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Estimation of economic and environmental potentials of variable rate versus uniform N fertilizer application to spring barley on morainic soils in SE Norway

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Abstract Spring barley was grown for 4 years (2001–2004) in field trials at two sites on morainic soil in central SE Norway, with five N level treatments: 0, 60, 90, 120 and 150 kg N ha^{-1}. Regression analyses showed that a selection of soil properties could explain 95–98% of the spatial yield variation and 47–90% of the yield responses (averaged over years). A strategy with uniform fertilizer application of 120 kg N ha^{-1} (U_{N120}) was compared with two variable-rate (VR) strategies, with a maximum N rate of either 150 kg N ha^{-1} (VR$_{\mathrm{N150}}$) or 180 kg N ha^{-1} (VR$_{\mathrm{N180}}$). These strategies were tested using either Norwegian prices (low price ratio of N fertilizer to yield value; P$_{\mathrm{N}}$/P$_{\mathrm{Y}}$), or Swedish prices (high P$_{\mathrm{N}}$/P$_{\mathrm{Y}}$). The VR$_{\mathrm{N180}}$ strategy had the highest potential yield and net revenue (yield value minus N cost) at both sites and under both price regimes. Using this strategy with Norwegian prices would increase the profit of barley cropping as long as at least 40 and 31% of the estimated potential increase in net revenue was realized, respectively. Using Swedish prices, uniform application appeared to be as good as or even better economically than the VR methods, when correcting for extra costs of VR application. The environmental effect of VR compared with uniform application, expressed as N not accounted for, showed contrasting effects when using Norwegian prices, but was clearly favourable using Swedish prices, with up to 20% reduction in the amount of N not accounted for.

Keywords Environmental impact · Fertilizer strategy · Net revenue · Price ratio effect · Spatial Variation · Variable N rate · Yield · Yield response

Introduction

The basic hypothesis for precision agriculture is that the optimum rates of inputs to a crop vary spatially within a field (Lark & Wheeler, 2003). Varying N rates between or within fields is often said to improve both farmers' profits and the environment.

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The profitability of site-specific fertilization has over the years been tested for a range of crops, such as seed potato (Watkins, Lu, & Huang, 1998), sorghum (Yang, Everitt, & Bradford, 2001), spring wheat (Walley, Pennock, Solohub, & Hnatowich, 2001), winter barley (James & Godwin, 2003), maize (Koch, Khosla, Frasier, Westfall, & Inman, 2004), citrus (Zaman, Schumann, & Miller, 2005) and soybean (Lambert, Lowenberg-DeBoer, & Malzer, 2006). Spring barley is the most widely grown cereal in Norway. The work of Carr, Carlson, Jacobsen, Nielsen, and Skogley (1991) is widely regarded as pioneering in increasing the profitability of barley cropping through spatially variable rate (VR) application of fertilizer (James & Godwin, 2003). Basing the VR fertilizer strategy on soil information (by dividing the field into soil units) they found additional returns in two out of five fields (\$ 54 to \$ 59 ha^{-1}) compared with a strategy of uniform field treatment. Wibawa, Dludlu, Swenson, Hopkins, and Dahnke (1993) also found that VR-application of fertilizer increased the yields of barley as compared with uniform fertilizer application, but not sufficiently to compensate for the increased costs associated with the variable strategy. Reviewing nine published field research studies on VR fertilizer application, Swinton and Lowenberg-DeBoer (1998) found that profitability results correlated closely with the gross revenue earning potential of the crop. Thus VR fertilizer application was profitable in sugar beet, sometimes profitable in maize, and unprofitable in wheat and barley. In Denmark, Friis and Knudsen (1999) found potential profits of 5–21 € ha^{-1} (40–166 DKK ha^{-1}) for variable rate application of N to spring barley.

There are few published studies which provide data on the environmental effect of a VR fertilizer strategy. Ferguson et al. (2002) measured reduced residual NO_3–N in the 0.9 m root zone after maize cropped with a VR fertilizer strategy in three out of 13 site years, compared with a uniform treatment. Simulating different fertilizer strategies for seed potatoes with the EPIC growth model, Watkins et al. (1998) reported that variable rate application of fertilizer gave about the same N losses as the uniform strategy. However, some studies indicate indirectly that a VR fertilizer strategy may have an improved impact on the environment. Koch et al. (2004) found that a VR strategy in maize consistently reduced the total N fertilizer by 6–46% compared with uniform management. Zaman et al. (2005) reported a 38–40% saving in fertilizer costs when variable N rates were applied to a citrus grove. To our knowledge, the environmental benefit of using a VR fertilizer strategy for spring barley cropping has not previously been tested.

The success of VR fertilizer strategies appears to be largely dependent upon a range of factors, such as soil properties and the price ratio of fertilizer N to yield value (P_N/P_Y ratio) of the specific crop. This ratio is relatively high in Norway compared to that in the EU-region (and the global market), mainly due to cereal prices being about twice those in the EU. The high price level in Norway is a result of national agricultural policy and may be affected by the current negotiations (the Doha agenda) of the World Trade Organization (WTO, www.wto.org).

The objectives of this study were (i) to measure within-field variation in spring barley yield levels and responses to N fertilizer on a soil typically used for spring barley cropping, (ii) to establish whether such variability follows a similar pattern from year to year, (iii) to relate within-field variations in yield and N response to measurable soil properties, (iv) to test the ‘precision agriculture hypothesis’ of whether variable rate N application would give economic and environmental benefits in spring barley cropped in SE Norway, and (v) to test how the results in (vi) would be affected by an increase in the P_N/P_Y ratio to the level in EU.

Material and methods

Experimental sites

Field trials with spring barley (*Hordeum vulgare* L., cv. Ven) were performed at two sites in SE Norway, Apelsvoll and Kise. Apelsvoll Research Centre (60°42′ N, 10°51′ E, 250 m asl) is located on the western shore of lake Mjøsa, and Kise Research Station (60°46′ N, 10°48′ E, 130 m asl) is located on its eastern shore. Both sites have a mean annual precipitation of around 600 mm, a mean annual temperature of 3.6°C and a mean growing season (May–September) temperature of around 12°C. The experimental area at Apelsvoll slopes 3–6% eastwards, is on imperfectly drained brown earth (Gleyed melanic brunisoils, Canada Soil Survey) with dominantly loam and silty sand textures (see Table 1 for details). That at Kise is gently undulating and has a range of soils from imperfectly drained brown earth (Gleyed melanic brunisoils, Canada Soil Survey) to humified peaty gley (Terric Humisol, Canada Soil Survey).

Experimental design

The field trials (10.5 × 160 m) consisted of 20 replicate blocks, each containing seven 1.5 × 8 m plots, with fixed location over all years. The sites were selected so as to maximize soil variation between blocks and to minimize it within replicate blocks. Five N level treatments were applied within each block: 0, 60, 90, 120 and 150 kg N ha^{-1} (designated N0, N60, N90, N120 and N150, respectively), with N given as calcium ammonium nitrate at sowing. The treatments were randomized between the five middle plots of each block,

Table 1 Selected soil properties of the experimental sites at Apelsvoll and Kise, respectively

Soil properties[a]	Apelsvoll			Kise		
	Mean	SD	Range	Mean	SD	Range
Gravel (0–0.25 m)	72.2	27.0	105	72.4	36.3	125
Gravel (0.25–0.6 m)	81.2	31.1	103	73.7	36.2	131
Sand (0–0.25 m)	570	42.2	163	442	64.5	180
Sand (0.25–0.6 m)	562	50.0	200	404	85.1	250
Silt (0–0.25 m)	307	17.1	51.0	364	36.2	120
Silt (0.25–0.6 m)	303	18.3	50.0	402	45.4	140
Clay (0–0.25 m)	123	31.2	117	194	34.7	110
Clay (0.25–0.6 m)	137	44.7	160	194	72.1	210
EM_H (shallow signal)	7.45	1.43	5.40	6.56	1.36	6.44
EM_V (deep signal)	9.68	1.67	6.30	7.68	0.95	4.40
Ignition loss (0–0.25 m)	50.9	11.8	43.5	123	54.1	167
Ignition loss (0.25–0.6 m)	50.9	17.6	49.0	466	38.6	138
Initial N_{min} (0–0.25 m)	11.7	1.85	6.30	20.9	5.99	19.4
Initial N_{min} (0.25–0.6 m)	9.20	2.76	7.50	10.9	6.74	23.7
CEC (0–0.15 m)	11.8	2.40	10.1			
pH (H_2O) (0–0.15 m)	5.68	0.22	0.90			
Organic C (0–0.25 m)	18.3	3.12	12.0			
Total N (0–0.25 m)	1.42	0.25	0.85			

Means, standard deviations (SD) and range

[a] Units: Gravel given in g kg^{-1} bulk soil, EM_H (apparent soil electrical conductivity, EC_a, measured with EM38 in horizontal mode) and EM_V (EC_a measured with EM38 in vertical mode) in mS m^{-1}, initial N_{min} (NO_3-N and NH_4-N measured at the beginning of the experiment) in mg kg^{-1} fine earth (<2.0 × 10^{-3} m), CEC (cation exchange capacity) in cmol$_c$ kg^{-1}, and other components in g kg^{-1} fine earth

while the border plots on either side of the blocks received 120 kg N ha^{-1}, thus giving three plots per block with N120. Phosphorus and potassium were band-placed before sowing each spring (21.5 kg P ha^{-1} and 73.1 kg K ha^{-1}, given as PK compound fertilizer). Plant protection (herbicides, fungicides and insecticides) was carried out according to the current practice. The straw was removed from the field after harvest each year.

Measurements

Soil samples were taken in 2001 at two depths (0–0.25 m and 0.25–0.6 m) from each replicate block and analyzed for particle size, ignition loss and mineral N content (extraction with 1 N KCl (1:5 w/w), NO_3–N and NH_4–N determined colorimetrically by Aquatec 5400 Analyzer, Tecator, Sweden). At the same time, the apparent electrical conductivity of the soil (EC_a) was measured on all replicate blocks, using a magnetic dipole soil conductivity meter (EM38, Mississauga, ON, Canada; www.geonics.com). The device was operated manually by placing it directly on the ground in both horizontal and vertical modes, denoted EM_H and EM_V, respectively. At Apelsvoll, the topsoil samples were additionally analyzed for total-N, organic C, pH, P-AL (AL denotes the ammonium lactate/acetic acid mixture used for extraction, Égner, Riehm, & Domingo, 1960), Mg-AL, Ca-AL, Na-AL, K-AL, K-HNO_3 and the apparent bulk density of disturbed soil. Prior to sowing/fertilizing in 2003, a new set of topsoil samples (0–0.15 m) were taken from each replicate block at Apelsvoll, extracted with 1 M ammonium acetate, and exchangeable Ca^{2+}, K^+, $Mg^{2+}$and Na^+ were analyzed spectrophotometrically (ICAP 1100, Thermo Jarrell Ash Corp, US). Exchangeable H^+ was determined by titration (NaOH) and CEC was calculated as the sum of the five cations.

At maturity, a plot harvester was used to harvest 6.5 × 1.5 m plots between the sprayer tramlines. Grain yields were corrected to 15% (w/w) moisture content. Nitrogen contents were calculated from crude protein values measured by near infrared reflectrometry (INFRA 250, Technicon, US), assuming 16% N in the barley grain protein. Due to a malfunctioning sowing machine in 2002, the results from this year were excluded from the dataset.

Statistics and calculations

The statistical software package MINITAB (Release 14.13, MINITAB inc., www.minitab.com) was used for basic statistics (correlations), variance analysis (ANOVA) and linear regression analysis (stepwise selection, $\alpha = 0.15$). p-levels < 0.05 were regarded as significant.

Three alternative N response functions for yield were compared, a quadratic function (Q), a Mitscherlich function (Cerrato & Blackmer, 1990) and a linear-plateau function (LP):

$$\text{Q} \quad Y = a + bN + cN^2 \tag{1}$$

$$\text{M} \quad Y = d - (d - a)e^{-bN} \tag{2}$$

$$\text{LP} \quad Y = a + bN \quad \text{if} N < N_1 \tag{3}$$

$$a + bd \quad \text{if} N \geq N_1$$

where Y is yield, N is nitrogen fertilizer, a represents the response without fertilizer ($N = 0$), b is the slope at the origin, c is the quadratic component (function Q), d is the response when N tends to infinity (functions M and LP) and N_1 is the fertilizer level at which the linear-plateau function switches from a linear increase to a plateau.

In order to test whether soil information could be used to predict yields and N responses over a continuous range of N, the parameters in each function were fitted simultaneously to the data by minimizing the squared residuals between measured and estimated three-year-mean yields for each replicate block, using the Nelder-Means algorithm in MatLab 7.0.0 (MathWorks Inc., www.mathworks.com). After optimization, the residual mean square error (RMSE) was calculated for each set of measurements and estimates and the function with the lowest total RMSE (RMSE summarized over all replicate blocks) was selected to represent all the replicate blocks. The quadratic function gave the best overall fit at both locations (mean RMSE $= 2.2$, $\text{SE}_{\text{RMSE}} = 0.20$, mean $R^2 = 0.98$, $\text{SE}_{\text{R-square}} = 0.003$). Data which could not be fitted satisfactorily (here defined as RMSE > 10) by the quadratic function, were removed. This was necessary in one case at Kise. The fitted parameters of the quadratic function, a, b and c (Eq. 1), were then used as dependent variables in regression models, using all the measured soil properties as potential predictors. The resulting models thus provided a method to estimate the parameters of the quadratic function for each replicate block, based on the available soil information. The ability of this indirect approach to estimate yields was then tested by comparing measured yields with yields calculated by evaluating the quadratic function using parameters estimated from the soil properties. The yield responses for N (both measured and estimated) were calculated from the corresponding yields, by subtracting the yield obtained at one N-level from the yield obtained at that above, divided by the difference in applied N.

When applying the multiple regression models, the predictors were checked for multicolinearity by calculating the variance inflation factors (VIF). The VIF should not exceed 10 in order to avoid serious problems (Montgomery & Peck, 1992), and only variables with VIF < 10 were allowed as predictors in the same regression model.

In addition, a more direct, but discrete approach to link soil information to yield and N-response was tested. Here linear regression models using all the measured soil properties as potential predictors were fitted separately for each fertilizer level (or fertilizer increment) to the measured three-year-mean yields (or three-year-mean response to N) of each replicate block and site.

The three N response functions (Eqs. 1–3) were also used to calculate the economic optimum fertilization rate (N_{opt}) for each replicate block and year. To do so, the parameters in each function were fitted simultaneously to the data by minimizing the squared residuals between measured and estimated yields for each replicate block and year, as described above. Data which could not be fitted satisfactorily (here defined as RMSE > 10) by any of the three response functions, were removed. This was necessary in one case at Apelsvoll and four at Kise, out of the total of 120 cases (20 replicate blocks × three years × two sites).

The economic optimum fertilization rate was then calculated as the rate at which the marginal cost of N fertilizer equals the marginal revenue:

$$N_{\text{opt(Q)}} = \frac{[(P_{\text{N}}/P_{\text{Y}}) - b]}{2c} \tag{4}$$

$$N_{\mathrm{opt(MI)}} = -\frac{\ln\left[P_{\mathrm{N}}/P_{\mathrm{Y}}b(d-a)\right]}{b} \tag{5}$$

$$N_{\mathrm{opt(LP)}} = N_1 \qquad \text{if} P_{\mathrm{N}} \geq bP_{\mathrm{Y}}, \text{else} \quad N_{\mathrm{opt(LP)}} = 0 \tag{6}$$

where P_{N} is the price of fertilizer N (set to 1.070 € kg N^{-1} for 21–4–10 compound NPK fertilizer, which is the most commonly used fertilizer for barley in Norway), P_{Y} is the price of barley (set to 0.226 € kg^{-1}, which was the price in Norway in 2005) and a, b, c and d are the same as in Eqs. 1–3.

Based on the calculated N optima, the corresponding yields were estimated for each replicate block and year using the respective function chosen. The resulting pairs of optimum fertilizer rate and yield may be regarded as the 'theoretical' potential for a fertilizing strategy with variable N-rates (VR). In some cases, where the yields increased substantially up to the highest fertilizer level, the calculated N optima became unreasonably high and a maximum rate had to be chosen. Based on the measured yield levels and the Norwegian fertilizer recommendation scheme (Riley, Hoel, Kristoffersen, & Tandsæther, 2002), the maximum recommended N rates would be about 150 kg N ha^{-1}. In practice, however, some farmers tend to have very optimistic yield expectations, and rates larger than the recommendations are not uncommon. We thus tested both a regime based on realistic yield expectations and recommendation guidelines (maximum N-rate set to 150 kg N ha^{-1}: VR$_{\mathrm{N150}}$), and a regime that is representative for farmers who tend to operate with higher N-rates (maximum N-rate set to 180 kg N ha^{-1}: VR$_{\mathrm{N180}}$). These two strategies were compared with a strategy with uniform fertilizer rates of 120 kg N ha^{-1} (U_{N120}), chosen to represent typical farmer practice in the region.

Price levels are generally high in Norway, especially those of cereals, the price for barley being about twice that in Sweden. To test the effects of changes in the price level, we ran the same three scenarios (U_{N120}, VR$_{\mathrm{N150}}$, and VR$_{\mathrm{N180}}$) using a Swedish price level (P_{N} = 0.747 € kg N^{-1}, P_{Y} = 0.090 € kg^{-1}).

The apparent fertilizer recovery (AFR) was calculated as

$$\mathrm{AFR} = \left[(N_{\mathrm{grain}} + N_{\mathrm{straw}})_{\mathrm{N}_x} - (N_{\mathrm{grain}} + N_{\mathrm{straw}})_{\mathrm{N0}}\right]/N_x \tag{7}$$

where subscript N_x indicates fertilizer level (estimated for VR$_{\mathrm{N150}}$, and VR$_{\mathrm{N180}}$), and N_{grain} and N_{straw} are the N removed by grain and straw, respectively, calculated using Eq. 8, derived from a trial on similar soil by Riley, Laubo, and Abrahamsen (1996):

$$(N_{\mathrm{grain}} + N_{\mathrm{straw}}) = 1.336N_{\mathrm{grain}} + 0.019N - 3.81 \quad [\text{units : kg N ha}^{-1}] \tag{8}$$

From an environmental point of view, it is of interest to obtain information about how much of the applied fertilizer which is unaccounted for (i.e. not removed by the crop), since this N is partly prone to losses. Hence, the amount of unaccounted N ($N_{\mathrm{unaccounted}}$) was also calculated for each replicate block and year:

$$N_{\mathrm{unaccounted}} = (1 - \mathrm{AFR})N_x \tag{9}$$

Results

Within-field variation

At the zero N level (N0), there were significant yield differences between blocks ($p < 0.001$) at both Apelsvoll and Kise, with mean values of 2.27 (range: 1.52–3.15) and 2.55 Mg ha^{-1} (range: 1.28–4.49), respectively (Fig. 1). With N fertilization ($N > 0$), there were significant differences between blocks at Apelsvoll ($p < 0.001$) but not at Kise ($p = 0.312$). Corresponding mean values with fertilizer were 5.70 (range: 3.47–8.28) and 4.91 Mg ha^{-1} (range: 2.68–6.84, Fig. 1).

At both locations, all blocks had a positive yield response up to 120 kg N ha^{-1}, when averaged over years, but the mean yield response from 120 to 150 kg N ha^{-1} was negative in eight of the 20 replicate blocks at Apelsvoll and in five at Kise. The yield response between N-levels tended to correlate negatively with the yields at the lower N-level. This

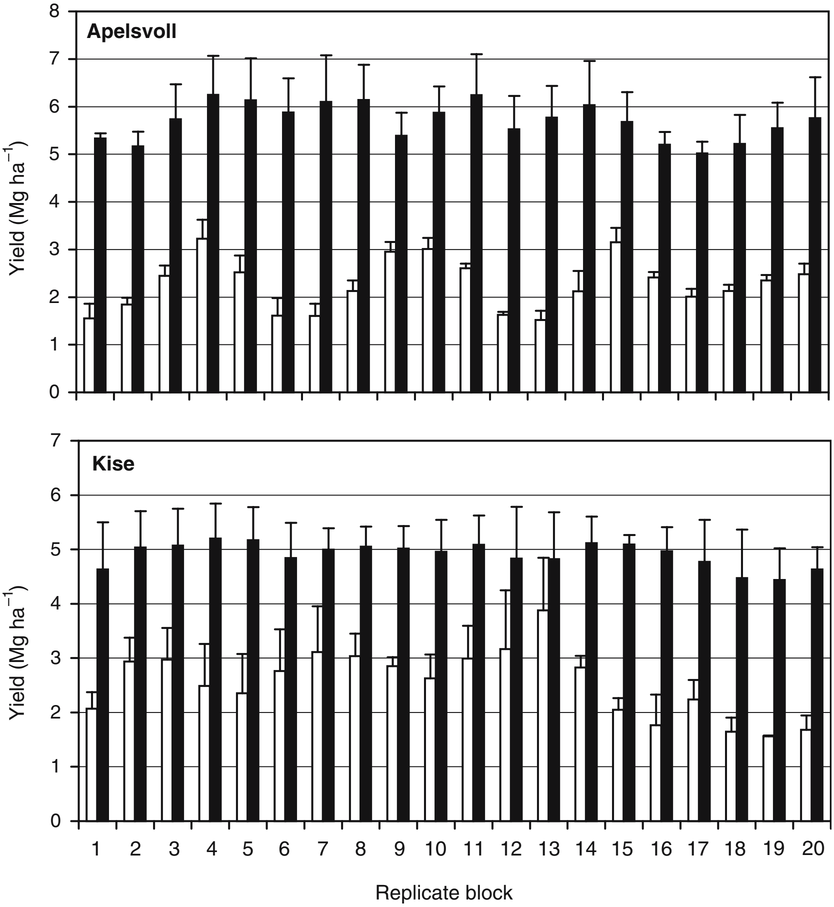

Fig. 1 Three-year yield means (2001,2003 and 2004) for unfertilized (N0; white bars) and fertilized treatments (mean of N60, N90, N120 and N150, black bars) at Apelsvoll (above) and Kise (below). Standard deviations are shown as vertical lines

correlation was significant for all steps at Kise ($0.44<|r| < 0.77$, $p < 0.05$) and from N0 to N60 ($r = -0.66$, $p = 0.001$) and from N90 to N120 ($r = -0.64$, $p = 0.002$) at Apelsvoll.

Variation between years

At Apelsvoll, the yield levels of the $N > 0$ treatments differed between years ($p < 0.001$), and the yields were on the whole larger in 2001 than in 2003 and 2004 (Fig. 2, above). There was no significant variation between years for the unfertilized plots ($p = 0.139$). At Kise, the yield levels of both the unfertilized and the fertilized plots differed between years ($p < 0.001$). As at Apelsvoll, the fertilized treatments gave the highest yields in 2001 (Fig. 2, below). At N0, 2003 was the best year at Kise, with an average yield close to 3 Mg ha^{-1}.

There were significant effects of year on the yield responses from N0 to N60 and from N120 to N150 ($p < 0.001$) at Apelsvoll and at all fertilizer steps at Kise ($p < 0.004$). At Apelsvoll, there was in 2001 a tendency to decreased yield response at the highest N-step. A quadratic function best described the yield response to N fertilizer on half of the replicate blocks. Such a decrease was not so common in 2003 and 2004, when the

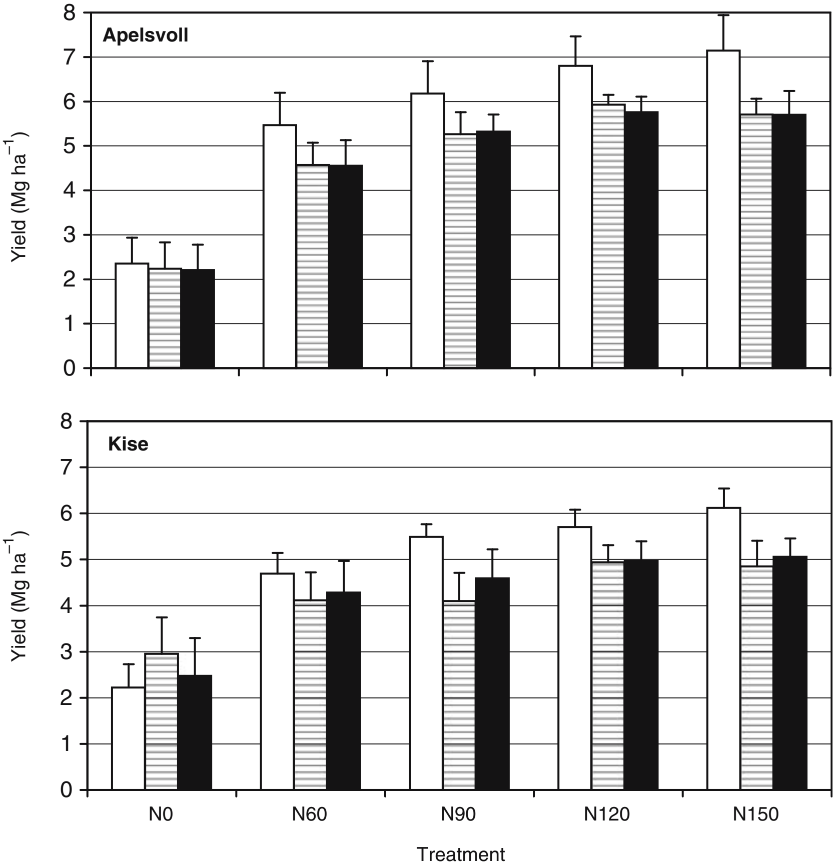

Fig. 2 Mean yields at Apelsvoll (above) and Kise (below) in 2001 (open bars), 2003 (hatched) and 2004 (filled). Standard deviations are shown above the bars

non-decreasing functions (Mitcherlich's and Linear-Plateau) dominated. At Kise, the non-decreasing functions dominated in all 3 years, particularly in 2001, when the quadratic function was selected for only two blocks.

Effects of soil heterogeneity on yields and yield responses

The parameters of the quadratic response function fitted to the three-year-yield means by minimizing the squared residuals could all be estimated by means of multiple regressions using selected soil properties as predictors. At Apelsvoll, 71, 81 and 90 % of the variation in the parameters *a*, *b* and *c* could be explained by regression models, using 3, 5 and 5 predictors (soil properties), respectively. At Kise, the corresponding degrees of explanation were 63, 76 and 61 %, obtained by using 1, 4 and 4 predictors, respectively. All predictors contributed significantly to the regressions.

The resulting parameter set (i.e. the parameters *a*, *b* and *c* of the quadratic function as estimated from the regression models) was then used to estimate the average (three-year-means) yield for all fertilizer levels at each replicate block and site. There were significant relationships between estimates and measurements for all fertilizer levels at Apelsvoll, whereas at Kise, these was found for the N0 and the N60 treatments only (Table 2, indirect approach). For yield responses, as calculated directly from the yield data, significant relationships between measured and estimated could be obtained at all but the second highest fertilizer increment (90–120 kg N ha^{-1}) at Apelsvoll and at the two lowest at Kise (0–60 and 60–90 kg N ha^{-1}). When pooling all data, 89–90% of the variation in yields and 62–73% of the variation in yield response could be described using this indirect approach.

The direct approach, where yields and yield responses were estimated directly by regression models calibrated to the measurements at each fertilizer level (and fertilizer increment in the case of yield responses), using soil properties as predictors, resulted in yield estimates closer to the measurements than those obtained with the indirect approach (Table 2). Using this method, 95–98% and 47–86% of the variation in measured yields and yield responses, respectively, could be explained by the estimates (Fig. 3).

At Apelsvoll, the yields of the two extreme treatments (N0 and N150) were estimated poorly (by the direct approach), whereas at Kise the yields of the zero-treatment (N0) was estimated best (by both methods). For the yield response, the direct approach tended to be better at Apelsvoll, whereas the indirect approach resulted in better predictions at Kise. Regardless of method, the yield response to the lowest fertilizer increment (0–60 kg N ha^{-1}) was best estimated at Apelsvoll, whereas the increment above (60–90 kg N ha^{-1}) was best estimated at Kise (Table 2).

Comparison of fertilizer strategies

The chosen response functions generally fitted the yearly yield data very well (mean RMSE = 2.8, $\mathrm{SE}_{\mathrm{RMSE}} = 0.19$, mean $R^2 = 0.98$, $\mathrm{SE}_{\text{R-square}} = 0.005$). At Apelsvoll, quadratic functions fitted data best in 22 cases, Mitcherlich's functions in 17 and the linear-plateau functions in 20 cases. The corresponding numbers of cases at Kise were 14, 27 and 15.

When averaged over years, the variable-rate approaches ($\mathrm{VR}_{\mathrm{N150}}$ and $\mathrm{VR}_{\mathrm{N180}}$) suggested that increased yields could be obtained at both locations and under both price regimes (Table 3), compared to the uniform approach (U_{N120}). The increase appeared to be higher at Kise than at Apelsvoll and this difference was more pronounced using Norwegian prices. The strategy with highest maximum N rate ($\mathrm{VR}_{\mathrm{N180}}$) showed the highest yield

Table 2 Relations between measured and estimated three-year-mean yields and yield responses for N at Apelsvoll and Kise, respectively, expressed as adjusted degree of explanation (R^2_{adj}). All available soil information was considered in the estimation process, and both a direct and an indirect approach were tested

N-level	Apelsvoll						Kise					
	Yield			Yield response			Yield			Yield response		
	Direct[a]	Pr[b]	Indirect[c]	Direct[d]	Pr	Indirect[e]	Direct	Pr	Indirect	Direct	Pr	Indirect
N0	0.704	5	0.678	0.775	6	0.745	0.873	3	0.586	0.509	1	0.585
N60	0.859	3	0.732	0.187	1	0.198	0.313	1	0.263	0.549	3	0.598
N90	0.799	3	0.328	n.s.[f]		n.s.	0.385	1	n.s.	0.168	1	n.s.
N120	0.905	3	0.180	0.454	3	0.383	0.364	1	n.s.	n.s.		n.s.
N150	0.592	1	0.224				0.247	1	n.s.			
All[g]	0.983		0.899	0.861		0.734	0.949		0.892	0.466		0.615

[a] Yields estimated by linear regression models, which were calibrated separately for each fertilizer level, using selected soil properties as predictors

[b] Number of predictors (soil properties) used in the regression models (direct approach)

[c] Yields estimated by a quadratic yield response function (Eq. 1), of which the parameters *a*, *b* and *c* were estimated separately by linear regression models using selected soil properties as predictors. The number of predictors used to estimate *a*, *b* and *c* was 3, 5 and 5 at Apelsvoll, and 1, 4 and 4 at Kise, respectively

[d] Yield responses estimated by linear regression models, which were calibrated separately for each fertilizer increment, using selected soil properties as predictors

[e] Yield responses calculated from the estimated yields (see[a])

[f] N.s.: non-significant regression ($p \geq 0.05$)

[g] All pairs of measurements and estimates resulting from the evaluation at each N-level were pooled, without fitting any new regression model to the data at this level

increase at both locations and under both price regimes, but there were large differences between years.

The estimated N use with the VR-strategies increased slightly compared with U_{N120}, when using Norwegian prices and averaging over years (at both locations). The opposite tendency was observed when using Swedish price levels in the calculations. Compared with the U_{N120} approach, the VR-strategies increased net revenue by an average of 20–30 € ha^{-1} at Apelsvoll and 30–39 € ha^{-1} at Kise with Norwegian prices. The corresponding increases when using Swedish prices were 8–10 € ha^{-1} at Apelsvoll and 12–14 € ha^{-1} at Kise. The VR_{N180} approach gave the highest calculated increase in net revenue, regardless of site and price regime.

The apparent fertilizer recovery was overall larger at Apelsvoll (77–81%) than at Kise (58–61%) and this was of course reflected by the smaller amounts of N unaccounted for at Apelsvoll, which were about half as high as those at Kise (Table 3). The differences in the amounts of N unaccounted for were roughly of the same magnitude, and never more than 7 kg N ha^{-1}, for all strategies at both locations, although the direction of the changes varied.

At Apelsvoll, the VR-strategies tended to reduce the amounts of N unaccounted for (both price regimes), with up to 20 % reduction (VR_{N150}, Swedish prices), compared with the uniform strategy. Here, the environmental benefits of the VR approaches were slightly larger using Swedish prices compared to a Norwegian price regime, and VR_{N150} was the overall better strategy. At Kise, the VR strategies tended to reduce the amounts of N unaccounted for only under the Swedish price regime. When using Norwegian prices, the VR_{N180} strategy resulted in a 14 % increase in the amounts of N unaccounted for, compared with U_{N120}.

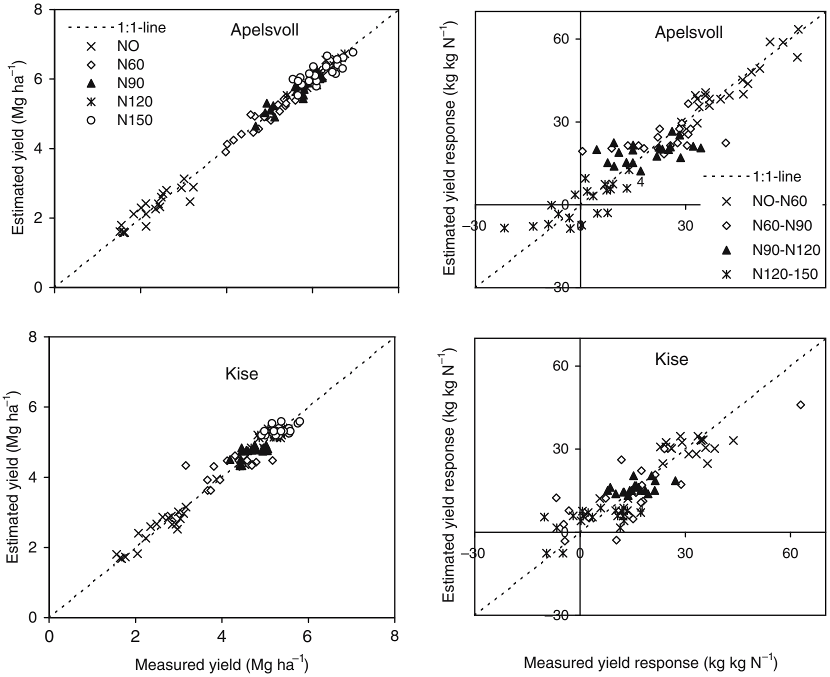

Fig. 3 Measured three-year-yield means and their estimates predicted separately for each N-level by linear regressions, using selected soil properties as predictors (left subplots), and measured yield responses for N (three-year-means) and their estimates predicted by the same method as for yields (right subplots), at Apelsvoll (above) and at Kise (below)

Discussion

The lack of significant yield differences at Kise between replicate blocks within the same cropping season was unexpected, considering the high soil variation between replicate blocks (Table 1). The lower yield level at Kise, compared to that at Apelsvoll, probably contributed to the larger dominance of year-specific factors affecting yield variation, such as weather and plant diseases.

When averaged over years, however, it could at both locations be shown that soil variation explained much of the spatial variation in yields (89–98%). Soil variation explained also a fair amount of that in yield response to N (47–86%, Table 2). Two methods of relating the soil variation to yields and yield responses were tested, one indirect and one direct approach. In the indirect approach, parameters of a response function were first fitted by means of soil property data and the parameters obtained were thereafter used to estimate yields (and indirectly yield responses). This approach performed less well than the direct approach, where the yields and yield responses were estimated directly by means of soil properties and regression models. A disadvantage of the indirect method is the propagation of errors associated with the sequential estimation procedure. An advantage, however, is that it returns continuous response functions, which can then be used to make fertilizer recommendations according to the soil variation.

A system using average yield expectations, calculated from soil properties as a basis for VR recommendations for N fertilizer, would offer an alternative where split application of

Table 3 Estimated effects of various fertilizer strategies on yield, N use, net revenue and N unaccounted for. Strategies tested were uniform application of 120 kg N ha^{-1} (U_{N120}) and variable rate application of N with a maximum rate of either 150 kg N ha^{-1} (VR_{150N}) or 180 kg N ha^{-1} (VR_{180N}). All three strategies were run with both Norwegian and Swedish prices of barley and fertilizer-N

	Norwegian prices[a]			Swedish prices[b]		
	U_{N120}	VR_{N150}	VR_{N180}	U_{N120}	VR_{N150}	VR_{N180}
Apelsvoll						
Yield (Mg ha^{-1})						
2001	6.80	7.12	7.30	6.80	7.09	7.23
2003	5.94	5.86	5.89	5.94	5.85	5.85
2004	5.76	5.79	5.84	5.76	5.77	5.80
Mean	6.17	6.26	6.34	6.17	6.23	6.30
N use (kg N ha^{-1})						
2001	120	139	155	120	134	145
2003	120	112	115	120	109	110
2004	120	113	118	120	109	112
Mean	120	122	130	120	118	122
Net revenue[c] (€ ha^{-1})						
2001	1409	1460	1484	520	535	541
2003	1214	1205	1206	443	442	442
2004	1173	1188	1194	427	435	437
Mean	1266	1286	1296	464	472	474
N unaccounted for[d] (kg N ha^{-1})						
2001	11	12	19	11	12	16
2003	34	26	28	34	24	25
2004	37	31	35	37	29	31
Mean	27	23	28	27	22	24
Kise						
Yield (Mg ha^{-1})						
2001	5.70	6.00	6.10	5.70	5.96	6.02
2003	5.02	5.03	5.13	5.02	5.00	5.08
2004	4.97	5.08	5.12	4.97	4.98	5.00
Mean	5.23	5.37	5.45	5.23	5.31	5.37
N use (kg N ha^{-1})						
2001	120	123	133	120	116	120
2003	120	126	135	120	121	128
2004	120	123	128	120	107	109
Mean	120	124	132	120	114	118
Net revenue (€ ha^{-1})						
2001	1160	1225	1237	422	448	450
2003	1006	1003	1015	361	358	360
2004	994	1016	1020	356	366	367
Mean	1057	1087	1096	381	393	395
N unaccounted for (kg N ha^{-1})						
2001	23	22	29	24	17	20
2003	68	79	85	68	75	78
2004	59	56	59	59	46	48
Mean	49	50	56	49	44	46

[a] Norway: $P_N = 1.070$ € kg N^{-1}, $P_Y = 0.226$ € kg barley^{-1}

[b] Sweden: $P_N = 0.747$ € kg N^{-1}, $P_Y = 0.090$ € kg barley^{-1}

[c] Net revenue is here defined as yield value after subtracting the N costs

[d] N unaccounted for is calculated as N-use minus the N in the barley crop originating from the applied N (N in grain and straw corrected for N in unfertilized grain and straw from the same replicate block)

fertilizer is not an option. When the time of split application is early in the growing season (as for spring barley), such a system would provide an additional source of information. Early split application implies that a large part of the cropping season lies ahead at the time of fertilization, which reduces the value of in-season crop observations as a predictor of total nutrient demand. The results presented here indicate, however, that under the current conditions, the predicting ability of the indirect method is too poor to be used for fertilizer recommendations, particularly in the most relevant range of N rates (90–150 kg N ha^{-1}, Table 2). The direct approach appears more promising, particularly at Apelsvoll (Fig. 3). However, both methods rely on rather extensive soil sampling and analyses, as up to six soil properties were needed as predictors in the regressions (Table 2). Considering the high costs of soil analyses, it is questionable whether such methods would be of practical interest.

In this paper, a strategy with uniform fertilizer application (U_{N120}) was compared with two variable-rate (VR) strategies, with a maximum N-rate of either 150 kg N ha^{-1} ($\mathrm{VR_{N150}}$) or 180 kg N ha^{-1} ($\mathrm{VR_{N180}}$). The economic optima for the VR strategies were calculated retrospectively, i.e. the true N responses were known in advance, which is, of course, never the case in practice.

The price of N fertilizer and barley used to calculate the optima, were set according to the current level in Norway, and, alternatively, to that in Sweden. The rationale for testing two price regimes is that the Norwegian price level is very high compared to the rest of Europe (and the global market price), particularly for cereals, due to national agricultural policy. This price level may be affected by the current negotiations (the Doha agenda) of the World Trade Organization (WTO, www.wto.org). Since the price ratio of fertilizer N and crop directly affects the economic optimum fertilization rates, it is of interest to see how a change in this ratio affects the different fertilizer regimes tested here. Swedish prices were selected as an alternative since the Swedish price regime is representative of the EU-region and since Sweden is fairly comparable to Norway with regard to agricultural practice.

The VR strategies had the highest potential yield and net revenue at both sites and under both price regimes, with $\mathrm{VR_{N180}}$ as the best strategy overall. To be of practical interest, the net revenue should be larger than the costs of implementing variable rate application of fertilizer. In Norway, a system for VR is yet not commercially available, but such a service is available and widely used in Sweden. There, the extra cost of applying N at a variable rate (by local contractor) was about 12 € ha^{-1} in 2002 (110 SEK, Nissen, Gustafsson, & Söderström, 2003). Assuming such costs and Norwegian prices for N and barley in our calculations, there was a potential profit of 8–27 € ha^{-1} (averaged over years), when N was applied variably, compared to uniform application. The VR strategy would thus improve the profit of barley cropping, even at sub-optimal N rates under practical conditions, as long as the increase in net revenue surpassed the extra costs of variable N application. This was the case when 40 and 31% of that potentially attainable was realized at Apelsvoll and Kise, respectively ($\mathrm{VR_{N180}}$).

By contrast, uniform application appeared to be as good as (at Kise) or even better than the VR method (at Apelsvoll), when assuming Swedish prices corrected for the extra costs of VR application. This illustrates that increasing the price ratio of N and crop ($P_{\mathrm{N}}/P_{\mathrm{Y}}$), by reducing the price of the products more than the price of the inputs, reduces the economic potential of precision farming. These findings also indicate a larger economic potential of using a VR strategy for high-value crops, such as potatoes, compared to cereals.

In Denmark, Friis and Knudsen (1999) found potential profits of 5–21 € ha^{-1} (40–166 DKK ha^{-1}) for variable rate application of N to spring barley. By contrast, James and Godwin (2003) found no economic benefit of the VR strategy for winter barley in the UK.

The environmental aspect is not considered in the economic calculations but should nevertheless be discussed as it is of great public interest to reduce the negative environmental impacts of farming activities. In order to evaluate the environmental impact, we calculated the amount of N applied as fertilizer which was not accounted for in the N export via grain and straw (N unaccounted for). At the time of harvest, this N fraction will include the amounts of N originating from the fertilizer N, which is built into barley roots and stubbles, weeds and soil fauna, as well as that lost to the atmosphere as nitrous gases or to drainage, and that remaining in the inorganic N pool in the soil. The latter pool is highly relevant from an environmental perspective, since inorganic N left in the soil after harvest is prone to leaching during autumn and winter, as shown in numerous publications (e.g. Korsaeth, Henriksen, & Bakken, 2002). It is obvious that an increase in the fraction of N unaccounted for implies an enhanced risk for N losses to the environment.

Using Norwegian prices, there were contrasting effects of using a VR strategy compared to uniform N application on the amounts of N unaccounted for. At Apelsvoll, there appeared to be an environmental benefit for the most restrictive VR approach (VR_{N150}), which reduced the N unaccounted for by about 15% relative to that of the uniform strategy, whereas at Kise, both VR strategies resulted in an increase in N unaccounted for (2–14%).

One reason for these contrasting findings may be that the yield responses at Kise tended to be lower than those at Apelsvoll (Fig. 3). Increasing the N rates above that of the uniform strategy still paid off in many cases, resulting in a lower apparent fertilizer recovery and a higher level of N unaccounted for, compared to that at Apelsvoll. It should be noted that the level of N unaccounted for at Kise was about twice that at Apelsvoll as a result of the significantly lower yield level at Kise.

Under the Swedish price regime, the results were clearly in favour of using the VR-strategies, with reductions in N unaccounted for of up to 20 % (VR_{N150}, Apelsvoll) compared with the uniform strategy. It is uncertain how much of this reduction affects the N leaching risk but if we assume that about half of the N unaccounted for was leached, the VR_{N150} strategy would reduce N leaching by about 2.5–3 kg N ha^{-1}, compared with the uniform strategy. This is approximately 8 % of the total N leaching losses from a mainly cereal cropping system, measured in a field lysimeter at Apelsvoll (Korsaeth & Eltun, 2000).

As emphasized above, this paper shows the *potential* benefits of VR, while the results attainable under practical conditions may be expected to be less favourable. To be able to realize this potential, a crucial requirement will be to find a robust method to measure variation in crop and growth conditions and to use this information to optimize fertilizer rates. This area of research is receiving much attention at present; particularly multi- and hyper-spectral canopy reflectance analyses appear to be a promising approach (e.g. Lukina et al. 2001).

Conclusion

The ‘precision agriculture hypothesis’, that varying N rates would both increase farmers’ profit and benefit the environment, appears to be highly dependent on both location and price level. A higher price ratio of fertilizer N to yield value appears to reduce the profitability of varying the N rates but it increases the environmental benefit. This emphasizes that more focus should be put into research on VR strategies applied to high-value crops, such as vegetables, which often pose high environmental risks due to high fertilizer rates.

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