AGRICULTURAL AND FOOD SCIENCE

Agricultural and Food Science (2024) 33: 164–174

https://doi.org/10.23986/afsci.143565

Optimum N-rate and effect of split N fertilization timing on yield and quality in spring oat varieties

Lena Engström, Sofia Delin, Anders Jonsson, Syed Rehmat Ullah Shah and Johanna Wetterlind

Department of Soil and Environment, Swedish University of Agricultural Sciences, 532 23 Skara, Sweden

e-mail: lena.engstrom@slu.se

Split nitrogen (N) application to oats delays final decisionson total application rate, which could help achieve the economic optimum fertilization rate (OptN) and reduce nitrogen losses. Later topdressing allows adjustment of fertilizer level at a stage when it is easier to predict nitrogen supply from soil. The objectives were: to investigate whether topdressing can be applied after stem elongation and to assess effects on yield and quality in different oat varieties; and to study the variation in optimum N-rate and the possibility to predict and readjust it during the growing season. In 14 field experiments conducted in Sweden 2020–2022, the effect of split nitrogen application, with topdressing at growth stage (GS) 32, GS45, or GS55–61, on yield and quality in six different oat varieties was evaluated. Late topdressing increased grain protein concentration and decreased fat content, but variety was more important for target quality. Compared with a single early application, late topdressing did not affect yield significantly. Year and site influenced yield and quality, similarly for all varieties, but had an impact on the effect N-treatment had on protein. A multiple regression analysis showed that yield at OptN and N-uptake in unfertilized plots at GS31–47, can explain the variation in OptN and thus be used to estimate OptN. Topdressing as late as at GS45–61 increased the chances both of higher protein and more accurate prediction of OptN. Therefore, recommendations for late topdressing can be preferable if there is a target for high protein or if there are incentives to use crop sensors for late and accurate adjustments of N fertilization rates between and within fields. The recommendations should not be dependent on variety.

Key words: oats, fat content, protein concentration, topdressing, sensor-measures, N-uptake, N-yield

Introduction

Oats (*Avena sativa* L) is currently Sweden's third largest cereal and production is increasing to supply new markets, such as substitutes for rice and dairy products. With this growing importance, a better basis for fertilizer recommendations for oat crops is justified. So far, fertilizer recommendations for oats in Sweden have largely been based on spring barley, and applied to different oat varieties and different quality demands. In Swedish spring oats, nitrogen (N) is currently mainly applied at sowing, with an optional topdressing shortly after crop emergence. Methods using crop sensor data or satellite information to optimize the fertilization rate, as used in other cereals, have not yet been calibrated for oats. Based on previous Swedish experiments on oats, N fertilizer can be split into two doses, with the second applied at stem elongation (growth stage GS32–37), without affecting yield compared with applying all N at sowing (Gruvaeus 2008, Krijger 2010, Krijger 2011). One benefit of split fertilizer application is that it allows fertilizer level to be adjusted at a stage when it is easier to predict soil N delivery during the growing season (Delin et al. 2014, Walsh and Walsh 2020). Adjustment of N fertilization to current crop status within and between fields using crop sensors has been successfully performed for other cereals (Berger et al. 2020, Diacono et al. 2012, Mulla 2013). However, assessing soil N delivery at stem elongation can still be difficult (Walsh and Walsh 2020), since much of the soil N present may become available later (Delin et al. 2014). Therefore, this study investigated whether a topdressing to different oat varieties can be applied even later, at different growth stages up to panicle emergence (GS55) and flowering (GS61). Later application of N could also be expected to affect grain quality parameters. For instance, if N uptake is similar but yield is reduced, protein concentration could be expected to increase (Allman et al. 2021). If applying less N in early stages affects the number of panicles or grains, thousand-grain weight (tgw) or specific weight could be affected. Previous studies on oats have shown that increasing N fertilization rate results in lower grain weight (Ma et al. 2017, Peltonen-Sainio and Peltonen 1995). However, Allman et al. (2021) found that supplying higher N rates to winter oats increased yield and grain protein content, and reduced grain fat content and volume weight, and concluded that the response of tgw to N is variety-dependent. A study by McCabe and Burke (2021) found that volume weight decreased as N rate increased in spring-sown oats, with no effect observed in winter-sown oats. Splitting N in different ways between GS30 and GS32 had no significant effect on grain yield and grain weight in autumn sown oats in a study by Finnan et al. (2019). However, little is known about the effect of timing of split N application to spring oats and the impact of site and year is seldom explained. Using oats as a substitute for dairy products has led to increased

Received 23 February 2024 / Accepted 28 May 2024
The Scientific Agricultural Society of Finland

demand for high protein content in oat grain. Consequentlythere is a need to further test the possibility to push for extra-high protein content in oats by increasing the N application rate and applying a larger proportion of the N at later growth stages. The main aim of this study was therefore to examine: 1) the effect of split N applications on yield and different quality parameters in spring oats depending on variety, site, and year; 2) the optimum N-rate for different oat varieties; and 3) the possibilities to predict optimal N-rate at different growth stages.

Materials and methods

Field trial design

Four experiments per year were conducted at three sites in south-west Sweden (Götala 58°22’N, 13°29’E, Multorp 58°21’N, 12°37’E, Lanna 58°20’N, 13°7’E) in 2020, 2021, and 2022. The soil type was sandy loam at Götala, silty clay loam at Multorp, and silty clay at Lanna. The sowing date was mainly around 15 April, but varied from 3 April at Götala in 2020 to 22 April at Lanna in 2022. The preceding crop was winter wheat or spring oats at all sites and in all years. The experiments had a split-block design, with four oat varieties in large plots with four replicates, and with nine (2020) or 10 (2021 and 2022) fertilizer treatments in subplots within each large plot. The selected varieties were a classic variety (Belinda) used as reference in variety testing for many years, one of the currently most popular varieties (Galant), one special variety with higher fat content (Fatima), and a variety with large yellow grains and the potential for being more commonly grown (Lion in 2020, Delfin in 2021 and 2022). The reason for changing from Lion to Delfin was that it was feared that Lion would be excluded from Swedish oat production, and Delfin was an established variety with similar characteristics. Five (2020) or six (2021 and 2022) fertilizer treatments with different N levels from 0 to 190 kg N ha^{-1}, applied at sowing, were used to study yield response and calculate economic optimum N rate (OptN) for the different varieties. The 190 kg N ha^{-1} treatment was added in 2021, since OptN in 2020 was higher than expected. The 100 kg N ha^{-1} (NPK 22-6-6 with 13.2% ammonium-N and 8.4% Nitrate-N) treatment applied at sowing was compared with split application, with 70 kg N ha^{-1} at sowing and 30 kg N ha^{-1} as calcium nitrate at stem elongation (GS32), booting (GS45), or panicle emergence (GS55). The 100 kg N ha^{-1} level was chosen for this comparison, since it was expected to be slightly below OptN, and therefore provided the possibility to see differences in fertilizer use efficiency between application times that could have been masked if excess amounts of nitrogen had been applied. The 130 kg N ha^{-1} at sowing treatment was compared with split application of 70 kg N ha^{-1} at sowing and 60 kg N ha^{-1} at GS32. At one of the sites (Lanna), the experiment was duplicated with half the replicates irrigated shortly after topdressing if there was no or very little rain in the weather forecast. In statistical analyses, this experiment was treated as two separate trials (Lanna and Lanna$_{irrig}$). Irrigation amount in 2020 was 25 mm (12 and 15 June), in 2021 it was 15 mm (18 and 23 June), and in 2022 it was 15 mm (20 June).

To investigate the possibility of maximizing protein with even later topdressings and high total N rates (190 and 220 kg ha^{-1}) two additional field trials, which we refer to here as “High-protein trials”, were performed at Lanna and Mulltorp in 2022. In these, 100 or 130 kg N ha^{-1} were applied early at sowing and additional applications were made at GS45 and GS61, resulting in total N-rates of 190 kg N ha^{-1} (130+60 and 100+60+30) and 220 kg N ha^{-1} (130+60+30; 100+90+30; 100+60+60). The varieties were Belinda and two high-protein varieties, Armstrong and Active.

Yield measurements and grain analyses

At harvest, yield was measured with a combine harvester in 13.6 m^2 large plots and 500 ml samples of grain were taken. The grain samples were analyzed in the laboratory for N, fat, and protein concentration, using near infrared transmission (NIT) spectroscopy. Thousand-grain weight (tgw) was measured using a Contador 2, 5-Channel seed counter, (PFEUFFER GMBH, Germany). Moisture content was measured and yield adjusted to 15%.

Optimal N rate, N uptake, and sensor measurements

Grain yield was plotted against N fertilization rate in the treatments with different N fertilization rates. Second-order polynomials were fitted to these scatter-plots. The grain yield response curves were then used to estimate OptN by identifying the value at which the slope of the curve equaled the price ratio of grain to fertilizer, which was set to 8.0 based on prices during the previous 10-year period. Differences in OptN between varieties, sites, and years were tested statistically with one-way ANOVA, followed by Tukey comparison test (Minitab18, Ltd., Coventry, UK).

To estimate soil N supply during the growing season, the crop was cut (2×0.25 m^2) in the unfertilized treatment but also in treatments with 70, 100 and 160 kg N ha^{-1}, for all varieties in each plot at GS31–32 and GS43–47. Crop samples were dried at maximum 55 °C and then N-concentration was analyzed and N-uptake calculated. To investigate whether the variation in OptN-rate could be explained by expected yield (yield at OptN used) and N-uptake in unfertilized plot at GS31–32 or GS43–47, regression analysis were performed (Minitab18, Ltd., Coventry, UK). At the same time, all plots were scanned using the handheld version of the Yara N-sensor® (Yara Gmbg, Hanninghof, Germany; as described by Reusch 2005) to see whether its index (S1) for estimating N-uptake in winter wheat could be used to estimate N-uptake in oats and thereby facilitate predictions of OptN and variable rate applications within fields. The S1-index is calculated based on 730 and 760 nm (Reusch 2006). Linear regression models were calibrated to analyze the relationship between sensor data and N-uptake. In order to use N-uptake in unfertilized plots for estimation of OptN, it had to have a good correlation with final soil N delivery. This was investigated by comparing N-sensor measurements at the two different growth stages with final N-yield in the unfertilized plots. A regression model including OptN-yield and final N-yield in unfertilized plots (Nyield0N) was also calibrated.

Statistical analysis

Differences in grain yield and in quality parameters between treatments with different times of topdressing application were tested statistically with one-way ANOVA, mixed effects model, followed by Tukey comparison test (Minitab, Ltd., Coventry, UK). In the model, blocks were treated as random effect and N-treatment, variety, site, and year as fixed effects. To analyze the effect of split and no split applications in the 100 and 130 kg N ha^{-1} treatments, all interactions for variety (year, site and N-treatment) and N-treatment (year, site and variety) were also included in the model.

Results

Weather

Spring 2020 was cool and dry, followed by a rainy summer (Fig. 1), resulting in many green shoots. In 2021, there was a rainy period during May, followed by a hot summer, and the crop at Götala, where biomass was high after the moist period in spring, was particularly affected by the hot temperatures. In 2022, conditions were very favorable, with well-timed rainfall for crop growth and no extreme temperatures.

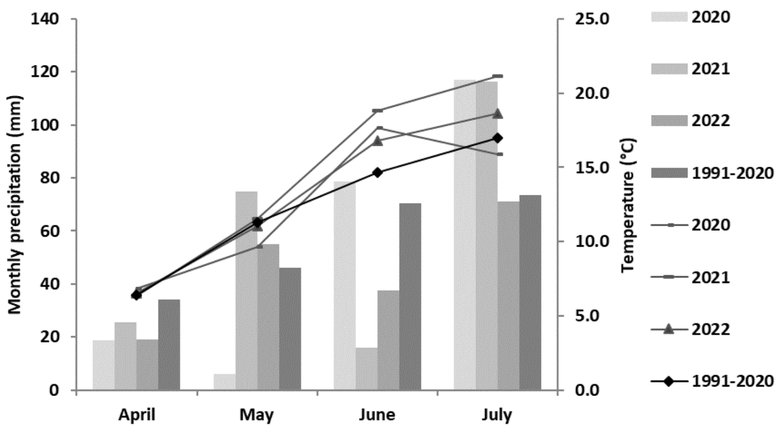

Fig. 1. Monthly accumulated precipitation and average temperature at Lanna research station, 2020-2022, and long-term average for the period 1991–2020

Impact of variety on effects of split N application

Statistical analysis revealed no interactions (*p*-value: 0.34–0.99) between variety and N treatment for yield and quality, when comparing split application with no split at 100 kg N ha^{-1}. On average for the varieties, yield was similar between the N treatments, but there was a small tendency for a yield decrease with topdressing at GS32–GS55 compared with one single application (Table 1). The effect of split application at 100 kg N ha^{-1} was mainly apparent in grain protein content and was significantly higher for all split applications compared with one single application. Higher protein content was also obtained with later topdressings at GS45 and GS55 than at GS32. As a consequence of the tendency for lower yield and higher protein in the topdressing treatments, there were no significant differences in N yield. Grain fat content was affected in the opposite way to protein, and tended to be reduced with later topdressing. There was a small tendency for higher tgw with later split application, but specific weight was not affected.

Split application at a higher N rate (130 kg ha^{-1}) had a similar effect on yield and quality as at the lower N-rate (100 kg ha^{-1}). Increasing N fertilization rate (from 70 to 190 kg N ha^{-1}) increased yield and also the protein content in oat grain, but reduced the fat content, specific weight, and tgw (Table 1). However, the effect of fertilization rate or N-strategy on fat content, specific weight, and tgw was negligible compared with differences between varieties (Table 1). Comparing the varieties in the 100 kg N ha^{-1} treatments, Fatima had lower yield, tgw, and specific weight, but higher grain protein and fat content, than the other varieties (Table 1, Fig. 2). Belinda had higher yield and N yield than the other varieties. Delfin/Lion had the highest tgw and, together with Galant, the highest specific weight. The quality of the varieties agreed well with their documented properties described by the suppliers.

Table 1. Effect of increasing N-rate and split nitrogen (N) application on grain yield (15% moisture content) and quality in four oat varieties. The split application treatments comprised total N-rates of 100 N ha^{-1} and 130 kg N ha^{-1}, with all N (100 or 130 kg ha^{-1}) applied at sowing compared with 70 kg ha^{-1} applied at sowing and 30 or 60 kg ha^{-1} at growth stage GS32, GS45, or GS55. Results from 12 field trials in Sweden, 2020–2022. Different letters indicate significant differences between mean values at $p < 0.05$ as calculated by Tukey's least significant difference test.

N treatment	At sowing	Yield		Protein		N yield		Specific weight		Fat		Tgw[1]	
kg N ha^{-1}	+ top dressing	t ha^{-1}		%		kg N ha^{-1}		g l^{-1}		%		g	
0	0	3.2	e	11.0	f	48	f	526	c	6.28	bc	38.0	a
70	70	5.8	d	11.1	f	88	e	539	a	6.43	a	37.6	abc
100	100	6.4	c	11.4	e	99	d	537	ab	6.37	ab	37.4	bcd
100	70+30 GS32	6.3	c	11.8	d	100	d	534	ab	6.33	abc	37.3	cd
100	70+30 GS45	6.3	c	12.0	c	102	d	536	ab	6.26	bc	37.9	abc
100	70+30 GS55	6.2	c	12.1	c	101	d	536	ab	6.23	c	38.0	a
130	130	6.7	b	12.0	cd	108	c	534	ab	6.32	bc	37.3	cd
130	70+60 GS32	6.7	b	12.4	b	113	b	534	ab	6.25	c	37.3	cd
160	130+30 GS 32	7.0	a	12.4	b	116	ab	532	bc	6.27	bc	37.0	d
190	130+60 GS 32	6.9	ab	12.8	a	120	a	532	abc	6.28	bc	37.0	d
	p-value:	<0.001		<0.001		<0.001		<0.001		<0.001		<0.001	
Average for 100 kg N ha^{-1} treatments:													
Variety													
Galant		6.2	c	11.4	c	96	c	543	a	5.1	c	36	c
Delfin/Lion		6.5	b	11.6	b	102	ab	546	a	5.1	c	43	a
Belinda		6.6	a	11.7	b	105	a	526	b	6.3	b	38	b
Fatima		5.8	d	12.6	a	98	c	521	c	8.7	a	33	d
p-value:		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001	
Year													
2020		6.1	b	11.4	b	94	b	522	b	6.3	b	36.9	b
2021		5.4	c	12.3	a	90	b	519	b	6.1	c	35.5	c
2022		7.4	a	11.8	b	118	a	566	a	6.5	a	40.6	a
p-value:		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001	
Site													
Götala		6.4	a	12.2	a	105	a	539	ab	6.3	a	38.8	a
Lanna		5.9	a	12.1	a	96	a	532	bc	6.3	a	36.2	b
Lannairrig		6.5	a	12.0	a	106	a	523	c	6.2	a	36.9	b
Multorp		6.3	a	11.0	b	95	a	548	a	6.3	a	38.8	a
p-value:		0.1-071		<0.001		0.032		<0.001		0.533		<0.001	

[1] Thousand grain weight

Impact of year and site on variety performance

Year and site had an impact on yield and quality of the varieties in the 100 N ha^{-1} treatments, with interactions as described below (Fig. 2). In all years, yield was in the order (high-low) Belinda > Delfin/Lion > Galant > Fatima, which agreed with the order for OptNYield (Table 2). There was a difference in yield between years, where in 2021 and 2022 only Fatima was significantly different from the other varieties, but in 2020 there were differences between all varieties. In all years, the order for protein content was (high-low) Fatima >Belinda >Delfin/Lion >Galant, which agreed with protein content at OptN (Table 2). However, in 2020 and 2021 only Fatima had significantly different protein content from the other varieties, while in 2022 Galant had a significantly lower protein content than all other varieties. Fatima also had a higher fat content than the other varieties in all years and Belinda had a higher fat content than Galant and Delfin/Lion. The fat content was lower in 2021 than 2022 for all varieties except for Belinda. In every year, there were significant differences between all varieties in tgw, in the order Delfin/Lion > Belinda > Galant > Fatima. However, tgw was lower in 2021 than 2020 and 2022 for Galant and Belinda, while for Fatima and Delfin/Lion it was the same in 2021 as in 2020.

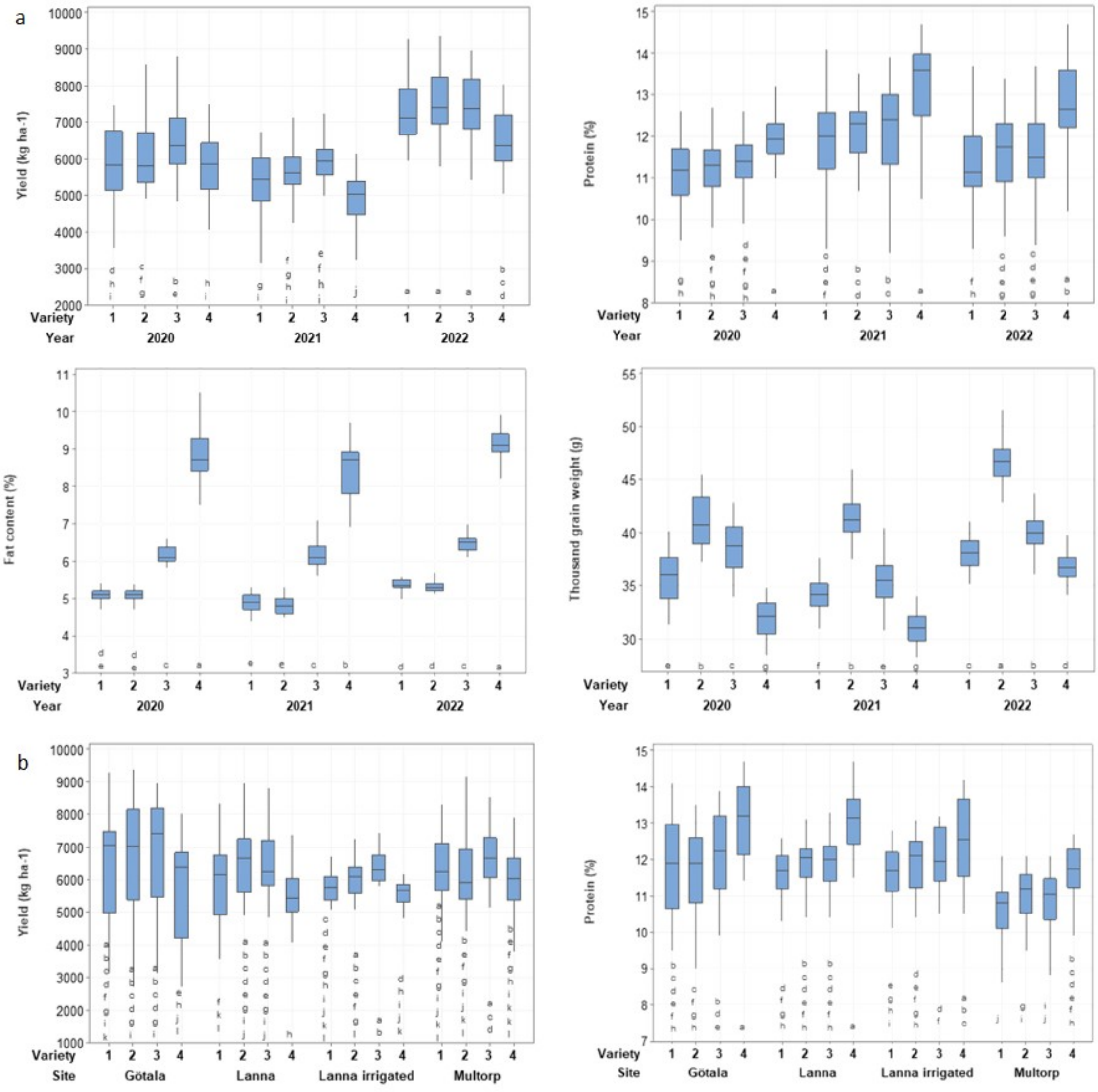

Fig. 2. Interactions (p <0.001) between variety and year (a) and variety and site (b) in spring oats for (i) yield, (ii) protein, (iii) fat content, and (iv) thousand grain weight. Four varieties (1= Galant, 2= Delfin/Lion, 3= Belinda, 4= Fatima) were grown in four N treatments comprising: all N (100 kg ha^{-1}) applied at sowing, or split application with 70 kg ha^{-1} applied at sowing and 30 kg ha^{-1} at growth stage GS32, GS45, or GS55. Results from 12 field trials at three sites, 2020–2022. Different letters above varieties indicate significant differences based on Tukey's least significant difference test (p <0.05).

At the different sites, yield of the varieties was generally in the same order as reported above for the different years. The main difference between sites was that Galant yielded the same or less than Belinda and Delfin/Lion at all sites except Multorp, where Galant, Delfin/Lion and Fatima had lower yield than Belinda. Fatima had the highest protein content at all sites. There were no differences between the other varieties at Lanna and Lanna$_{irrig}$, but at Götala Belinda had higher protein content and at Multorp Galant had lower protein content than Delfin/Lion, but similar protein content to Belinda. Fat content was in the order Fatima > Belinda > Delfin/Lion and Galant at all sites (same as for years). The only difference between sites was that Fatima had higher fat content at Götala than at Lanna, whereas the other varieties had the same fat content at all sites. Tgw was in the order Delfin/Lion > Belinda > Galant > Fatima at all sites (same as for years). All varieties had lower tgw at Lanna and Lanna$_{irrig}$ than at the other two sites, the only difference between sites being whether the decrease was significant or not.

Impact of year and site on effects of split N application

Site and year had no impact on how yield and fat content were affected by split or no split application at 100 kg N ha^{-1}, i.e., there were no significant interactions for these variables (Table 1). However, there were significant interactions for protein and tgw (Fig. 3). In all years, protein cconcentration increased with split application compared with no split. The later topdressings (GS45 and 55) increased protein more than topdressing at GS32 only in 2022. Tgw was higher with the two later topdressings in 2021 and 2022, but in 2020 there was no significant effect of any topdressing.

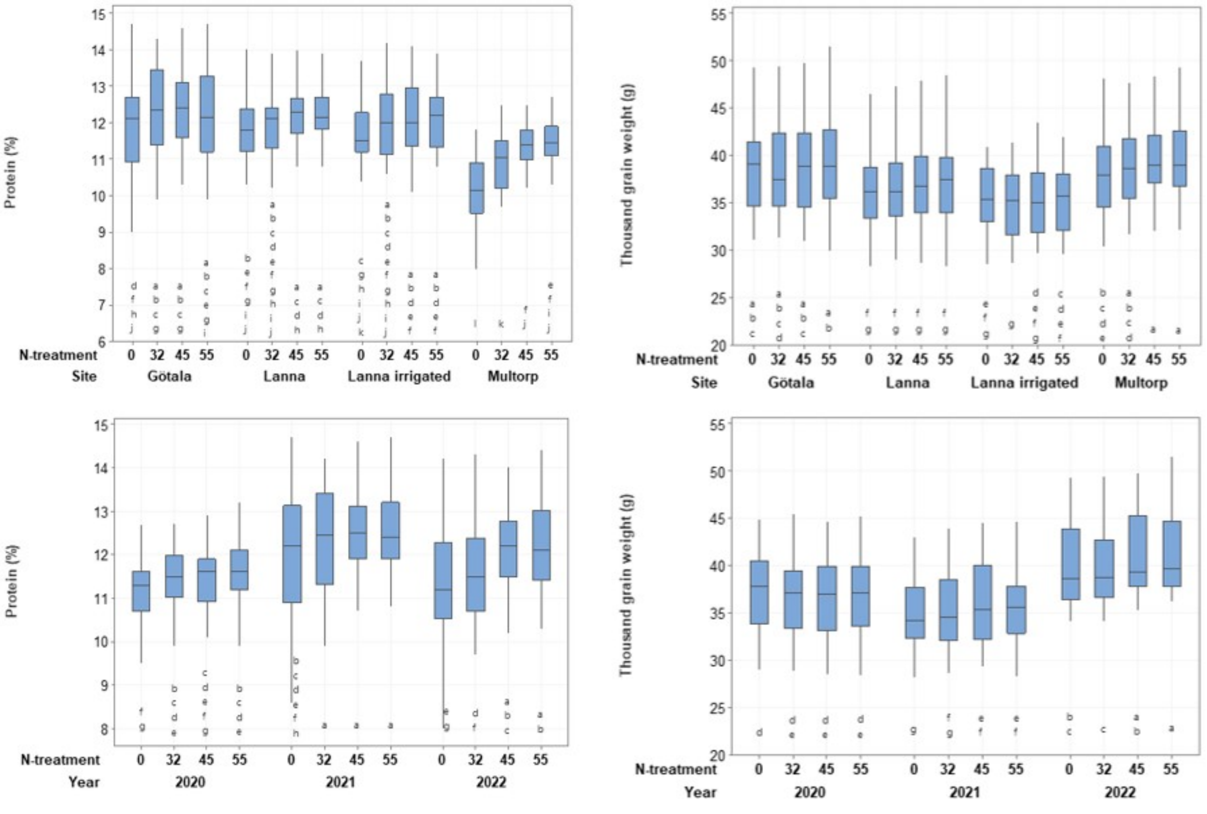

Fig. 3. Interaction between site and nitrogen (N) treatment and year and N treatment in spring oats for (i) protein (p <0.001, site and year) and (ii) thousand grain weight (p =0.013/site and p <0.001/year). The four N treatments were: all N (100) applied at sowing (0), or split application with 70 kg ha^{-1} applied at sowing and 30 kg ha^{-1} at growth stage GS32 (32), GS45 (45), or GS55 (55). Results from 12 field trials at three sites, 2020–2022. Different letters above N-treatment labels indicate significant differences based on Tukey's least significant difference test (p <0.05).

The protein concentration was significantly higher for all three split applications compared with no split at Götala and Multorp, whereas at Lanna and Lanna$_{irrig}$ it was higher for only the two later applications. At Multorp, where grain protein concentration was at a much lower level than at the other sites, the increase in protein with split applications was much higher. Tgw was higher with the later topdressings at Multorp and Lanna$_{irrig}$ but at Lanna and Götala there was no significant effect of split applications, although there was a similar trend.

Economic optimum nitrogen fertilization rate (OptN)

The OptN values differed significantly between sites and years, but not between varieties (Table 2). Multorp had the highest OptN value, on average 50–70 kg N ha^{-1} higher than the other sites. Yield at OptN was highest at Multorp and there were no differences in protein at OptN between sites. In 2020, OptN was higher and Yield0N lower than in the other two years.

The differences in OptN between sites and years were closely related to the differences in unfertilized yield, which acted as an indicator of soil N supply (the lower soil N supply, the higher the OptN value). This was confirmed by the fact that OptN was well explained (r^2=0.80) by a regression model including OptNyield and the final N-yield in unfertilized plots (Nyield0N) (regr. 1). One exception was OptN at Multorp in 2021, which was much higher than could be explained by yield and soil N supply and was therefore excluded from the regression calculation. With data from Multorp 2021 included, the r^2-value was reduced to 0.65.

Table 2. Economic optimum N-fertilization rate (OptN), yield (15% moisture content) and protein at OptN, yield in an unfertilized plot (0N) of spring oats and N yield in grain at OptN on average for sites, years, and varieties in 12 field trials in southwest Sweden, 2020–2022. Different letters indicate significant differences between mean values at *p* <0.05 as calculated by Tukey's least significant difference test.

	OptN		Yield at OptN		Protein at OptN		Yield at 0N		N yield at OptN	
	kg ha^{-1}		kg ha^{-1}		%		kg ha^{-1}		kg N ha^{-1}	
Site										
Götala	106	b	5.7	b	12.1	a	3.6	a	92	b
Lanna	127	b	5.6	b	12.3	a	2.5	b	93	b
Lanna$_{irrig}$[1]	125	b	6.2	ab	12.1	a	2.6	ab	102	ab
Multorp	178	a	6.7	a	11.9	a	2.2	b	107	a
p-value:	*<0.001*		<0.001		0.607		<0.001		0.008	
Year										
2020	156	a	6.2	b	12.0	ab	1.9	b	101	a
2021	120	b	5.1	c	12.6	a	3.0	a	87	b
2022	126	b	6.9	a	11.6	b	3.2	a	108	a
p-value:	*<0.001*		<0.001		<0.003		<0.001		<0.001	
Variety										
Galant	136	a	6.0	ab	11.7	b	2.6	a	94	a
Delfin/Lion	130	a	6.1	ab	11.9	b	2.9	a	99	a
Belinda	141	a	6.5	a	11.9	b	2.8	a	104	a
Fatima	130	a	5.5	b	12.9	a	2.6	a	96	a
p-value:	0.734		0.010		<0.001		0.691		0.207	

[1] Irrigated field trial

The variation in OptN between sites and years was also explained by crop N-uptake measured in cut crops. It was better explained in cuts at GS43–47 (r^2=0.86) than at GS31–32 (r^2=0.70), according to regression functions 2 and 3, also including OptNyield. The field trial at Multorp in 2021 was again excluded from the analysis, due to unreasonably high OptN.

OptN = 61 + 20 × OptNyield (tonnes ha^{-1}) – 1.0 × Nyield0N (kg ha^{-1}) (regr. 1)

At GS31-32: OptN= 93 + 11 × OptNyield (tonnes ha^{-1}) – 1.7 × N-uptake (kg ha^{-1}) (regr. 2)

At GS43-47: OptN= 74 + 14 × OptNyield (tonnes ha^{-1}) - 1.0 × N-uptake (kg/ ha^{-1}) (regr. 3)

N-sensor measurements

There was a good correlation between N-uptake during crop growth in the plots with different N-treatments and N sensor measurements (S1-values) (r^2= 0.76–0.79), and the correlation was similar for the four varieties (Fig. 4a) and at both growth stages (Fig. 4b). There was also a good correlation between N-sensor measurements (S1-value) on all unfertilized plots and final N-yield in these plots (Fig. 4c), indicating that measurements in zero-plots at these growth stages were also useful for predicting final soil N delivery. The correlations were fairly similar at both growth stages, but stronger at GS43–45 than at GS31–32.

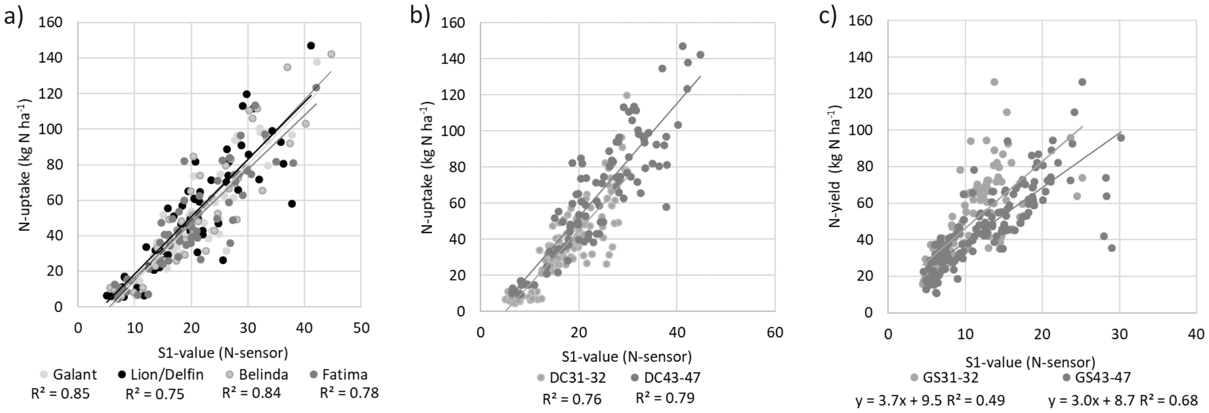

Fig. 4. Correlation between nitrogen (N) uptake and sensor values (S1, Yara N-sensor) measured at two growth stages in plots with different N treatments (0–160 kg N ha^{-1}) for different a) oat varieties and b) oat growth stages, and c) correlation between final N-yield (grain) and N-sensor measurements (S1-values) in unfertilized plots at two growth stages (GS)

High-protein trials

In the additional two field trials in 2022 with N-rates of 190 and 220 kg N ha^{-1}, aiming for high protein concentration, the protein concentration was higher on average for each variety (12.9–16.8%) than in the field trials described above with the 100 kg N ha^{-1} treatment (11.4 and 12.6 %), but yields were similar. For both sites and treatments (Table 3), Belinda had the lowest protein content (12.9–14.3%), Armstrong was intermediate (13.1–14.9%), and Active had the highest protein concentratoin (14.7–16.8%). Yield levels were significantly different between the varieties, in the order Belinda>Armstrong>Active at both sites, with 5.0-6.1 tonnes ha^{-1} at Lanna and 5.5–6.7 tonnes ha^{-1} at Multorp.

Table 3. Effect of late topdressing (oat growth stages GS39–45 and GS61) at two high N-rates (190 and 220 kg N ha^{-1}) on protein content in three oat varieties at two sites (Lanna and Multorp), 2022. Different letters indicate significant differences between mean values at p <0.05, as calculated by Tukey's least significant difference test

N-treatments	Lanna, protein (%)						Multorp, protein (%)					
(NPKS+NO_3+NO_3)	Active		Armstrong		Belinda		Active		Armstrong		Belinda	
130+60	15.9	bc	14.2	d	13.3	e	14.7	cd	13.1	e	13.3	e
100+60+30	15.7	c	14.4	d	14.3	d	15.5	abc	13.9	de	12.9	e
130+60+30	16.5	ab	14.7	d	13.2	e	15.5	abc	13.9	de	13.5	e
100+90+30	16.8	a	14.6	d	13.9	de	16.1	a	13.9	de	13.2	e
100+60+60	16.8	a	14.7	d	14.1	d	16.0	ab	14.9	bcd	13.5	e
p-value interaction:			0.081						0.009			

Neither of the field trials showed any significant effect of the higher N-rate or more N in the form of later topdressings on yield. Higher protein was expected, but the results were not clear. For Belinda, a higher N-rate had no effect on grain protein content, but at Lanna there was an effect of more N as topdressing (+1.0%). For Active, the protein content increased at the higher N-rate (+0.9%) at Lanna and a similar trend was seen at Multorp (+0.8%), but more N in later topdressings had no effect. For Armstrong, there was no significant effect of either N-rate or topdressing strategy.

Discussion

Effect of split N application

The effect of the different N strategies tested in this study on yield and quality of oat grain did not depend on variety, as there were no interactions between variety and treatment. The results showed that a second application of N to oats can be performed at GS32, GS45, or GS55 without significantly affecting grain yield, but that earlier application may be more consistent in producing high yield (Table 1).

An Irish study on autumn-sown oats also found that the timing of N application was of no importance for yield, as long as all N was applied by GS32 at the latest (Finnan et al. 2019). As long as the N is readily available to the crop, this would be expected since the period until this stage is when spikelet and panicle number is determined (Sadras 2007). Nitrogen applied at later stages affects yield more by increase in grain size, which may explain the small tendency for lower yield observed when applying a second N dose at later growth stages in the present study. Increased protein content with later topdressings (GS45 and 55) compared with earlier (GS32) is in accordance with results obtained in winter wheat (Hu et al. 2021). This could be explained by the combination of tendency for lower yield and higher nitrogen yield after fertilization at later development stages (Table 1).

Grain fat content was significantly negatively affected by later topdressing at GS45 and GS55, although the differences were very small. Humphrey et al. (1994) found similar results, with N applied at GS40–GS43 tending to increase grain protein content and decrease fat content. Future research needs to establish the effects of N-strategies on protein composition and on fat and fiber quality in relation to the contentThe ability of β-glucan (a dietary fiber abundant in oats) to reduce cholesterol depends on its molecular weight and viscosity (Lan Pidhainy et al. 2007).

Tgw, but not specific weight, was significantly increased by later topdressings. Adding more nitrogen early may have contributed to more grain sites and higher grain numbers (Browne et al. 2006) and therefore reduced grain weight compared to if top dressing was applied later, since later topdressing does not have any effect on spikelet number (McCabe and Burke 2021). In contrast, Finnan et al. (2019) found that splitting N rates of 120 and 150 kg ha^{-1} between GS30 and GS32 had no effect on yield and tgw in autumn-sown oats, although specific weight decreased when a higher proportion of N was applied at GS32 rather than at GS30. The spring oats in the present study were fertilized slightly under OptN in the split application treatments (70+30 kg ha^{-1} and 70+60 kg ha^{-1}), and the topdressing was relatively small in relation to the dose at sowing, which may explain why split application did not affect specific weight. However, there was a tendency for reduced specific weight at higher N-rates (Table 1), which agrees with findings by McCabe and Burke (2021).

When comparing the split applications in this study, it must be borne in mind that different forms of N were applied at sowing and topdressing. The nitrate-based fertilizer applied at topdressing is known for having a more rapid effect, and if an ammonium-based fertilizer had been used the topdressings might have had a smaller effect.

Impact of year and site

The interactions between varieties and years, and between varieties and sites, were of no importance, since they did not indicate any differences in what would be the best choice of variety depending on year and site (Fig. 2). The general trend was well described by the average values for varieties, sites, and years (Table 1), which also agreed well with the corresponding values for OptN (Table 2). The higher yield in 2022 compared with the other years can be explained by the very beneficial weather conditions in that year, with well-timed rainfall for crop growth, resulting in higher tgw and specific weight. The favorable weather conditions can also explain the better effect of later topdressings on yield and protein in that year (Fig. 3). The importance of water for N availability and N use efficiency was further confirmed by the increase in N yield with irrigation at Lanna (Tables 1 and 2).

The higher protein concentration in 2021 could be related to a lower yield level than in 2022. On the clay soils at Lanna and Multorp, this decrease in yield was partly related to a hard crust formationin the upper layer of the topsoil, reducing the crop emergence and number of plants, whereas at Götala it was most likely caused by hot, dry summer weather lowering the survival of yield components. The cool, dry spring in 2020 resulted in low tiller density, which can explain why the yield potential was lower than in 2022. OptN was 50 kg N ha^{-1} higher in 2020 than in the other two years, most likely due to unfavorable conditions for soil N mineralization and fertilizer N uptake in early spring, followed by heavy rains in the summer stimulating late tiller production and higher N requirement and uptake. The heavy rainfall could also have caused N losses from the soil.

Multorp had a higher OptN value than the other sites. That could be partly explained by lower soil N supply at this site, as indicated by the lower N yield of 42 kg N ha^{-1} in unfertilized plots at Multorp, compared with 46 kg N ha^{-1} at Lanna and 50 kg N ha^{-1} at Götala. However, the differences in OptN were even greater, e.g., 50 kg N ha^{-1} between Lanna and Multorp, and could not be explained by differences in yield potential. One explanation could be losses of fertilizer N. The site at Multorp is known for its very small contributions of N from the soil, perhaps due to the rather moist and compact soil structure, posing a risk of high losses through denitrification. Another explanation could be that the combi-seeder distributed the fertilizer unevenly within the plots, as the crop stand appeared lighter in color at one end of all fertilized plots compared with the other in the beginning of the season in all three years. The lower grain protein concentration at Multorp can be related to high yield in combination with low soil N supply, as explained above.

The interaction between year and N-treatment showed the importance of favorable growing conditions, as in 2022, to achieve the greatest increase in protein and a better effect of the two later topdressings than the earlier one, as well as higher N-yield than in the other years. Site had a modifying impact on the effect of the N-treatments, as seen at Multorp with a lower protein level for a single application and a higher increase in protein concentration with topdressing compared with the other sites (Fig. 2). This indicates low use efficiency of the fertilizer applied at sowing, probably related to N-losses, e.g., denitrification (as discussed above). Splitting the total N-rate meant that less N was applied in early spring, when soil moisture content can often be high and N-uptake low due to small plants, thus reducing the risk of N losses.

Estimation of OptN and adjustment during the growing season

Calculation of OptN from expected yield level and soil N delivery during the growing season was successful in oats, as seen previously for winter wheat (Engström 2010), although estimation of yield level during the season can be a challenge (but is naturally easier later in the season). The results also showed that it is possible to use crop sensors to make adjustments of N fertilization to current crop status during the growing season (N-uptake) within and between fields, as done in other cereals (Berger et al. 2020, Diacono et al. 2012, Mulla 2013).

High-protein trials

The results varied between the varieties, but showed that it was possible to increase protein concentration to 16.8% by applying a higher total N-rate to the high-protein variety Active and to 14.1–14.3% by supplying more N as topdressings to Belinda, without negative effects on yield. However, the N-rates involved were well above the OptN and would only be economically viable with extra payment for protein concentration and quality. Greatly exceeding the optimal N-rate would increase the amount of unutilized N in the soil after harvest, with associated increased risks of N losses and negative effects on the environment (Delin and Stenberg 2014, Wallman et al. 2022).

Conclusions

Different N application strategies had differing effects on yield and quality, but these effects were not variety-dependent. Late topdressing tended to increase grain protein content and decrease grain fat content, but variety had a more important effect in achieving target grain quality. Overall, the results showed that when using split N application in spring oats, the second dose can be applied at growth stage GS32, GS45, or GS55 without affecting yield and with an increase in protein content and N yield, compared with a single early application. With later topdressings (GS45 and 55), the chances of obtaining higher protein level were higher than with earlier topdressing (GS32), although there was a small tendency for yield to decline. Under favorable growing conditions the effect of later topdressings on protein content will be greater, but later topdressings can be just as good an alternative to an early single application. At sites with a high risk of N losses after a single early application, a split application is recommended.

A further increase in grain protein concentration, without negative effects on yield, was achieved but the results varied between the varieties and needs further research. Nevertheless, later topdressing is preferable since OptN can be better estimated from predicted yield level and N-uptake in unfertilized plots at later stages (GS43–47) than earlier (GS31–32). A good correlation between sensor values and N-uptake during the growing season was confirmed in this study. This makes variable rate application possible between and within fields by using e.g., crop sensors, drone images, or satellite images, which could be positive from both an economic and environmental perspective.

Acknowledgments

Our thanks to Swedish Board of Agriculture and the Swedish Foundation for Strategic Research (The Industrial Research Center ScanOats) for funding the work; Johannes Forkman for specialist advice on the statistical analyses; and Mary McAfee for language check of the manuscript.

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