Acta Agriculturae Scandinavica Section B – Soil and Plant Science, 2009; 59: 402–413

ORIGINAL ARTICLE

Importance of soil mineral N in early spring and subsequent net N mineralisation for winter wheat following winter oilseed rape and peas in a milder climate

L. ENGSTRÖM & B. LINDÉN

Department of Soil Sciences, Division of Precision Agriculture, Swedish University of Agricultural Sciences, Box 234, SE-532 23 Skara, Sweden

Abstract

Nine biennial field experiments, 2000–2004, in south Sweden, 55–56°N, with winter wheat following winter oilseed rape, peas, and oats, were used to estimate the impact of a future milder climate on winter wheat production in central Sweden, 58–60°N. The trials included studies 1) on losses during winter of soil mineral nitrogen (N_{min}, 0–90 cm soil), accumulated after the preceding crops in late autumn, 2) on soil N mineralisation (N_{net}) during the growing season of the wheat (early spring to ripeness) and 3) on grain yield and optimum N fertilisation (Opt-N rate) of the wheat. Average N_{min} in late autumn following winter oilseed rape, peas, and oats was 68, 64, and 45 kg ha^{-1}, respectively, but decreased until early spring. Increased future losses of N_{min} during the winter in central Sweden due to no or very short periods with soil frost should enhance the demand for fertiliser N and reduce the better residual N effect of winter oilseed rape and peas, compared with oats. Their better N effect will then mainly depend on larger N_{net} (from March to maturity during the winter wheat year). Owing to more plant-available soil N (mainly as N_{net}) Opt-N rates were lower after oilseed rape and peas than after oats despite increased wheat yields (700 kg ha^{-1}) at optimum N fertilisation. In addition to these break crop effects, a milder climate should increase winter wheat yields in central Sweden by 2000–3000 kg ha^{-1} and require about 30–45 kg ha^{-1} more fertiliser N at optimum N fertilisation than the present yield levels. Increased losses and higher N fertilisation to the subsequent winter wheat in future indicates a need for an estimation of the residual N effect at the individual sites, rather than using mean values as at present, to increase N efficiency.

Keywords: *Net N mineralisation, optimum N fertiliser rates, residual N effect, soil mineral N, yield increase.*

Introduction

Climate change will lead to future milder and moister winters in Sweden and in other Nordic countries (Anonymous, 2007a). These changes should influence nitrogen dynamics in agricultural soils and also affect the supply of soil N to crops. Until the late 1980s, or before climate change became obvious, cold winters with frozen soils and/or with a snow cover lasting for several months were normal in Sweden as far to the south as about 58–60°N. During the present decade, however, the ground has mainly remained bare and almost unfrozen during the winter up to 58–60°N, except for shorter periods. Until the late 1980s, frozen soils generally decreased runoff during the winter in central and north Sweden, and runoff was to a large extent concentrated to the period of snowmelt in early spring (March–April). Simultaneously a considerable surface runoff occurred on the frozen ground (Uhlen, 1978; Gustafson, 1983). This reduced nitrogen leaching (Gustafson, 1983), and soil mineral nitrogen (ammonium and nitrate N, N_{min}) frequently increased from late autumn until early spring (Lindén, 1981). In the southernmost parts (about 55–56°N) with a maritime, mild winter climate, however, considerable winter runoff in combination with the limited time that the soils were frozen provoked a more or less continuous and

Correspondence: L. Engström, Department of Soil Sciences, Division of Precision Agriculture, Swedish University of Agricultural Sciences, Box 234, SE-532 23 Skara, Sweden. Tel: +46 511 67141. Fax: +46 511 672134. E-mail: lena.engstrom@mv.slu.se

(Received 28 February 2008; accepted 10 June 2008)

ISSN 0906-4710 print/ISSN 1651-1913 online
DOI: 10.1080/09064710802282739

heavy leaching of agricultural soils (Gustafson, 1983). In recent years this leaching pattern has become common up to about 58–60°N.

The amounts of N_{min} after cereal crops normally are comparatively small in late autumn and early spring (Lindén et al., 1992). After winter oilseed rape (*Brassica napus* L.) and field peas (*Pisum sativum* L.), on the other hand, larger amounts are generally found (Jensen, 1996; Ryan et al., 2006) thus affecting the nitrogen supply to the subsequent crop more than with cereals as preceding crops. The expected milder and moister winters, however, may lead to increasing losses of N_{min} during the winter. Therefore, the soil nitrogen supply to a cereal crop, such as winter wheat (*Triticum æstivum* L.), following winter oilseed rape or peas may decrease under future Swedish conditions, thus increasing the demand for fertiliser N. Furthermore, it is not clear when the majority of the enhanced soil N supply after these preceding crops occurs or what its origin is, although in many studies increased soil mineral N and greater N uptake have been recorded on a number of occasions during cultivation of the subsequent crop (Jensen & Haahr, 1990; Heenan, 1995; Kirkegaard et al., 1997; Ryan et al., 2006). A related question is in what proportions overwintering N_{min}, compared with nitrogen mineralisation during the following growing season, contributes to the N supply for the subsequent winter wheat crop. Knowledge of the temporal course of N mineralisation during the growing season is important for determining the timing of N applications.

Moreover, climate change will increase yields in Sweden. Therefore, the question is how changed soil N dynamics and increased yields in central Sweden will influence the economically optimum nitrogen fertilisation rate (Opt-N rate) to winter wheat following the mentioned preceding crops. Winter oilseed rape and peas are known as effective break crops due to a number of separate positive effects on yield potential of winter wheat: reduced root disease incidence, improved soil structure, and increased soil N supply, or a combination of two or more of these benefits (Chan & Heenan, 1991; Angus et al., 1994; Heenan, 1995). The greater supply of plant-available soil N is assumed to be partly used by the increased yield potential of wheat and, if large enough, it can also reduce the opt-N rate (Engström & Gruvaeus, 1998).

The fate of N_{min} during the winter and the temporal course of nitrogen mineralisation following winter oilseed rape and peas, as influenced by a milder climate, may be estimated with simulation models. For this, however, basic field experimental data are needed for parameterisation. The consequences for future cultivation of winter wheat following winter oilseed rape or peas in central Sweden (about 58–61°N), or still more to the north and in similar north European regions, may therefore be studied in present agriculture in the southernmost parts of the Nordic region, such as the province of Skåne in south Sweden (about 55–56°N). In order to achieve such knowledge, representative for a mild climate, the main objectives of the present investigation were to quantify the impact of winter oilseed rape and field peas, compared with oats: 1) on losses during winter of N_{min}, accumulated already in the autumn, and utilisation of the remaining nitrogen by a subsequent winter wheat crop, 2) on the temporal course of soil N mineralisation during the following growing season, and 3) on grain yield, crude protein content, and Opt-N rate of the winter wheat.

Materials and methods

Sites and field experiments

Nine biennial field trials were performed between 2000 and 2004 at different sites in the province of Skåne in southern Sweden, using a split-plot design with three replicates. In the first experiment year (Year 1), winter oilseed rape (sown in August in the year previous to Year 1), field peas and oats (both sown in spring in Year 1) were grown on main plots, with three replicates, each 40×20 m, and with barley as preceding crop. Winter wheat was grown in the second year (Year 2). Sites and soil properties are described in Table I. Precipitation data were taken from three meteorological stations in the region (Table II). Crop rotations before the start of the experiments are described in Table I. Farmyard manure was not applied in any of the experimental years. The crop on the surrounding field in Year 1 was winter oilseed rape. Average N fertilisation to winter oilseed rape was 50 kg N ha^{-1} in autumn (previous year) and 138 kg N ha^{-1} in spring, to oats 104 kg N ha^{-1} in spring (top dressing), and to peas 0 kg N ha^{-1}. After harvest of these crops (25 July–31 Aug), the above-ground crop residues were incorporated into the soil by stubble cultivation once or twice at one occasion, generally followed by ploughing (deep cultivation twice at site 3) before winter wheat was sown (9 Sept–10 Oct) in the main plots and on the surrounding field (Table III).

In Year 2, each main plot was divided into eight randomly allocated subplots (each 20×3.5 m) in which increasing amounts of fertiliser N were applied to the winter wheat (treatments A–H: 0, 0, 40, 80, 120, 160, 200, and 240 kg N ha^{-1}) (Table IV). The treatment with 0 kg N ha^{-1} was repeated twice

Table I. Experiment sites, crop rotations and soil characteristics (0–20 cm soil). The two years correspond to the growing season of the previous crop and the winter wheat.

						mg kg^{-1} air-dry soil		
Site and years	Site location	Soil type	Clay content (%)	Soil organic matter (%)	pH (H_2O)	P-AL	K-AL	Mg-AL
2000–2001								
1. Stävie*	55° 45′N, 13° 04′E	Sandy loam	18	2.5	6.9	0.57	1.0	0.72
2. Bollerup**	55° 30′N, 14° 04′E	Loamy sand	13	4.8	7.0	1.10	0.82	1.00
3. Steglarp*	55° 06′N, 13° 08′E	Sandy loam	17	2.3	7.4	0.64	0.95	1.20
2001–2002								
4. Bollerup**	55° 30′N, 14° 04′E	Loamy sand	14	2.4	6.3	1.40	1.20	0.60
5. Linelund*	55° 17′N, 13° 17′E	Sandy loam	17	1.9	6.9	0.64	0.79	0.96
2002–2003								
6. Linelund*	55° 17′N, 13° 17′E	Sandy loam	16	2.1	8.0	0.63	0.68	0.63
2003–2004								
7. Nytofta	55° 18′N, 13° 34′E	Sandy loam	16	2.1	7.8	0.64	0.99	0.76
8. Sandby gård**	55° 20′N, 14° 09′E	Clay soil	28	3.7	7.2	0.67	1.20	0.78
9. Lönnstorp*	55° 43′N, 13° 04′E	Sandy loam	17	3.2	6.5	0.86	0.89	0.78

*Crop rotations including sugar beet and winter oilseed rape. **Crop rotations including sugar beet, winter oilseed rape, and leys (with application of manures).

(designated A and B) to enable soil and plant sampling in one (B) and harvest determination in the other (A). On each side of the main plots, protection strips of 1 m width were established. The winter wheat was fertilised three times, in spring and early summer (Table IV). The first and second N applications consisted of ammonium nitrate and the third of calcium nitrate according to current recommendations. Application of phosphorus (P), potassium (K), sulfur (S), and the use of herbicides and pesticides were according to general recommendations for the site.

Table II. Average monthly precipitation (mm) and mean temperature (°C) for three meteorological stations in Skåne (Malmö, Helsingborg, and Lund) from the yield of previous crops to the harvest of winter wheat, 2000–2004.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation:												
2000								59	91	56	63	53
2001	39	42	23	60	24	68	32	112	124	47	54	57
2002	96	97	35	30	58	114	80	50	17	114	60	31
2003	45	10	12	51	71	53	81	54	36	52	63	66
2004	69	33	48	27	19	93	133	70				
Average												
2000–2004	62	46	29	42	43	82	81	69	67	67	60	52
Normal values												
1961–1990	53	32	45	41	44	58	72	65	66	62	68	63
Temperature:												
2000								15.9	13.0	11.4	7.4	3.4
2001	1.7	0.3	1.1	6.1	12.5	14.1	18.8	17.7	12.8	11.6	4.8	−0.1
2002	2.0	3.8	4.3	7.3	13.3	16.4	18.2	20.2	14.5	6.7	3.9	−0.7
2003	−0.6	−2.4	3.0	6.8	12.6	16.6	18.9	18.3	14.3	6.0	6.3	3.6
2004	−2.0	1.0	3.5	8.1	12.0	14.1	15.6	18.2				
Average												
2000–2004	0.3	0.7	3.0	7.1	12.6	15.3	17.9	18.1	13.7	8.9	5.6	1.6
Normal values												
1961–1990	−0.7	−0.6	1.9	6.0	11.4	15.2	16.5	16.3	12.9	9.1	4.4	1.2

Table III. Dates for soil cultivation after harvest of previous crops and sowing date of the subsequent winter wheat.

Site	Stubble cultivation	Ploughing or deep cultivation (dc)	Sowing
1. Stävie	20/8*	–	9/9
2. Bollerup	31/8*	15/9	20/9
3. Steglarp	–	19/9 (dc, twice)	20/9
4. Bollerup	21/8	6/9	6/10
5. Linelund	8/10	–	10/10
6. Linelund	–	12/9	17/9
7. Nytofta	2/8*	4/9	9/9
8. Sandby gård	25/8	5/9	15/9
9. Lönnstorp	5/9	12/9	18/9

*After oilseed rape: 3/8 (site 1), 9/8 (site 2), and 4/8 (site 7).

Soil sampling and analyses

At each site, composite soil samples consisting of 20 cores from the topsoil (0–20 cm) were taken for general soil analyses (Table I). Soil texture was determined by the sedimentation method (Gee & Bauder, 1986). Total N and carbon (C) contents were measured through dry combustion at 1250°C on a CNS-2000 analyser (LECO Corporation, St. Joseph, MI, USA). Soil organic matter content in the topsoil (0–20 cm) was calculated by multiplying the carbon content by a factor of 1.724. Soil pH(H_2O) was measured in deionised water at a soil–water ratio of 1:2.5. Ammonium lactate-extractable P (P-AL), K (K-AL), and Mg (Mg-AL) were determined according to Egnér et al. (1960).

Soil mineral nitrogen

The temporal course of soil N supply to winter wheat was estimated by determining N_{min} on up to seven occasions, from harvest of the preceding crops to ripening of the winter wheat (GS90; Zadoks et al., 1974). At all sites N_{min} was determined on four occasions: at harvest of the preceding crop (average sampling date: 9 August) and in late autumn (9 November) in Year 1, and in early spring (16 March) and at ripening (GS90, 1 August) of the winter wheat in Year 2. In four of the nine experiments, N_{min} was also determined on three additional occasions: at growth stages GS31, GS37-41, and GS61-70 (15 May, 30 May, and 25 June, respectively). Soil sampling was performed layer-wise to a depth of 90 cm (0–30, 30–60, and 60–90 cm) in main plots in year 1 and in treatment B (without N fertilisation in Year 2). In each treatment, 24 randomly distributed soil cores were taken from the 0–30 cm soil layer and 12 cores within the 30–60 and 60–90 cm layers and pooled to one composite sample for each layer and preceding crop. The samples were stored frozen until analysis, when they were ground and homogenised in a frozen state. Subsamples of 30 g were extracted with 100 mL of 2 M KCl. The analyses were performed using colorimetric methods on a TRAACS 800 (Technicon autoanalyser). The values obtained were calculated as kg N ha^{-1} assuming the dry bulk density of the soil material to be 1.25 g mL^{-1} within the 0–20 cm layer and 1.50 g mL^{-1} below 20 cm.

Yield, crop measurements, and analysis

Crop N uptake at ripening and C:N ratio in the straw of the preceding crops (Year 1) were determined by measuring the concentration of N and C in samples of above-ground plant parts in each of the nine main plots. The grain yields of the preceding crops were recorded by combine harvesting of 25 m^2 in each main plot. Seed and grain samples of 1000 g were collected at harvest for laboratory analysis.

The temporal course of soil N uptake by winter wheat during the growing season in Year 2 was determined in four of the nine experiments by measuring the amount of N in samples of above-ground plant parts (N_p) in subplots without N fertilisation (treatment B) on three occasions (GS31, GS37-41, and GS61-70), simultaneously with soil mineral N sampling in this treatment. To enable the residual N effect of the preceding crops

Table IV. Nitrogen fertilisation (kg N ha^{-1}) applied to the winter wheat in treatments A–H after all three preceding crops. GS = growth stage of the wheat (Zadoks et al., 1974).

Treatment	First application GS23-27	Second application GS30	Third application GS37-39	Total N amount
A	0	0	0	0
B	0	0	0	0
C	0	40	0	40
D	0	80	0	80
E	0	120	0	120
F	40	120	0	160
G	40	120	40	200
H	40	160	40	240

on winter wheat to be estimated, the total nitrogen content in the above-ground plant parts was determined in crop samples at stage GS90 in the subplots of treatment B, without N fertilisation, in all nine experiments. The grain yield of winter wheat was measured by combine harvesting of 18 m^2 in each subplot (A, C–H).

Crop samples in both years were cut at the soil surface within three randomly selected 0.24 m^2 subareas in each plot and then dried at 60 °C. Straw and grain were separated. Total N content in crop, seed, and grain samples, and total C in straw in Year 1 were determined using Dumas elemental analysis. Crude protein in winter wheat grain was calculated from the N content in the harvested sample by the conversion factor (for bread wheat) 5.7 (Sousulski & Imafidon, 1990). Straw yields [kg dry matter (DM) ha^{-1}] and their total N content (kg N ha^{-1}) in treatments A and B (both without N fertilisation to the wheat) were calculated by using the grain DM:straw DM ratio and N concentrations, respectively, from the plant samples in B and then adjusting the amount of straw to the combine-harvested amount of grain in A.

Net N mineralisation, calculations, and statistics

The total uptake of soil N in wheat at ripening (tot-N_p) was calculated as the sum of N content in grain, straw and roots. It was assumed that the roots contained 25% of the total amount of N in the crop (Hansson et al., 1987). Soil N mineralised during the wheat-cropping season was estimated as net N mineralisation (N_{net}) = (Total uptake of soil N in crop at ripening) + (Residual N_{min} in 0–90 cm soil at ripening) − (N_{min} in 0–90 cm soil in early spring, March). Here, N_{net} was defined as: (N mineralisation) − (N immobilisation) − (N losses) + (atmospheric NH_4-N and NO_3-N deposition).

Economic optimum N fertilisation rates (Opt-N rates) and their corresponding yields (Opt-N yields) were calculated for winter wheat following the three preceding crops at each site. Here, a cubical polynomial function ($y = a + bx + cx^2 + dx^3$) was used to describe the yield response to N fertilisation. This was done by identifying the points where the slope of the function was equivalent to the price ratio of grain to fertiliser, which was estimated as 10:1 from current Swedish prices of winter wheat grain and fertiliser N. Protein payment was not considered. Analysis of variance (ANOVA) was performed (MINITAB, version 14, Minitab Inc., USA) to compare the different effects of the three preceding crops on winter wheat at each site, as well as the average for the nine sites. Multiple linear regression analysis was carried out to investigate the possibility of explaining the differences in Opt-N rate by its corresponding grain yield and tot-N_p or N_{net} for all years together.

Results

Grain yield and N uptake in winter oilseed rape, peas, and oats prior to winter wheat

The grain yield levels of winter oilseed rape, peas, and oats were normal for the region in all years, on average 3880 (range: 3220–4780), 4100 (2340–4950), and 6390 (4600–7170) kg DM ha^{-1}, respectively, and crop N uptake at ripening in the above-ground plant parts was 165, 188, and 148 kg N ha^{-1}, respectively. The amount of N in above-ground crop residues after harvest of oilseed rape and peas was 43 (29–77) and 35 (22–51) kg N ha^{-1}, respectively, and for oats 28 (19-39) N ha^{-1}. The C:N ratio of the straw residues was on average 77 (48–99), 50 (35–74), and 94 (72–119) for oilseed rape, peas, and oats, respectively.

Soil mineral nitrogen, net N mineralisation in the growing season, and uptake of soil nitrogen in winter wheat following oilseed rape, peas, and oats

The amount of N_{min} at harvest of the previous crops was higher for winter oilseed rape ($P = 0.030$) and peas ($P = 0.161$) than for oats (Figure 1, Table V). From harvest to the beginning of November, in the following winter wheat, N_{min} increased to its maximum, 68, 64, and 45 kg N ha^{-1}, respectively, and was significantly larger after oilseed rape ($P = 0.002$) and peas ($P = 0.008$) than after oats. From late autumn until early spring, N_{min} decreased by 36,

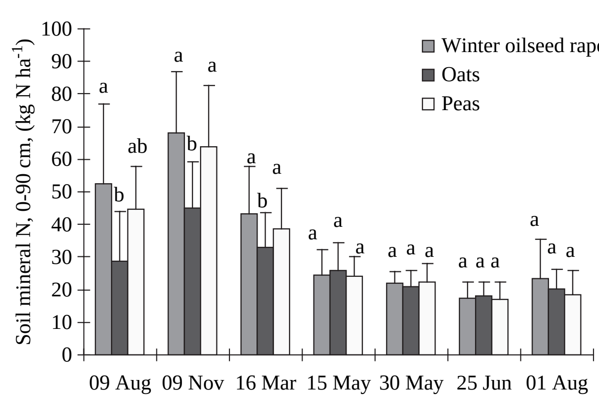

Figure 1. Soil mineral nitrogen (0–90 cm) at average sampling dates from harvest of the previous crops (winter oilseed rape, oats and peas) until ripening of the following winter wheat. Data from all nine field experiments except the samplings at 15/5, 30/5, and 25/6, which were carried out in four of the trials. Bars represent standard deviation values. Bars with different letters (a or b) are significantly different ($P < 0.05$) within the sampling date.

Table V. Soil mineral N (N_{min}, 0–90 cm) from harvest of the previous crops to ripening (GS90) of the winter wheat. Calculated net N mineralisation during the growing season of winter wheat (total uptake of soil N at ripening + soil mineral N at ripening – soil mineral N in early spring, N_{net}) following winter oilseed rape, oats, and peas.

	N_{min} (kg N h^{-1})				N_{net} (kg N ha^{-1})	
Experimental site and previous crops	At harvest of previous crops*	In late autumn*	In early spring*	At GS90 of winter wheat**	Absolute value**	Change compared with oats
1. Stävie						
Oilseed rape	32	51	40	10	67	19
Oats	15	24	26	11	48	0
Peas	22	34	32	9	58	10
2. Bollerup						
Oilseed rape	50	90	50	20	110	23
Oats	16	42	32	17	87	0
Peas	65	74	45	14	99	12
3. Steglarp						
Oilseed rape	41	–	38	24	90	19
Oats	29	–	28	23	71	0
Peas	58	–	32	14	86	15
4. Bollerup						
Oilseed rape	106	80	37	19	108	−2
Oats	37	48	24	18	111	0
Peas	52	62	24	20	113	3
5. Linelund						
Oilseed rape	22	32	23	22	87	−9
Oats	65	45	29	26	96	0
Peas	46	43	33	19	83	−13
6. Linelund						
Oilseed rape	50	68	61	22	97	34
Oats	24	51	50	23	63	0
Peas	44	78	54	15	83	20
7. Nytofta						
Oilseed rape	63	75	43	53	127	30
Oats	29	70	39	31	97	0
Peas	43	86	48	36	116	19
8. Sandby gård						
Oilseed rape	43	85	69	25	90	21
Oats	26	52	49	18	68	0
Peas	38	81	57	15	86	18
9. Lönnstorp						
Oilseed rape	65	63	31	17	106	37
Oats	18	29	20	15	69	0
Peas	36	54	24	20	102	33

*In main plots. **In treatment B (without N fertilisation).

39, and 27% following oilseed rape, peas, and oats, respectively. Nevertheless, there still remained somewhat more N_{min} after oilseed rape ($P = 0.001$) and peas ($P = 0.046$) than after oats, 10 and 6 kg N ha^{-1} more, respectively. From the middle of May (GS31), when N uptake increased rapidly, until ripening (GS90), N_{min} was at a low level and was similar for the three previous crops in treatment B (without N fertilisation). Calculated N_{net} from early spring (March) to ripening of winter wheat amounted to 98 and 92 kg N ha^{-1} after oilseed rape and peas, respectively, which was significantly more ($P = 0.001$ and 0.01, respectively) than after oats (79 kg N ha^{-1}; Figure 2, Table V).

The uptake of soil N by the non-N-fertilised winter wheat (treatment B) after oilseed rape was continuously and significantly larger than after oats (Figure 3) on all four sampling dates ($P = 0.002$, 0.015, 0.02, and 0.02, respectively) from the middle of May (GS31) to ripening (GS90). N Uptake by winter wheat after peas was significantly higher than after oats only on the first two of the four sampling dates ($P = 0.002$, 0,001, 0.075, and 0.14, respectively) but N uptake was not significantly different to

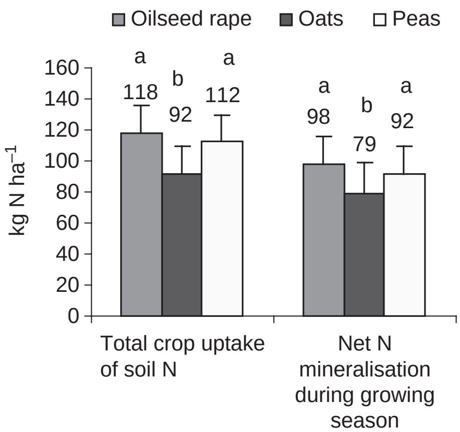

Figure 2. Total crop uptake of soil N (tot-N_p) by winter wheat at ripening (including estimated N content in roots) in treatment B (without N fertilisation), following winter oilseed rape, oats, and peas. Calculated net N mineralisation (N_{net}) from early spring until ripening. Bars represent standard deviation values ($n = 9$). Bars with different letters (a or b) are significantly different ($P < 0.05$) within the group.

that of wheat after oilseed rape at any time. The tot-N_p was 118, 112, and 92 kg N ha^{-1}, on average, following oilseed rape, peas, and oats, respectively (Table VI). The residual N effect of oilseed rape and peas, here estimated as tot-N_p in the following winter wheat (without N fertilisation) less tot-N_p of wheat after oats, was 26 and 21 kg N ha^{-1}, respectively.

Effects of winter oilseed rape, peas and oats on grain yield of winter wheat

On average for all the N fertilisation levels, grain yield of winter wheat following oilseed rape and peas

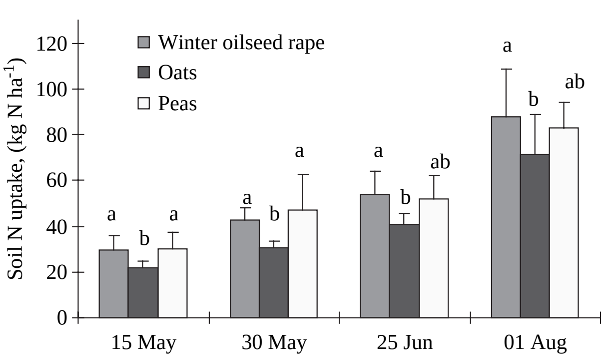

Figure 3. Soil N uptake of winter wheat in treatment B (without N fertilisation) following winter oilseed rape, oats and peas. Sampling of above-ground plant parts on four occasions (average sampling dates corresponding to GS31, GS37-41, GS61-70, and GS90, respectively) during the growing season. Bars represent standard deviation values ($n = 4$, sites 4–6 and site 9). Bars with different letters (a or b) are significantly different ($P < 0.05$) within the sampling date.

was significantly larger than after oats, 1210 and 1030 kg ha^{-1}, respectively. These differences persisted from the lowest fertilisation level to the highest, indicating that increased N fertilisation of wheat after oats could not compensate completely for the increased yield level of wheat after oilseed rape and peas (Figure 4). On average for all the fertilisation levels, however, the crude protein concentration in winter wheat grain was not affected by the previous crops (data not shown). ANOVA showed that there was no interaction between N fertilisation rate and previous crop.

Effects of winter oilseed rape, peas, and oats on Opt-N rate, corresponding grain yield, and protein concentration of subsequent winter wheat

The average Opt-N rate of fertiliser nitrogen to winter wheat was 25 kg N ha^{-1} lower after oilseed rape ($P = 0.034$) and 17 kg N ha^{-1} lower after peas ($P = 0.082$) than following oats (Table VI), whereas the average Opt-N yield was about 700 kg ha^{-1} higher after both oilseed rape and peas ($P = 0.003$ and 0.004, respectively). The Opt-N protein values were similar for winter wheat following all three previous crops (Table V).

Effect of grain yield and net N mineralisation or total uptake of soil N on Opt-N rates

Multiple regression analysis (Equations 1 and 2 in Table VII) showed that 69% of the variation in Opt-N rate could be explained by variations in the yield level of winter wheat at optimum and tot-N_P or by yield level of winter wheat and N_{net}. Both equations showed that a yield increase of 1000 kg ha^{-1} would demand an increase in N fertilisation rate of about 15 kg N ha^{-1}. Simultaneously, Equations 1 and 2 indicate that the Opt-N rate should be reduced according to the supply of plant-available soil N, i.e. by 1.14-times the tot-N_p or 1.24-times the N_{net}. According to Equation 1, the 8 kg ha^{-1} lower Opt-N rate to wheat after oilseed rape than after peas could be explained by the 6 kg ha^{-1} higher uptake of soil N in the wheat after oilseed rape (Figure 2), as yield levels were similar.

Discussion

Soil mineral nitrogen, net N mineralisation, and nitrogen uptake of winter wheat not fertilised with N

The N_{min}, N_p during the growing season, and tot-N_p indicate a continuously larger soil N supply to the winter wheat after oilseed rape and peas than after oats, from harvest of the previous crops to ripening

Table VI. Economic optimum N rates (Opt-N rate), grain yields (15% moisture), and protein concentration at optimum (Opt-N yield, and Opt-N protein, respectively), total uptake of soil N at ripening (tot-N_p) by winter wheat following winter oilseed rape, oats, and peas.

	Opt-N rate (kg N ha^{-1})		Opt-N yield (kg ha^{-1})			Tot-N_p (kg N ha^{-1})	
Experimental site, year, and previous crops	Absolute value*	Change compared with oats	Absolute value*	Change compared with oats	Opt-N protein (% of DM)*	Absolute value*	Change compared with oats
1. Stävie 2001							
Oilseed rape	156	−44	10 160	1130	8.9	97	34
Oats	200		9030		–	62	
Peas	181	−19	10 100	1070	9.1	81	18
2. Bollerup 2001							
Oilseed rape	80	−39	9800	600	10.2	140	38
Oats	119		9200		10.9	102	
Peas	105	−13	10 000	800	10.6	130	28
3. Steglarp 2001							
Oilseed rape	168	14	10 920	1000	11.0	103	27
Oats	154		9920		11.1	76	
Peas	108	−46	10 360	440	9.7	103	27
4. Bollerup 2002							
Oilseed rape	147	−55	13 360	−400	–	126	10
Oats	202		13 750		–	116	
Peas	190	−12	13 730	−20	–	117	1
5. Linelund 2002							
Oilseed rape	96	18		880	9.6	88	−11
Oats	77		5670		9.6	99	
Peas	103	26	6570	900	10.3	98	−2
6. Linelund 2003							
Oilseed rape	126	−15	8360	1010	10.6	135	46
Oats	142		7340		10.7	90	
Peas	108	−34	7870	530	10.2	122	32
7. Nytofta 2004							
Oilseed rape	90	−20	9060	1120	10.7	120	45
Oats	110		7930		11.4	75	
Peas	–	–	–	–	–	106	31
8. Sandby gård 2004							
Oilseed rape	112	−43	9020	510	12.3	133	34
Oats	155		8500		12.7	100	
Peas	114	−41	9100	590	11.8	127	28
9. Lönnstorp 2004							
Oilseed rape	141	−44	9230	40	11.6	117	11
Oats	185		9190		11.7	106	
Peas	146	−40	9230	50	11.2	128	22
Average for nine sites							
Oilseed rape	124^a	−25	9610^a	660	10.6^a	118^a	26
Oats	149^b		8950^b		11.2^a	92^b	
Peas	132^{ab}	−18	9620^a	670	10.4^a	112^a	21
P-value	0.028		0.001		0.123	0.000	

*Different letters (a and b) denote significant differences ($P<0.05$) within the column.

of the following winter wheat, thus a greater residual N effect of oilseed rape and peas. This agrees with several other studies (Jensen & Haahr, 1990; Angus et al., 1991; Kirkegaard et al., 1994; Ryan et al., 2006). The differences in N_{min} existing at harvest of the previous crops (Figure 1) remained in late autumn whereas the total amounts increased similarly after oilseed rape, peas, and oats, with 15, 19, and 16 kg N ha^{-1}, respectively. From late autumn, when N_{min} probably was at its highest level, to early spring, N_{min} was reduced by 25 kg N ha^{-1} after both oilseed rape and peas and by 12 kg N ha^{-1} after oats (Figure 1), probably due to leaching or denitrification losses during the winter. Since N mineralisation occurs in Sweden during winter, despite comparatively low temperatures (Lindén et al., 1994), N losses should have been larger than these differences. Large amounts of N_{min} in late autumn are at risk of

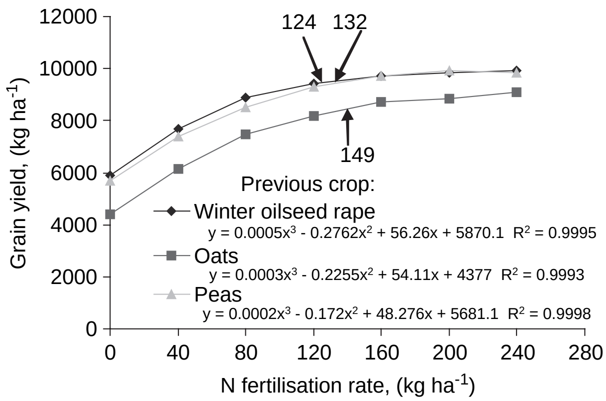

Figure 4. Grain yield of winter wheat (15% moisture) at increasing rates of fertiliser N after winter oilseed rape, oats, and peas. Arrows indicate economic optimum N rates ($n = 63$ for each preceding crop, including N fertilisation rates).

being lost, as they are followed by the main runoff period (November–March) in this region with mild winters, explaining why N_{min} in spring often is low. The average monthly air temperatures during the winter period of the experimental years (2000–2004) were above 0 °C and consequently the soil was not frozen (Table II), obviously allowing more or less continuous runoff and leaching. The impact of N losses are not just environmental, but also reduce the N_{min} available in early spring for the following crop, thus reducing the soil N supply and residual N effect. In this study, on average 34% of N_{min} present in late autumn was lost over winter. The larger amounts of N_{min} in late autumn following oilseed rape and peas (23 and 19 kg N ha^{-1} more, respectively) were reduced to 10 and 6 kg N ha^{-1} more than after oats, respectively, in early spring. According to the calculated N_{net} (Figure 2) there was 21 and 15 kg N ha^{-1} more mineralised during the growing season of wheat after oilseed rape and peas, respectively, than after oats, obviously constituting the main part of the improved soil N supply.

The tot-N_P was 92–118 kg N ha^{-1} after the preceding crops and the main part of this consisted of N mineralised (N_{net}) during the growing season of the wheat (Figure 2). The proportion of N_{net} was 83, 82, and 86% of tot-N_P for wheat following oilseed rape, peas, and oats and the additional contribution of overwintering N_{min}, calculated as the difference between tot-N_P and N_{net}, made up a smaller proportion (17, 18, and 14%, respectively). This confirms findings that the generally small amounts of N_{min} remaining in early spring in south Sweden will have a minor impact on the need for N fertilisation (Delin & Lindén, 2002).

Soil tillage, including stubble cultivation after harvest, deep cultivation and ploughing, before sowing of winter wheat in these field trials, most likely contributed to stimulation of soil N mineralisation from harvest to late autumn in the first year. This assumption is confirmed by the findings of Stenberg et al. (1999). In their study, ploughing soon after the harvest of cereal crops significantly increased the amounts of N_{min} until late autumn compared with treatments with omission of soil tillage during this period. Stubble cultivation after harvest increased N_{min} corresponding to about half of the effect of ploughing (Stenberg et al., 1999). This indicates that deep cultivation should have an intermediate effect. To reduce the stimulation of soil N mineralisation in the autumn and thus diminish the risk of N loss during winter, the alternatives would be omission of stubble cultivation after harvest and ploughing as late as possible in the autumn or spring ploughing, in both cases followed by a spring-sown crop. With omission of stubble cultivation after harvest, Stenberg et al. (1999) found that postponement of ploughing until late autumn or early spring reduced net N mineralisation in the autumn and during autumn and winter, respectively, and consequently also nitrate leaching.

Effects on Opt-N rates, grain yield, and protein concentration in grain

The increased yield of winter wheat after winter oilseed rape and peas compared with oats could not be compensated for by increased N fertilisation in this study, and was therefore not a purely residual N-effect, as also found in many other studies (Jensen & Haahr, 1990; Christen et al., 1992). For instance, there may be plant pathological reasons as mentioned above. On average for the nine sites, all with varied crop rotation histories, the results show

Table VII. Relationships between economic optimum rate of fertiliser nitrogen (Opt-N rate, kg N ha^{-1}) expressed as y, the dependent variable, and grain yield level (x_1, kg ha^{-1}) and total crop uptake of soil N (tot-N_p, kg N ha^{-1}) expressed as x_2, or net nitrogen mineralisation during the growing season (N_{net}, kg N ha^{-1}) expressed as x_3, as independent variables. The relationships are expressed as adjusted coefficients of determination (R_a^2), $n = 27$.

Equation no.	Relationships between Opt-N rate (y) and...	R_a^2	Equation
1	Grain yield (x_1) and total crop uptake of soil N (x_2)	0.69***	$y = 129 + 0.014\,x_1 - 1.14\,x_2$
2	Grain yield (x_1) and net N mineralisation (x_3)	0.69***	$y = 104 + 0.015\,x_1 - 1.24\,x_3$

***$P < 0.001$.

increased grain yield and lower Opt-N rate for winter wheat after winter oilseed rape and peas compared with after oats. Higher yield potential of wheat after winter oilseed rape and peas than after oats will require more N and increase the optimum N fertilisation rate, whereas more soil N available for the wheat crop will reduce the rate (Equations 1 and 2 in Table VII). On average for the nine sites, the increased soil N supply was obviously large enough for both the yield increase and lower Opt-N rate. Our results agree with those of Engström & Gruvaeus (1998) where winter wheat following winter oilseed rape, compared with following oats, enabled an average yield increase by 1000 kg ha^{-1} and 34 kg ha^{-1} lower Opt-N rate. In two of the trials (sites 3 and 5), however, the Opt-N rate to wheat following oilseed rape was higher than after oats, and in one experiment (site 5) it was higher after peas than after oats (Table VI). At site 5, for unknown reasons, soil N supply was lower after oilseed rape and peas than oats (Table V), but since Opt-N yield was higher following oilseed rape and peas this can explain the increased Opt-N rate. Excluding these trials, average Opt-N rate decreased by 37 kg N ha^{-1} after winter oilseed rape ($n = 7$) and by 29 kg N ha^{-1} after peas ($n = 7$) compared with after oats, which is in agreement with results in Denmark (Knudsen et al., 2002).

Wheat grain protein content was not affected by oilseed rape and peas compared with oats (Table VI). This could be due to the comparatively large yield increases at all N fertilisation levels, which used up the increased soil N. In other investigations (Angus et al., 1991; Engström & Gruvaeus, 1998), the protein content of winter wheat has been influenced inconsistently by preceding oilseed rape and peas, with both reduced and increased concentrations.

Implications for N fertilisation recommendations

As shown by the regression analysis (Equations 1 and 2) in this study (Table VII), prediction of the yield level and soil N mineralisation for individual fields and after previous crops is important for a more precise estimation of Opt-N rate. To estimate the yield level of a field, the farmer largely has to rely on his previous experiences of the field with different preceding crops. If a yield increase of 700 kg ha^{-1} at economic optimum (the average in this study) can be expected following break crops such as oilseed rape and peas, this would require about 10 kg N ha^{-1} more fertiliser N according to Equations 1 and 2. In this study, the residual N effect after oilseed rape and peas compared with after oats was 26 and 20 kg N ha^{-1}, respectively, corresponding to 40 and 27 kg N ha^{-1} of fertiliser N, assuming an N-use efficiency of 65% calculated on the basis of results published by Delin et al. (2008).The N fertilisation rate (including the yield increase) to wheat should then be reduced by 30 kg N ha^{-1} after oilseed rape (40 minus 10 kg) and 17 kg N ha^{-1} after peas (27 minus 10 kg), which is similar to the reduction in the average Opt-N rate (25 and 18 kg N ha^{-1}, respectively) found in this study. According to Equations 1 and 2, however, fertiliser N was equal to $1.14 \times$ tot-N_p or $1.24 \times N_{net}$, corresponding to a smaller N amount than required according to the 65% N-use efficiency used in the calculation above. The N-use efficiency in these nine trials was obviously high, probably due to generally good cultivation practices, and also normal rainfall during the growing season and therefore no large N losses. In the calculation above, we included conditions with higher spring and summer precipitation according to present climate trends in central Sweden, and soils with higher clay contents (30–50%) typical for that region, with risk for larger denitrification and thus greater N losses and less efficient N use. Moreover, we considered a larger incidence of plant diseases due to crop rotations in central Sweden dominated by cereal crops, also reducing N-use efficiency (Delin et al., 2008).

The investigations indicate that a milder climate in central Sweden (58-60° N) would lead to larger N losses during the winter and to less N_{min} in early spring. This implies that the larger amounts of N_{min} (0–90 cm soil depth) present in late autumn after winter oilseed rape and peas compared with oats (on average 68, 64, and 45 kg N ha^{-1}, respectively, in this investigation) would largely be lost during winter. If N_{min} were to be unaltered or even increase in the winter as during earlier decades, however, the differences between the autumn values and the remaining N_{min} at the maturity of winter wheat (about 20 kg N ha^{-1}) indicate that, on average, as much as 44, 46, and 25 kg N ha^{-1} should be available for the wheat. With less N_{min} remaining in the spring, the same amounts as in the trials in Skåne, on average only 19, 21, and 13 N ha^{-1} could be regarded as plant-available, thus reducing the residual N effect. If future N mineralisation from early spring until the ripening of winter wheat were to contribute the same large proportion of plant-available nitrogen as in the trials in Skåne, 82–86% of tot-N_p, and assuming no increase in N losses during the growing season, decreased N_{min} in spring would lead to higher rates of fertiliser nitrogen.

The economic optimum yields of the winter wheat in the trials in Skåne amounted to about 9000 kg ha^{-1} following oats and 9600 kg ha^{-1} after winter oilseed rape and peas. This was more than the so-called normal yields for this agricultural region, about 8000 kg ha^{-1} according to official statistics (Anonymous, 2007b). In the plain areas of central Sweden (about 58–60°N) normal winter wheat yields correspond to about 5100–5800 kg ha^{-1}. If climate change, together with general development of cultivation techniques, were to increase yield potentials in central Sweden the Opt-N rate would also increase. According to the results of this investigation, an increase of winter wheat yields by 1000 kg ha^{-1} at economic optimum would enhance the opt-N rate by 15 kg N ha^{-1}.

We conclude that future increasing losses of Nmin over winter after winter oilseed rape and peas will require development of cultivation strategies to reduce the risk for losses. The variation in yield increases and Opt-N rates to winter wheat after winter oilseed rape and peas, compared with after oats in this study, indicates a need for an estimation of the residual N effect at the individual sites, rather than using mean values as at present. This should contribute to the best possible N efficiency of future higher N fertilisation rates needed due to a milder climate. Predicting soil N mineralisation during the growing season is not yet possible, but applying split N doses and using optical sensors can help to adjust N fertilisation rates to temporal changes in soil N supply and crop growth during the growing season that are otherwise difficult to estimate.

Acknowledgements

The authors thank the Swedish Foundation for Oilseed Research and the Swedish Farmers Foundation for Agricultural Research for funding the work.

References

Anonymous (2007a). Sweden facing climate change – threats and opportunities. Final report from the Swedish Commission on Climate and Vulnerability. Swedish Government Official Reports, SOU 2007:60, 159 pp.

Anonymous (2007b). The yearbook of Agricultural Statistics 2007. Swedish Board of Agriculture, 77 pp.

Angus, J.F., Herwaarden, A.F.V., & Howe, G.N. (1991). Productivity and break crop effects of winter-growing oilseeds. *Australian Journal of Experimental Agriculture*, *31*, 669–677.

Angus, J.F., Gardner, P.A., Kirkegaard, J.A., & Desmarchelier, J.M. (1994). Biofumigation: isothiocyanates released from Brassica roots inhibit growth of the take-all fungus. *Plant and Soil*, *162*, 107–112.

Chan, K.Y., & Heenan, D.P. (1991). Differences in surface soil aggregation under six different crops. *Australian Journal of Experimental Agriculture*, *31*, 683–686.

Christen, O., Sieling, K., & Hanus, H. (1992). The effect of different preceding crops on the development, growth and yield of winter wheat. *European Journal of Agronomy*, *1*, 21–28.

Delin, S., & Lindén, B. (2002). Relations between net nitrogen mineralization and soil characteristic within an arable field. *Acta Agriculturae Scandinavica, Section B. Soil & Plant Science*, *52*, 78–85.

Delin, S., Nyberg, A., Lindén, B., Ferm, M., Torstensson, G., Lerenius, C., & Gruvaeus, I. (2008). Impact of crop protection on nitrogen utilisation and losses in winter wheat production. *European Journal of Agronomy*, *28*, 361–370.

Egnér, H., Riehm, H., & Domingo, W.R. (1960). Untersuchungen über die chemische Bodenanayse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. II. Chemische Extraktionsmethoden zur Phosphor- und Kaliumbestimmung (Investigations on soil chemical analysis as a basis of the evaluation of plant nutrient status of soils. II. Chemical extraction methods for phosphorus and potassium determination. *Annals of the Royal Agricultural College of Sweden*, *26*, 199–215.

Engström, L., & Gruvaeus, I. (1998). Optimal kvävegödsling till höstvete (Optimum nitrogen fertilisation to winter wheat). Department of Soil Sciences, Division of Precision Agriculture, Swedish University of Agricultural Sciences, Report 3, (in Swedish, with English summary).

Gee, G.W., & Bauder, J.W. (1986). Particle-size analysis. In: Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, pp. 383–411. A. Klute (Ed.). American Society of Agronomy, Madison, Wisconsin, USA.

Gustafson, A. (1983). Leaching of nitrate from arable land into groundwater in Sweden. *Environmental Geology*, *5*, 65–71.

Hansson, A.-C., Pettersson, R., & Paustian, K. (1987). Shoot and root production and nitrogen uptake in barley, with and without nitrogen fertilization. *Zeitschrift fur Acker- und Plfanzenbau*, *158*, 163–171.

Heenan, D.P. (1995). Effects of broad-leaf crops and their sowing time on subsequent wheat production. *Field Crops Research*, *43*, 19–29.

Jensen, E.S. (1996). Rhizodeposition of N by pea and barley and its effect on soil N dynamics. *Soil Biology and Biochemistry*, *28*, 65–71.

Jensen, E.S., & Haahr, V. (1990). The effect of pea cultivation on succeeding winter cereals and winter oilseed rape nitrogen nutrition. *Applied Agricultural Research*, *5*, 102–107.

Kirkegaard, J.A., Gardner, P.A., Angus, J.F., & Koetz, E. (1994). Effect of Brassica Break Crops on the Growth and Yield of Wheat. *Australian Journal of Agricultural Research*, *45*, 529–545.

Kirkegaard, J.A., Hocking, P.J., Angus, J.F., Howe, G.N., & Gardner, P.A. (1997). Comparison of canola, Indian mustard and Linola in two contrasting environments. II. Break-crop and nitrogen effects on subsequent wheat crops. *Field Crops Research*, *52*, 179–191.

Knudsen, L., Birkmose, T., Hansen, O.M., Østergaard, H.S., Hørfarter, R., Thomsen, K.K., Thomsen, A., & Berntsen, J. (2002). Gødskning og kalkning. Oversigt over landsforsøgene. Forsøg og undersøgelser i de landøkonomiske foreninger 2002. Landbrukets rådgivningscenter, Århus, Danmark, 158–210.

Lindén, B. (1981). Relationships between cultivation practices and the supply of mineral nitrogen in the soil. The Royal Swedish Academy of Agriculture and Forestry, Report 5, pp. 67–123 (in Swedish with English summary).

Lindén, B., Lyngstad, I., Sippola, J., Søegaard, K., & Kjellerup, V. (1992). Nitrogen mineralization during the growing season. I. Contribution to the nitrogen supply of spring barley. *Swedish Journal of Agricultural Research*, *22*, 3–12.

Lindén, B., Gustafson, A., Torstensson, G., & Aronsson, H. (1994). Nitrogen in the soil profile: impact of nitrogen mineralisation during autumn and winter for nitrogen leaching and the supply of nitrogen to crops. *Kungliga. Skogs- och Lantbruksakademiens Tidskrift*, *133*, 71–84 (in Swedish).

Ryan, M.H., Kirkegaard, J.A., & Angus, J.F. (2006). Brassica crops stimulate soil mineral N accumulation. *Australian Journal of Soil Research*, *44*, 367–377.

Sousulski, F.W., & Imafidon, G.I. (1990). Amino acid composition and nitrogen-to-protein conversion factors for animal and plant foods. *Journal of Agricultural and Food Chemistry*, *38*, 1351–1356.

Stenberg, M., Aronsson, H., Linden, B., Rydberg, T., & Gustafson, A. (1999). Soil mineral nitrogen and nitrate leaching losses in soil tillage systems combined with a catch crop. *Soil & Tillage Research*, *50*, 115–125.

Uhlen, G. (1978). Nutrient leaching and surface runoff in field lysimetres on a cultivated soil. I. Runoff measurements, water composition and nutrient balances. Scientific Reports of the Agricultural University of Norway 57, no. *27*, 26 pp.

Zadoks, J.C., Chang, T.T., & Konzak, C.F. (1974). A decimal code for the growth stages of cereals. *Weed Research*, *14*, 415–421.