield at a 15% water content was calculated per unit ground area. The percentage of chaff was determined using an MLN sample cleaner (Pfeuffer, GmbH, Kitzingen, Germany), and the thousand kernel weight (TKW) at a 15% water content was determined using a Contador 2 seed counter (Pfeuffer, GmbH, Kitzingen, Germany) and the EK-2000i balance (as above). The content of protein, gluten, starch and ergosterol per grain dry weight was determined through near infrared transmittance (NIT) analysis using an Infratec TM 1241 (Foss, Hillerød, Denmark). The volume weight (VW) was determined using the same Infratec instrument but with a lab-specific scale pan.

The grain yield determined from the grain samples is denoted as *point-based yield*. That yield measure does not capture any differences between sampling points that were caused by different prevalences of sowing gaps and tramlines. Therefore, yield was also determined for a zone around each sampling location using drone-based yield mapping (more details in later sections). The latter yield measure is denoted as *area-based yield*.

Soil analyses

The soil samples were dried at below 40 °C, crushed, and sieved through a 2 mm mesh. After preparation, the following analyses were conducted:

- pH in water was determined according to SS ISO 10390:2005 (SIS, 2007).
- Plant-available P, K, magnesium (Mg), and calcium (Ca) were determined by extraction in an ammonium lactate/acetic acid solution (AL-solution) according to SS 28,310 (SIS, 1993). Element concentrations were determined through Inductively Coupled Plasma Optical Emission spectroscopy (ICP-OES), according to SS-EN ISO 11885:2009 (SIS, 2009).
- Pseudo-total contents of P, K, and copper (Cu) were determined by extraction in an hydrogen chloride (HCl) solution according to KLS (1965) followed by the determination of element concentrations by ICP-OES, according to SS-EN ISO 11885:2009 (SIS, 2009).
- Soil organic matter (SOM) content was determined by a modified version of KLS (1965); 10–15 g soil was dried overnight in 105 °C, weighed, dried in 500 °C for 180 min and then weighed again after cooling. The loss on ignition was corrected depending on clay content using a lab-internal method.

Soil texture, i.e. the fractions of clay (<0.002 mm), silt (0.002–0.063 mm) and sand (0.063–2.00 mm), was determined following a modified version of ISO 11277:2020 (SIS, 2020). The clay fraction was determined using a SP2000 robotic analyser (Skalar Analytical B.V., Breda, The Netherlands). Sand was determined by wet sieving. Silt was determined as the remaining fraction once the fractions of clay and sand were determined.

Retrospect computation of target fertilizer rates

For each sampling location, retrospect target fertilizer rates were estimated. These are rates which would have been appropriate to apply based on measured values of yield, protein content, and the plant available contents of P and K in the soil.

The target N-rate was chosen to be the N-rate needed to achieve a protein content of 11.5% (often the lower limit for bread wheat) and is denoted as $N_{11.5}$. It was estimated from the applied N-rate ($N_{applied}$), expressed as kg ha^{-1} , and the measured protein content ($Protein$), expressed as percent of dry matter, according to Eq. 1.

$$N_{11.5} = N_{applied} - 71 \times (Protein - 11.5\%) \quad (1)$$

Factor 71 was derived from twelve winter wheat fertilization trials conducted in south Sweden from 2019 to 2021 (data subset: cultivar Etana and total N-rates 140, 200 and 260 kg ha^{-1}). The slope of the linear regression between $(N_{applied} - N_{11.5})$ and $(Protein - 11.5\%)$, which was forced through origo, was statistically significant ($r^2=0.90$; $p<0.001$).

Target rates of P and K, denoted as P_{rec} and K_{rec} , were computed from observed yield (tonnes ha^{-1}) and measured values of P-AL or K-AL ($\text{mg } 100 \text{ g}^{-1}$) according to Eqs. 2–3. The equations were derived from tabulated recommendations by the Swedish Board of Agriculture (2024).

$$P_{rec} = 27 - 2.2 \times P_{soil} + 3 \times (Yield - 7) \quad (2)$$

$$K_{rec} = 48 - 3 \times K_{soil} + 5 \times (Yield - 5) \quad (3)$$

Statistical analyses

Linear mixed-effects models were fitted for each response variable. Fixed-effects factors were type (levels: field and forest) and distance (levels: 8 m, 26 m and 45 m). In addition, field (levels: 1, 2, ..., 4) and transect (levels: a, b, ..., p) were included as random-effects factors, with the levels of the transect factor nested within the levels of the field factor. The residuals of the fitted models were inspected visually, but no concerning trends over the fitted values were observed. The main effects and interactions of the distance and type factors were tested. In case of a significant distance effect, pairwise tests were conducted. In case of a significant interaction between distance and type, the differences between the three distances were tested for each type and differences between the two types were tested for each distance.

In one of the transects (n), the 8 m observation plot was located on a sandy deposit. For some variables, the values for this location deviated entirely from the rest of the samples. Before the analysis, extreme outliers (values that were more extreme than the median \pm three times the interquartile range) were removed. The removed values were the contents of protein, gluten and starch in the grains, as well as the fraction of sand, all at an 8 m distance from the field edge in transect n.

All analyses were carried out using the statistical programming language R (R Core Team, 2024). The models were fitted using the *lmer* function of the lme4 package (Bates et al., 2015). Type 3 tests of fixed effects (distance, type, and their interaction) were carried out

using the *anova* function as implemented by the *lmerTest* package (Kuznetsova et al., 2017), calculating the degrees of freedom using the Kenward-Roger's approximation. The pairwise tests were done using the *emmeans* function of the *emmeans* package (Lenth, 2024).

Remote sensing

A multispectral camera (MAIA-S2 camera; Eoptis Srl, Trento, Italy) with nine bands corresponding to the bands 1–8 and 8 A of the Sentinel-2 mission (European Space Agency, Paris, France) was used. It was mounted in a fixed position on a quadcopter (Explorion XLT; Airolit AB, Gothenburg, Sweden). The remote sensing was conducted in half-way anthesis–medium milk crop development stages (Zadoks' growth stage 65–75 (Zadoks et al., 1974)). The drone missions were planned and flown using a customized version of QGroundControl (Dronecode Foundation, <https://dronecode.org/>). The flight altitude was 120 m above ground, and the speed was 9 m s^{-1} . The nine-band images were collected at a frequency of 1 Hz, with an overlap of 70% parallel to and across the flight paths. Drone data collection was conducted on June 21 and 24 under the most uniform lighting conditions possible. The flights were carried out at midday (11:30–12:30), when the sun's altitude ranged from 50° to 54° . Four $50 \text{ cm} \times 50 \text{ cm}$ near-Lambertian reflectance plates with a reflectance of 2%, 9%, 23%, and 44% (MosaicMill Oy, Vantaa, Finland) were placed on racks within the flight area.

Image processing

After co-registration of the nine bands, the images were geometrically and radiometrically corrected using the MAIA camera software (MultiCam Sticher Pro 1.1). The radiometric correction was done using data from an incoming light sensor, which continuously recorded data during the flight.

The images were stitched to one raster mosaic per field (spatial resolution $\approx 6 \text{ cm}$) using the Solvi web application (<https://solvi.ag>; Solvi AB, Gothenburg, Sweden). The median digital numbers were extracted for the reflectance panels using ArcGIS Desktop (version 10.8; ESRI Inc., Redlands, CA, USA). Linear regression models between known panel reflectance values and the digital numbers extracted from the mosaics were used to calibrate each of the nine bands of the mosaic.

Drone-based yield mapping

Chlorophyll index (CI) raster maps were computed from bands 6 (red edge; 740 nm) and 7 (near infrared; 785 nm), using the equation by Gitelson et al. (2003). The CI maps were converted to yield maps for each field individually as follows: Mean CI within a radius of 4 m was extracted for each sampling point and paired with point-based yield data. The result was a table with twelve CI values and corresponding yield values. A linear regression model was fitted to the data, with yield as the dependent variable and CI as the independent variable. A dummy row for zero yield was added to the data table CI set to the 3-percentile of the CI for the field. Another linear regression model was fitted, this time to a dataset with two rows: the sample with the lowest observed CI (now called threshold-CI) and the new dummy row for zero yield. The yield map was computed from the CI raster using the first regression model for $\text{CI-values} > \text{threshold CI}$ and the second regression model for $\text{CI} < \text{threshold CI}$.

The coefficients of determination (r^2) for linear regressions between the created drone-based yield maps and the yield determined by manual harvesting were 0.29, 0.39, 0.39 and 0.56. The respective uncertainties of the two datasets, the difference in support and the uncertainty in the georeferencing of the drone mosaic, should be considered when assessing these correlations. In a previous study, similar comparisons between drone-based yields and yield determined in field trial plots had r^2 values of 0.80–0.90 (Söderström et al., 2021). The two presently used yield datasets, both have strengths and weaknesses, and it was therefore judged valuable to use both (one direct with small support and one indirect with larger support). An example of the drone-based yield map is presented in Fig. 2.

For each of the 48 sampling points, mean yield was extracted from the yield maps for an area surrounding the sampling point. The areas were derived as follows: A circle with a 20 m radius was created around the sample location. Then this circle was restricted to (clipped by) a minimum and a maximum distance from the field edge. For the 8 m samples, the yield area was clipped to be within 2–16 m of the field edge. The corresponding interval was 16–35 m for the 26 m samples and 35–60 for the 45 m samples.

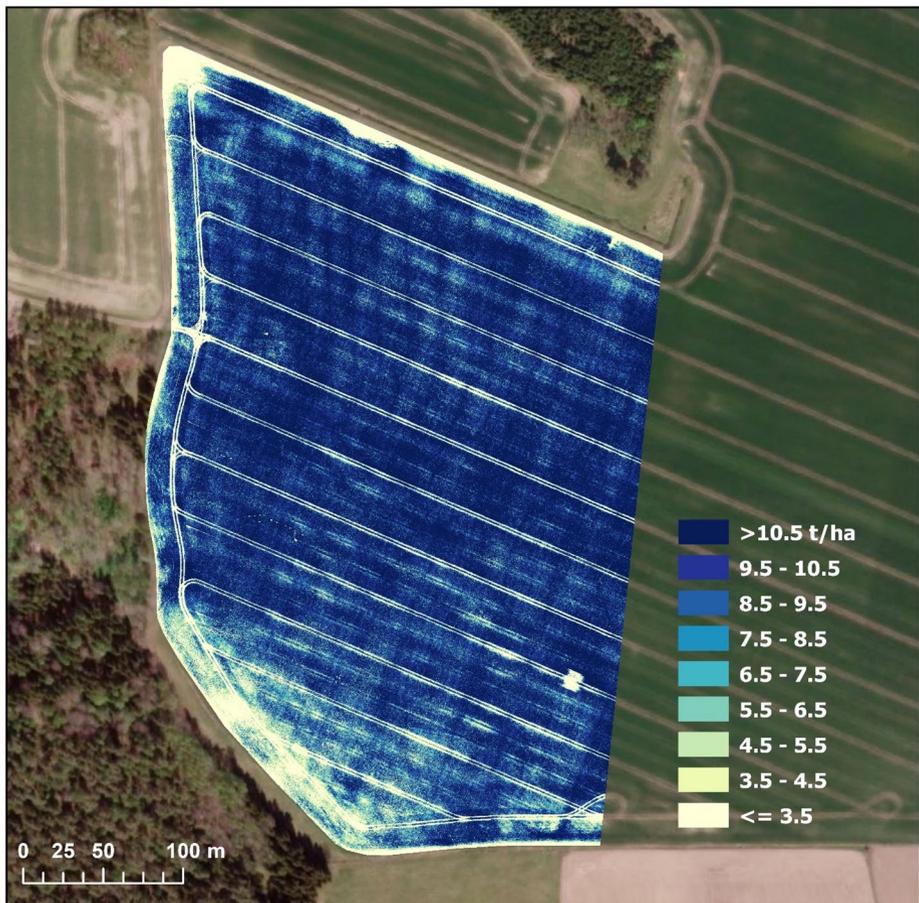


Fig. 2 Example of drone-based yield map. The map covers part of one of the project fields

Results and discussion

Descriptive statistics and differences between groups

Crop properties

Descriptive statistics of grain properties, topsoil properties and computed fertilizer rates are presented in Table 1; Fig. 3, while the results from the statistical tests of these variables are presented in Table 2. A significantly lower point-based yield was found near forest edges, and a significantly lower area-based yield was found near field edges, regardless of type of adjacent land. The lower yield near forest edges was accompanied by significantly lower TKW and VW. The percentage of chaff, and the contents of protein and gluten were significantly higher near edges, irrespective of adjacent land use, while the contents of starch was significantly lower near field edges (both types). There was a tendency of higher ergosterol content closer to both types of edge, but the trend was not statistically significant.

Table 1 Descriptive statistics (mean±standard deviation)

Variable	Field			Forest		
	8 m	26 m	45 m	8 m	26 m	45 m
<i>Grains</i>						
Yield (point) (dt ha ⁻¹)	88.1±11.3	90.2±7.9	92.8±12.4	68.1±14.5	88.6±9.1	94.9±7.0
Yield (area) (dt ha ⁻¹)	74.0±10.9	79.1±9.6	87.2±6.7	77.8±8.2	81.2±6.9	91.1±8.7
Protein (%)	12.7±0.4	12.4±0.5	12.2±0.4	12.6±0.4	12.2±0.5	12.2±0.6
TKW (g)	46.7±3.1	47.4±2.0	47.0±2.4	42.8±3.3	45.6±2.7	45.7±3.2
Gluten (%)	28.6±0.9	28.0±1.2	27.4±1.2	28.3±0.9	27.2±1.0	27.6±1.3
Starch (%)	65.5±0.6	65.9±0.9	66.2±0.7	65.3±0.8	65.9±1.1	66.0±0.9
VW (g L ⁻¹)	802±19	805±13	805±11	781±16	797±13	803±12
Ergosterol (mg kg ⁻¹)	7.2±0.7	7.1±0.4	6.9±0.6	7.4±0.5	7.0±0.7	7.1±0.3
Chaff (%)	0.37±0.15	0.31±0.07	0.28±0.05	0.50±0.18	0.41±0.15	0.33±0.12
<i>Topsoil</i>						
pH	6.9±0.4	6.9±0.3	7.0±0.4	6.8±0.4	6.7±0.4	6.9±0.5
P-AL (mg 100 g ⁻¹)	5.5±1.7	4.1±1.1	3.9±0.8	6.4±1.8	4.4±1.0	4.1±1.1
P-HCl (mg 100 g ⁻¹)	59.9±5.8	57.0±7.9	55.8±7.3	60.8±10.5	55.9±7.7	55.2±9.1
K-AL (mg 100 g ⁻¹)	10.2±2.4	8.7±2.1	9.2±1.8	11.4±2.3	9.7±1.6	9.7±1.6
K-HCl (mg 100 g ⁻¹)	193±71	199±65	199±67	185±49	186±56	194±57
Mg-AL (mg 100 g ⁻¹)	12.2±7.8	13.7±8.8	13.7±8.6	8.1±3.4	10.3±4.0	13.0±4.5
Cu-HCl (mg kg ⁻¹)	6.2±2.2	6.4±1.8	6.0±1.6	7.2±2.3	6.6±1.6	6.4±1.7
Ca-AL (mg 100 g ⁻¹)	210±55	204±46	223±44	198±64	206±60	233±68
SOM (%)	4.7±0.7	4.4±0.8	4.7±0.7	5.2±0.8	5.2±0.6	5.3±1.1
Clay (%)	18.8±11.0	18.9±9.4	16.4±8.0	14.0±6.6	17.5±8.2	16.8±9.9
Sand (%)	25.8±10.9	23.0±8.2	22.3±8.6	27.6±5.6	27.8±12.3	23.9±10.8
<i>Rates</i>						
N-rate (kg ha ⁻¹)	202±16	215±21	224±19	207±19	224±22	222±25
P-rate (kg ha ⁻¹)	20.4±4.4	24.1±3.6	25.4±4.3	14.4±3.4	22.9±3.8	25.5±3.5
K-rate (kg ha ⁻¹)	36.4±8.5	41.8±7.0	41.8±8.9	22.8±8.8	38.2±3.6	41.4±6.5

TKW=Thousand kernel weight. VW=volume weight, SOM=Soil organic Matter. N, P, and K rates are not as applied but calculated in retrospect based on crop and soil properties

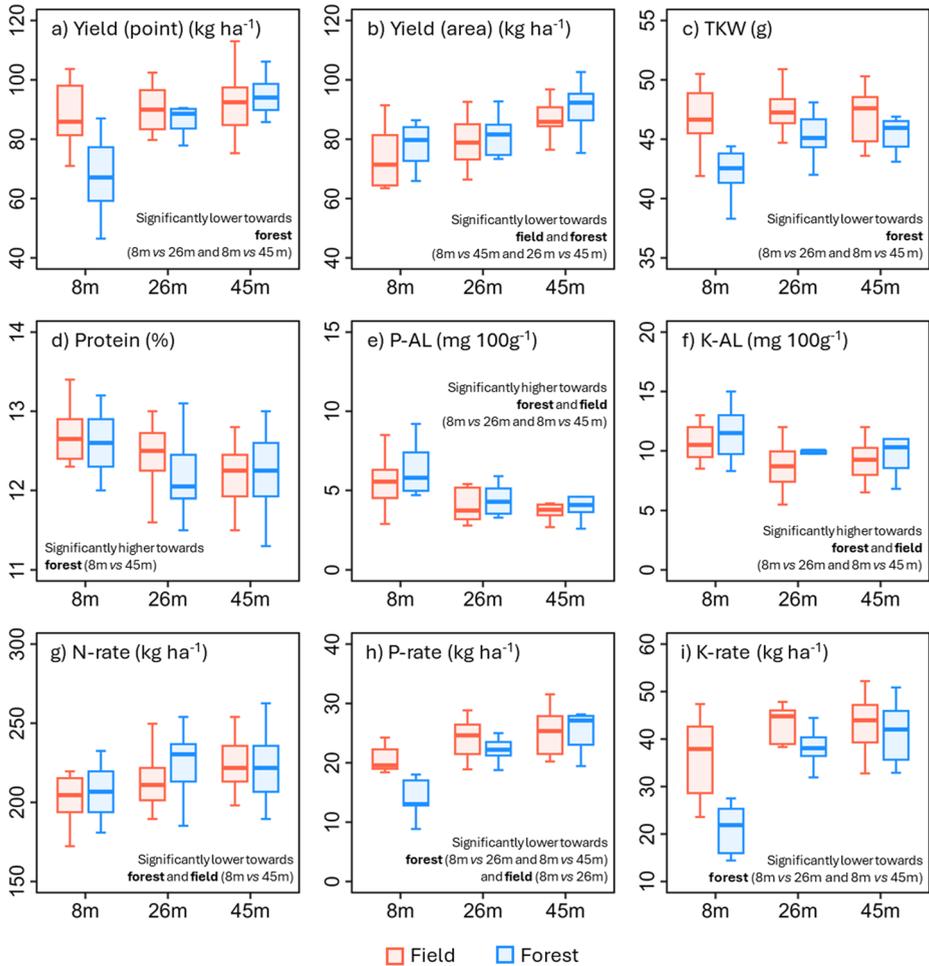


Fig. 3 Boxplots showing frequency distributions for selected variables: (a–d) results from grain analyses, (e–f) results from soil analyses, and (g–i) computed fertilizer rates. The boxes span the interquartile ranges (IQR), the whiskers span the non-outlier ranges (defined as the highest/lowest observation within 1.5 IQR from the box). Midlines show median values. TKW=thousand kernel weight. Please note that not all y-axes start at 0. Further details on statistically significant differences between groups are presented in Table 2

Soil properties

The plant-available content of P and K (P-AL and K-AL) in the topsoil were both significantly higher near edges, regardless of type, as was the pseudo-total content of P (P-HCl), but the pseudo-total content of K (K-HCl) showed no statistically significant differences. The plant-available content of Mg (Mg-AL) was significantly lower in the observation plots closest to the field edges, and the content of sand was significantly higher in these plots. The other tested soil properties (Cu-HCl, Ca-AL, SOM, Clay and pH) were not statistically different between groups.

Table 2 Results from the two-way analyses

Variable	Main effects			Pairwise comparisons											
	Type	Dist	Dist × Type	Field and forest ^a			Field ²			Forest ²			26m ²	45m ²	8m ²
				26 m vs. 45 m	26 m vs. 8 m	45 m vs. 8 m	26 m vs. 45 m	26 m vs. 8 m	45 m vs. 8 m	26 m vs. 45 m	26 m vs. 8 m	45 m vs. 8 m	Field vs. Forest	Field vs. Forest	Field vs. Forest
<i>Grains</i>															
Yield (point)	ns	***	**	---	---	---	ns	ns	ns	ns	***	***	ns	ns	***
Yield (area)	ns	***	ns	***	ns	***	---	---	---	---	---	---	---	---	---
Protein	ns	*	ns	ns	ns	*	---	---	---	---	---	---	---	---	---
TKW	*	**	*	---	---	---	ns	ns	ns	ns	**	**	ns	ns	**
Gluten	ns	*	ns	ns	ns	*	---	---	---	---	---	---	---	---	---
Starch	ns	**	ns	ns	*	**	---	---	---	---	---	---	---	---	---
VW	ns	***	**	---	---	---	ns	ns	ns	ns	***	***	ns	ns	**
Ergosterol	ns	ns	ns	---	---	---	---	---	---	---	---	---	---	---	---
Chaff	*	*	ns	ns	ns	*	---	---	---	---	---	---	---	---	---
<i>Topsail</i>															
pH	ns	ns	ns	---	---	---	---	---	---	---	---	---	---	---	---
P-AL	ns	***	ns	ns	***	***	---	---	---	---	---	---	---	---	---
P-HCl	ns	**	ns	ns	*	**	---	---	---	---	---	---	---	---	---
K-AL	ns	***	ns	ns	***	**	---	---	---	---	---	---	---	---	---
K-HCl	ns	ns	ns	---	---	---	---	---	---	---	---	---	---	---	---
Mg-AL	ns	***	ns	ns	*	***	---	---	---	---	---	---	---	---	---
Cu-HCl	ns	ns	ns	---	---	---	---	---	---	---	---	---	---	---	---
Ca-AL	ns	ns	ns	---	---	---	---	---	---	---	---	---	---	---	---
SOM	ns	ns	ns	---	---	---	---	---	---	---	---	---	---	---	---
Clay	ns	ns	ns	---	---	---	---	---	---	---	---	---	---	---	---
Sand	ns	*	ns	ns	ns	*	---	---	---	---	---	---	---	---	---
<i>Rates</i>															
N-rate	ns	*	ns	ns	ns	*	---	---	---	---	---	---	---	---	---
P-rate	ns	***	*	---	---	---	ns	ns	**	ns	***	***	ns	ns	**
K-rate	ns	***	***	---	---	---	ns	ns	ns	ns	***	***	ns	ns	**

TKW=Thousand kernel weight, VW=volume weight, SOM=Soil organic Matter. N- P- and K-rates are not as applied but calculated in retrospect based on crop and soil properties. ns= $p \geq 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, --- = not tested

Fertilization rates

The higher protein content in the grains and the higher P-AL and K-AL in the soil suggest that the lower yields near edges were not a result of N, P or K limitations. In the fields studied, it would therefore make sense to adapt fertilizer rates to the lower yields in FEZs. The statistical tests showed that suitable N-rates and P-rates were significantly lower at 8 m from the edge in both types of edges. Also, K-rates were lower in both types of FEZs, but the difference was only statistically demonstrated in FEZs bordering forests. Based on the present results, one can apply an average of 22 kg less N, 5 kg less P and 6 kg less K per hectare of FEZ bordering open land (8 m compared with 45 m) and an average of 28 kg less N, 13 kg less P and 19 kg less K per hectare in FEZs bordering forests (8 m compared with 45 m). Expressed as percentages, the computed N, P and K fertilization rates are 9%, 19% and

13% smaller in FEZs towards other fields and 12%, 51% and 45% smaller in FEZs towards forests when 8 m rates are compared with 45 m rates.

Assuming these figures are valid for Sweden, it is possible to make an approximate estimate of the general impact this would have. In Sweden, winter wheat is produced on about 0.5 M ha, and about 10% of this area is within 10 m of a field edge. If all edges are assumed to border other fields (not forests to avoid overestimation), this means that total N and P applications could be reduced by c. 1 and 0.2 M t yearly without losing yield if the rates are reduced outside the outer tramline of the fields (for simplicity, assumed to be about 10 m from the edge). Even though these numbers are rough estimates, the calculation shows the potential importance of considering the conditions in the FEZ when determining fertilization requirement.

a) Tested in case of a statistically significant main effect of distance, but no significant interaction between distance and type. 2) Tested in case of a significant interaction. Differences between distances were tested for each type and difference between types were tested for each distance.

Edge effects on grain yield in relation to forests in different Cardinal directions

Edge effects of forests on crop yield can be expected to be different depending on the cardinal direction of the field edge. A forest in the south could be expected to cause more shadow,

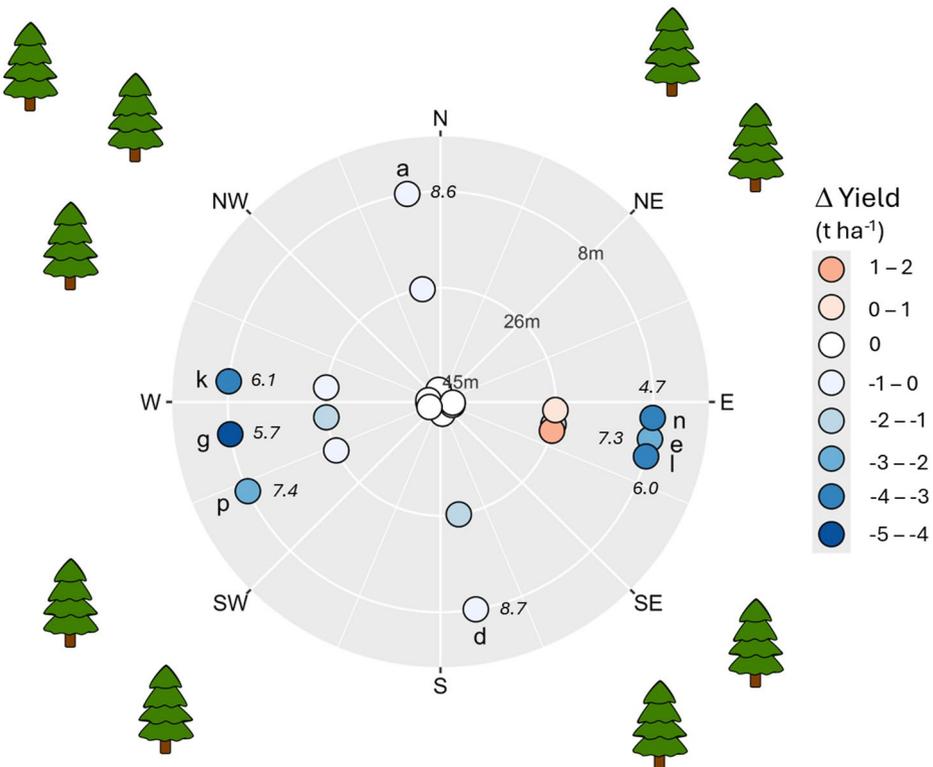


Fig. 4 Edge effects on grain yield in relation to forests in different cardinal directions. Δ Yield is the difference in yield compared to the yield at 45 m in the same transect (negative Δ Yield values mean that yield was smaller closer to the edge). The perimeter of the diagram represents the field edge. Lowercase letters indicate transect id and uppercase letters indicate cardinal direction. Italic numbers show yield ($t\ ha^{-1}$)

and a forest in the dominating wind direction would cause more shelter. Figure 4 shows yield differences (Δ Yield) between each observation plot and the yield at 45 m from the edge in the same of the eight transects. The results indicate that the forest effect on crop yield is greatest when the forest is in the west or in the east of the field, while only small differences are observed for the two FEZs with forest in the north or the south. One could hypothesise that when the forest is in the north, the negative effect on crop yield is negligible, even at 8 m from the field edge (the high yield at 8 m in transect a supports this), while the effect of the forest in the south is also substantial at 45 m (although the high yield at 8 m in transect d contradicts this). There are too few observations in the present study to draw any firm conclusions on the edge effects on grain yield in relation to forests in different cardinal directions.

Field edge effects May be caused by natural variation or crop management

Some observed differences between FEZs and field interiors are caused by natural variation and linked to the land use distribution in the landscape. For example, the higher content of sand close to forest edges may be since, in the study area (and often elsewhere), it is the lower areas with finer-textured soil that have been cultivated, while elevated landscape elements with coarser soil and till have been attributed to forests. The higher levels of plant-available P and K in FEZs are, on the other hand, likely a result of many years of lower P and K removal from the lower yields (i.e., the over application in relation to crop requirements).

The fact that the area-based yields were lower irrespective of field edge type, while the point-based yield was significantly lower only by field edges bordering forests indicates that there may be several factors contributing to the reduced yields in FEZs and that their importance differs between zone types. The point-based yield depends more on conditions directly affecting crop growth, such as microclimate and water availability, while the area-based yield is also affected by the frequency of gaps in the crop canopy caused by, for example, irregular sowing or frequent field traffic.

Low yield levels: remedy or accept and adapt to

Low yields in certain parts of a field may have different causes, as illustrated in Fig. 5. Some are temporary and some are permanent, some are local and some are regional. Many factors are manageable, immediately or over time (e.g., suboptimal soil pH or poor soil structure), while other restrictions can be regarded as fixed and cannot be affected or are not worthwhile managing (e.g., soil texture or soil depth) (e.g. Larscheid et al., 1997). In such cases, one must accept the yield level and adapt management to the prevailing conditions (e.g., adjust the nutrient rates).

In FEZs, just like in any other part of the field where yield is limited, it is essential to understand the reason for the limited crop growth before deciding on any actions. Low yields near field edges caused by soil texture (e.g., the higher sand content), competition with woody vegetation, or a greater number of tramlines or sowing gaps may be difficult to manage. In these cases, it may be a good idea to adapt N, P and K rates to the lower yield levels. In extreme cases, one can take a problem area out of production—sowing a flower strip may then be an attractive alternative.

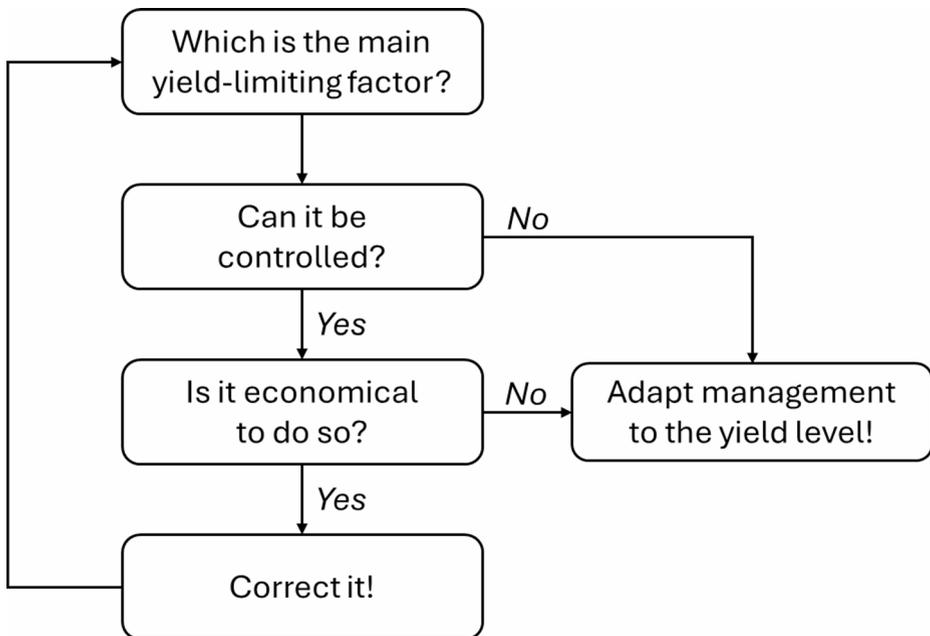


Fig. 5 It is essential to understand the reason for the limited crop growth before deciding on any action

How wide is a border zone?

How wide is a FEZ and how far into the field shall management be adapted? Raats et al. (2019) found that 95% of mid-field winter wheat yields were reached at about 11 m from mid-field islets and at about 18 m from hedgerows or forests and Wilcox et al. (2000) observed that yields of winter cereals reached a stable level at around 30 m into the field. In the present study, only three distances from the field edge were tested. Suitable fertilizer rate-reductions at 8 m from the edge were computed relative to 45 m into the fields, but rate-reductions at 26 m compared with 45 m were not computed because the differences in suitable fertilizer rates between these two distances were not statistically demonstrated (Table 2). On the other hand, the rate differences between 8 m and 26 m were not statistically significant in all cases either. Thus, the present data does not support more than a coarse assessment of a suitable width of a FEZ in which to adapt fertilizer rates, somewhere between 8 and 45 m. Extended data collection, in more fields and in transects with more than three distances from the field boundary, would be needed to gain greater insights into how far into the field crop and soil conditions are affected in this type of agricultural landscape. When determining the width of a FEZ in which to adapt fertilizer rates, one needs to be pragmatic and to make practical considerations.

Environmental relevance of the results

Avoidance of excess fertilization means a reduced risk of nutrient pollution of surface waters and less residual nitrogen in the soil available for denitrification and nitrous oxide emission. Delin and Stenberg (2014) showed that nitrate leaching in a Swedish cereal increased

exponentially when site-specific optimal N rates were exceeded, and Karlsson Potter et al. ((Karlsson 2022)) simulated a 15% decrease in nitrous gas emissions by site-specific N optimization in Swedish fields. When it comes to phosphorous, Börlling et al. (2004) showed that the accumulation of P in agricultural soils, caused by excess fertilization, increased the risk of P leaching to surface waters; they demonstrated exponential — but soil-specific— relationships between potential P release and soil-test P content in long-term field trials. This relationship has been confirmed by later studies (Svanbäck et al., 2013). It can therefore be considered important to avoid excess nutrient use, with site-specific fertilization in FEZs contributing to the achievement of international and national environmental goals, including the Farm to Fork Strategy in the European Green Deal, which aims to reduce nutrient losses (especially P and N) to the environment by 50%, with a first goal of 20% by 2030, while securing nutritious and affordable food for every person (EU, 2023).

Options for guidelines

The results indicate that there is scope to save on N, P and K fertilizer without losing yield by adjusting rates in FEZs. Continued data collection is recommended for well-founded guidelines to be made on how to adapt fertilization to the special conditions in FEZs. There are several possible tiers of recommendations for N, P and K rates in FEZs. These include:

- I. **Experience-based reductions** in the form of a simple reminder to give the FEZs some extra thought and to adjust fertilizer rates based on experience, such as knowledge of constantly low-yielding FEZs.
- II. **Tabulated reductions** in zones within a certain distance or bordering a certain land use. This type of simple recommendation can easily be followed manually or implemented in decision support systems for variable-rate applications; rates can be automatically reduced in a buffer zone along the edge when the user ticks a box.
- III. **Site-specific reductions** based on, for example, soil sampling, soil sensor measurements or drone-based yield maps. All field edges are different. If tabulated adjustments are found to be too coarse, one could instead develop recommendations for how to design and use soil sampling and crop measurements in border zones, which can be used to tailor adjustments.

Options for precision fertilization in FEZs

For the practical implementation of precision management in FEZs, it would be easiest for the farmer if a reduction in fertilizer rates could be done automatically in the system that generates prescription files – with possibilities to manually adjust as needed. To be able to vary the adjustment depending on the type of FEZs, the system must be able to distinguish between parts of fields that border open land, or forest. This type of topological relationships can be a challenge to implement. An example N topdressing prescription map generated by a satellite image-based decision support system is shown in Fig. 6. Field margins bordering open land and forest are marked, in this case the FEZ is 20 m wide. According to the results in this study, the reduction of N along the borders could be around 10% (9% adjacent to open land and 12% adjacent to forest), without affecting the yield. P-rates and K-rates are commonly varied in relation to inter-

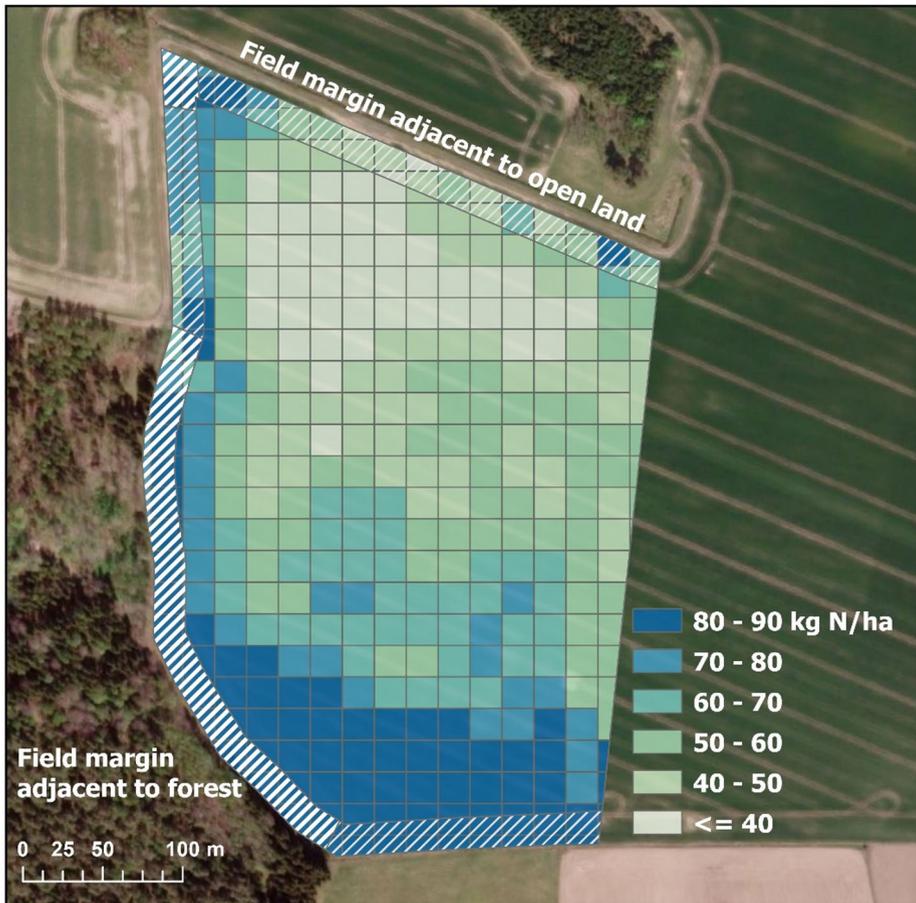


Fig. 6 An example nitrogen topdressing prescription map with field edge zones marked. The area covers part of one of the project fields

polated maps of plant-available P and K determined in soil samples and the rate-reductions in the FEZ can be made to the prescription maps in the same way exemplified in Fig. 6.

Further research needs

This pilot study was conducted on two farms managed by the same estate and is therefore limited. Further, it only tested one crop; more observations would be needed to support any special management recommendations in FEZs. Such a study should cover a larger proportion of Sweden's arable land, as well as more different types of FEZs (e.g. turning/non-turning headlands, forest/open land, till/no-till systems).

Conclusions

The present pilot study indicates that there is reason to adapt N, P and K rates along field edges. Grain yield was generally lower, but grain protein content was higher and the levels of plant-available P and K in the soil was higher close to field edges compared to field interiors. The magnitude of the observed differences would justify lower rates of N, P and K by 22, 5 and 6 kg ha⁻¹ in field margins bordering open land, and 28, 13 and 19 kg ha⁻¹ in field margins bordering forests. It should be noted that the smaller K-rate near edges facing open land was not statistically significant. Theoretically, a general reduction of N- and P-rates by 22 and 5 kg ha⁻¹, respectively, within 10 m of the field edge in Swedish winter wheat production would mean that 1 megatonne of N and 0.2 megatonnes of P could be saved without losing yield. It is recommended that further observations are made to support possible recommendations for adapted and/or improved methods for the mapping of soil and crop properties for fertilization in border zones.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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