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Effects of nitrogen fertilizer on the grain yield and quality of winter oats

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SUMMARY

Amounts of spring nitrogen (N) fertilizer (0–240 kg/ha), combined with three timing treatments (single, divided early or divided late), were tested at 14 sites in England and Wales between 1984 and 1988 to determine the optimum fertilizer N requirement for winter oats. The trials were superimposed on commercial crops of the cultivars Pennal (9 sites) or Peniarth (5 sites). Optimum amounts of N ranged from nil to 202 kg/ha (mean 119) and optimum yields varied between 5·8 and 9·9 t/ha (mean 7·3). Much (*c*. 60%) of the inter-site variation in N optimum was explained by differences in soil N supply, as indicated by N offtake in the grain at nil applied N. Mean yield differences between single and early (+0·08 t/ha) or late (−0·04 t/ha) divided dressings were slight, although significant ($P <$ 0·05) but inconsistent yield effects were obtained from early N at two sites and late N at three sites.

Lodging occurred at 11 of the 12 sites where lodging scores were recorded and always increased significantly ($P <$ 0·05) with applied N. The amount of crop lodging at N optimum was, on an area basis, < 50% at nine of the sites. The overall extent of site lodging was also influenced by soil N fertility and hence inversely related to N optimum. However, multiple regression, using site lodging as well as soil N supply, only accounted for slightly more (65%) of the variation in N optimum, which suggests that lodging was not a major limiting factor. Lodging was unexpectedly less from early N (mean 43%), but more from late N (53%) divided dressings, compared with a single N dressing (49%). Early N reduced lodging significantly ($P <$ 0·05) at four sites, although the actual reduction was only large at one site where early N also increased yield significantly (+0·57 t/ha).

Grain N concentrations increased significantly ($P <$ 0·05) with applied N, on average by 0·12% per 40 kg/ha N increment. Timing effects on grain N concentration were very small, with mean values of 1·94, 1·91 and 1·96%N respectively from single, early and late divided dressings. Apparent recovery in grain of fertilizer N at the optimum amount ranged from 13 to 57% (mean 37), with better N recovery at the more yield-responsive sites. Changes in mean grain weight due to the amount and timing of fertilizer N were small, with an average reduction of 0·6 mg/grain per 40 kg/ha N applied. The adverse effects of N fertilizer on grain quality were slight and unlikely to have commercial significance. The agronomic implications of these results on the N fertilization of winter oats are discussed.

INTRODUCTION

The use of N fertilizer is a major factor in the profitable production of most crops in temperate environments, but the benefits for oats are less clear-cut than for other cereal species. Amounts of fertilizer N applied to most cereals have increased in recent decades and, although yield responses have been notoriously variable, progress has been made in improving the prediction of optimum N requirement (Sylvester-Bradley *et al*. 1987).

A particular problem with winter oats has been its propensity to lodge, associated with long stems. This has limited the effectiveness of fertilizer N in maximizing yield and created harvesting problems. The application of the plant growth regulator chlormequat has been shown to reduce stem length and susceptibility to lodging in oats (Gill *et al*. 1974; Walther & Flisch 1983; Green *et al*. 1986; Leitch & Hayes 1989, 1990). The common use by farmers of chlormequat, together with improvements in the

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standing power of newer cultivars during the 1980s (Anon. 1991), reduced the susceptibility of winter oats to lodging and therefore possibly increased the effectiveness of fertilizer N.

Few experiments have investigated in detail the N requirements of autumn-sown oats. Most European work on N for oats has concentrated on the spring-sown crop (Bengtsson 1974; Anikst 1980; Brun 1982; Gunnardson 1983; Poelaert *et al.* 1983; Krzywy & Woloszyk 1984), as poor winter hardiness limits the area suitable for the cultivation of winter oats. A relationship between lodging resistance and N requirement is by no means clear from previous work: Bengtsson (1974) suggested that cultivars of oats with greater resistance to lodging were more responsive to N and Rho (1982) obtained significant differences in North America between three cultivars of oats in yield response to N. However, Yao (1984) and Marshall *et al.* (1987) found no major differences in response between conventional and semi-dwarf cultivars and Anderson & McLean (1989) found that the yield response of oats to applied N in Western Australia depended on soil N status, seasonal rainfall, sowing date, seed rate and cultivar.

Winter oats are grown more widely in the maritime climate of the UK but there has been a lack of recent experimental data on N effects on oats because of their relatively minor contribution to total cereal production. The area of oats in the UK, grown mainly for the animal feed market, declined from 1000000 ha in the mid-1950s to 68000 ha in 1986 (Bennett 1989). Subsequently, there was a slight increase in the crop area, associated with an emerging interest in oats for health foods and other uses (Welch 1989). Oil and protein content, as well as other beneficial attributes of oats, offer relative advantages for human consumption when compared to other cereals (Butler-Stoney & Valentine 1991; Loader 1991). Oats have normally been grown where the soil fertility is low, to minimize lodging risk. However, where oats are produced on mixed farms for use as a livestock feed, the greater degree of soil fertility in a ley–arable system may be unavoidable.

In view of the limited data available, a series of experiments was conducted from 1984 to 1988 to examine the spring N requirement of the two main cultivars of winter oats at that time and the extent to which lodging could be minimized through controlled timing of N applications. This paper reports the effects of both amount and timing of N on grain yield and quality and examines the extent to which lodging and other factors influenced best commercial practice in terms of N nutrition.

MATERIALS AND METHODS

Seasons and sites

Fourteen experiments, located in South East England and in Wales, were completed between 1984 and 1988, at 4, 2, 3, 3 and 2 sites in the successive years. In 1985, yields could not be taken at two further sites in Wales due to severe lodging and associated grain sprouting problems. The work continued over five seasons, to maximize seasonal variation. Sites were located on commercial farms with good husbandry, using crops which had established uniformly on mineral soils, following at least one previous cereal in the rotation. However soil N status was not always small. Site details are shown in Table 1.

The oat cultivar at all sites was either Pennal or the weaker strawed Peniarth (Anon. 1991), these being the dominant commercial varieties available at the start of the experiment. Husbandry inputs, apart from N, were applied according to prevailing commercial practice for the control of diseases, pests or weeds. The experimental plots at each site were superimposed on the field crop in late winter. Plot boundaries, typically 20–30 cm wide, were imposed using a non-selective herbicide and N was spread by hand as prilled ammonium nitrate. The whole experimental area at each site was sprayed with the recommended amount of chlormequat at the second node stage (GS32) (Tottman & Broad 1987), to reduce lodging risk.

Treatments

At each site, amounts of spring N from 80 to 200 kg/ha were tested with three different timings: (*a*) a single dressing at the beginning of stem extension (GS30–31), (*b*) a divided dressing applied 'early' as 40 kg/ha N during tillering (GS21–24) and the remaining amount at GS30–31, and (*c*) a divided dressing, with part applied at GS30–31 and 80 kg/ha N applied 'late' as flag leaves emerged (GS35–37).

The applications during tillering occurred between mid-February and late March, depending on site and season. Stem extension and flag leaf dressings were normally applied during April and May, respectively (Table 1). Additional treatments of nil and 40 kg/ha N (at the single timing) were included at all sites and, at eight sites, 240 kg/ha N was also tested at each of the three timings.

All treatments were replicated in two randomized blocks, each with 14 or 17 plots. Total plot size including pathways varied between sites from $2{\cdot}5 \times 25{\cdot}0$ m to $3{\cdot}0 \times 24{\cdot}0$ m, depending on size of the combine harvester used to record yield.

Measurements

Soil mineral N (N_{min}; kg/ha, 0–90 cm depth) was determined in early spring at seven sites (Sites 5–10 and 12, Table 1) in harvest years 1985–87; soil samples, each comprising nine cores divided into 0–15, 15–30, 30–60 and 60–90 cm depths, were taken between early February and early March from

Table 1. *Details of experimental sites in England* (*E*) *and Wales* (*W*), *1984–88*

Year and site code	Site Location	Soil description; series	Cultivar	Sowing date	Date of N application Early	Middle	Late	Harvest date
1984								
1	Barcombe, East Sussex (E)	Clay loam over silty clay; Denchworth	Pennal	25 Sep	—	6 Apr	8 May	6 Aug
2	Eridge, East Sussex (E)	Silt loam over silty clay loam/silty clay; Wickham	Peniarth	24 Sep	15 Feb	24 Apr	27 May	16 Aug
3	Abermule, Powys (W)	Silt loam over sandy loam; Sannan	Peniarth	28 Sep	23 Feb	2 Apr	31 May	10 Aug
4	Snead, Powys (W)	Silt loam over silty clay loam; Cegin	Pennal	26 Sep	23 Feb	17 Apr	31 May	16 Aug
1985								
5	Barcombe, East Sussex (E)	Silt loam over silty clay; Wickham	Pennal	26 Sep	23 Feb	17 Apr	31 May	16 Aug
6	Wisborough Green, West Sussex (E)	Silty clay loam over silty clay; Denchworth	Peniarth	25 Sep	18 Feb	12 Apr	26 May	28 Aug
1986								
7	Barcombe, East Sussex (E)	Silty clay loam over clay; Wickham	Pennal	30 Sep	24 Feb	7 May	22 May	9 Aug
8	Wisborough Green, West Sussex (E)	Silty clay loam over silty clay; Oxpasture	Peniarth	11 Oct	24 Feb	13 May	29 May	16 Aug
9	Bishops Castle, Powys (W)	Clay loam over silty clay loam; Heapey	Pennal	7 Oct	14 Mar	29 Apr	30 May	2 Sep
1987								
10	Cranbrook, Kent (E)	Silt loam over sandy/silty clay; Wickham	Pennal	27 Oct	25 Mar	30 Apr	20 May	15 Aug
11	Fonman, S. Glamorgan (W)	Clay loam over limestone; Ston Easton	Pennal	18 Sep	3 Mar	14 Apr	7 May	6 Aug
12	Trefnant, Clwyd (W)	Clay loam over clay; Salop	Peniarth	26 Sep	12 Mar	23 Apr	29 May	8 Sep
1988								
13	Adisham, Kent (E)	Calc. silty clay loam over chalk; Andover	Pennal	15 Oct	27 Feb	26 Apr	12 May	4 Aug
14	Bethersden, Kent (E)	Silty clay loam over clay; Denchworth	Pennal	30 Sep	16 Feb	25 Apr	13 May	8 Aug

untreated plots and stored frozen. The samples were analysed for ammonium- and nitrate-N by colorimetry after thawing and extraction of the field-moist samples with 2 M potassium chloride (Anon. 1986). Monitoring at each site during the growing season showed no major disease, pest or weed incidence apart from some crop infection by barley yellow dwarf virus (BYDV) at Site 13.

Each plot was assessed for the percentage of the crop area affected by leaning (stem $> 5°$ and $< 45°$

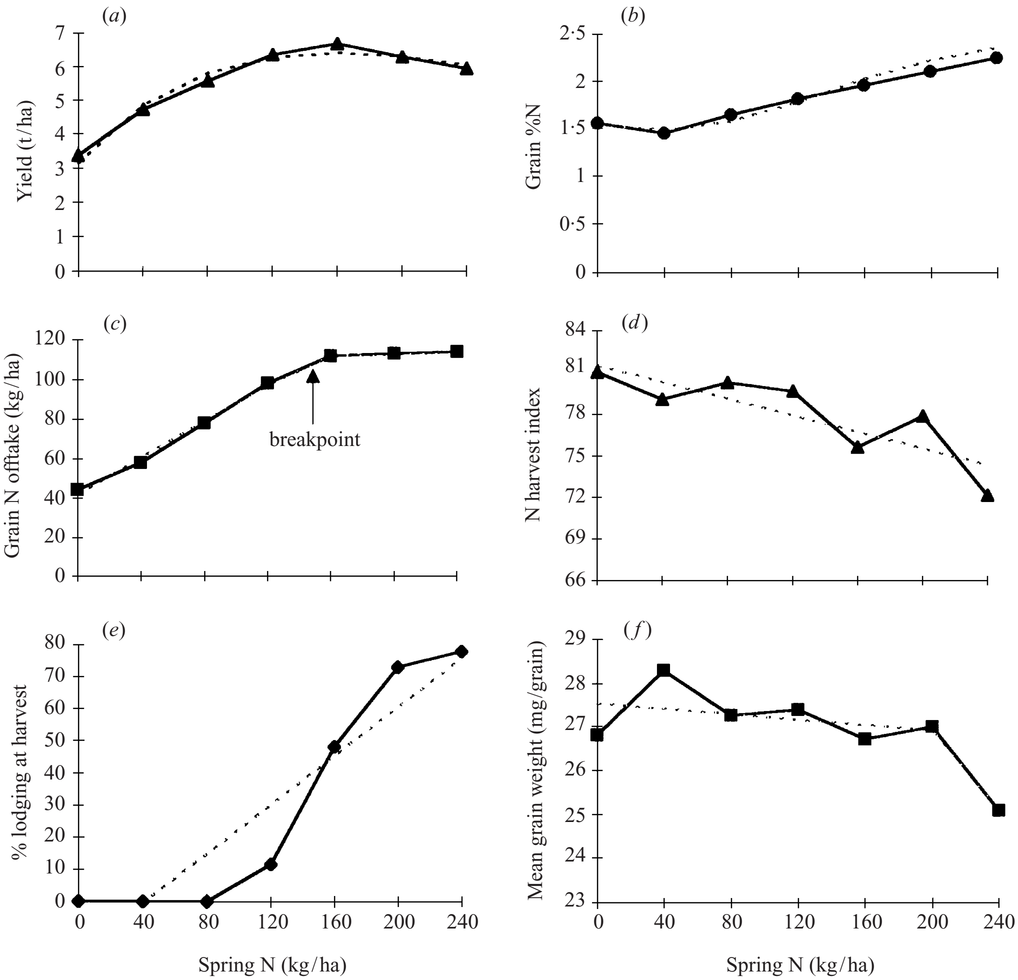

Fig. 1. Effect of applied N at Site 3 on (*a*) grain yield (▲), (*b*) N concentration in grain (●), (*c*) N offtake in grain (■), (*d*) N harvest index (▲), (*e*) crop lodging at harvest (◆), (*f*) mean grain weight (■). Actual (—), fitted (····).

from the vertical) or by lodging (stems > 45°) shortly before harvest. At Site 11, the origin of lodging (stem or root failure) was also recorded. Fertile shoots were counted at three sites (Sites 1, 2 and 6), using 5×50 cm lengths of two adjacent rows per plot. Whole crop samples were taken from each treatment at Sites 3 and 4 in 1984 to measure N harvest index (NHI), expressed as the (weight of N in grain)/(weight of N in grain + straw); shortly before harvest, shoots were cut at ground level from *c*. 50 cm length of row at three random points within each plot and bulked. The dry weight and N concentration of both the grain and straw were determined separately after threshing.

Plot yields were measured using farm or plot combines and a sample of grain was taken from each plot for analysis. A subsample was dried at 100 ± 2 °C for 40 h to determine dry matter (DM) content. A separate, cleaned and dried subsample was analysed for total N content by Kjeldahl digestion. A subsample of cleaned grain was passed through an electronic grain counter, weighed and the mean grain weight was corrected to 15% moisture content after the counted sample had been oven-dried.

Statistical analyses

Grain yield (t/ha, 85% DM), grain quality and other recorded data for each site were subjected to analysis of variance to test for statistically significant treatment effects. Yield data, averaged over timings, for each site were fitted with a linear plus exponential function of the form:

$$\text{Yield} = a + b \times (0{\cdot}99)^N + c \times N$$

where N is the total spring N amount (in kg/ha) and a, b and c are constants (Sylvester-Bradley *et al.*

1984). The amount of N for optimum yield (N_{opt}) was then given by:

$$N_{opt} = \frac{\ln(k-c) - \ln(b \times \ln(0{\cdot}99))}{\ln(0{\cdot}99)}$$

where k is the ratio of the cost of N fertilizer to the price of grain and taken as $k = 0{\cdot}003$. Standard errors for N_{opt} were also estimated, using the method of Cox & Hinckley (1974).

Concentrations of grain N (%) were also averaged over timings and were fitted with a function of the form:

$$\text{Grain N} = a - b\ (\exp\ (c) \times (N/10-d)^2)$$

where d is also a constant.

Minimum and maximum concentrations of grain N, and their equivalent amounts of fertilizer N, were then determined for each site from the fitted values using the method described by Murray & Nunn (1987).

Nitrogen offtake in the grain (N_{oft}, kg/ha) was calculated on a DM basis from the yield and N concentration of grain (N_{oft} = yield (t/ha) × % N × 10). Fitted values for N_{oft} were then calculated from the actual values, averaged over timings, using the two line function:

$$N_{oft} = (N < t) \times [a - b\ (t-N)] + (N > t) \times [a + c\ (n-t)]$$

where N is applied N (kg/ha) and a, b, c and t are parameters fitted for each site and n is a constant (Bloom *et al.* 1988). Nitrogen offtakes at nil fertilizer N (N_{oft0}) and at N_{opt} ($N_{opt,oft}$) were derived from the fitted function. Fitted values were used to calculate the apparent recovery of applied N both at the intersection of the two line function fit (i.e. 'break point', see Fig. 1 (*c*)), as represented by the gradient of the first line, and also at N_{opt}, by the equation:

$$\%\ \text{apparent recovery at}\ N_{opt} = \frac{(N_{opt,oft} - N_{oft0}) \times 100}{N_{opt}}$$

Fitted values for mean grain weight were calculated using either the same procedure as for N offtakes, or single line regression fits with or without inclusion of the nil N value; the fit giving the smallest Residual Mean Square was taken as the best description of the data. The gradient from either a single line fit (five sites, N_0 value included; six sites, without N_0 value) or the major line of a two line fit (three sites) was then taken as an estimate of the rate of decrease in mean grain weight with applied N at each site.

Linear regression, using data starting from the largest N rate with nil recorded lodging, was used to estimate, for each site, the minimum amount of fertilizer N to cause lodging (N_{L0}) (except for Site 12, where lodging occurred even without applied N) and the amount of N to cause 50% lodging (N_{L50}) on a crop area basis.

RESULTS

Grain yield

Examples of the responses to applied N for yield and the other variables are shown for Site 3 in Fig. 1. Mean yields for each site, also parameters from the fitted function, are shown in Table 2. Nitrogen application gave statistically significant ($P < 0{\cdot}05$) yield increases at all sites, ranging from 0·6 (10%) to 4·1 t/ha (132%) more than the yield at nil N, except at Site 12 where N significantly ($P < 0{\cdot}05$) depressed yield. This latter effect appeared to be due to high site fertility and extensive crop lodging. Optimum amounts of N fertilizer ranged from nil at Site 12 to 202 kg/ha N at Site 13 where there was some BYDV infection. The mean and median N_{opt} values for all sites were 119 (S.E. ± 13·2) and 135 kg/ha respectively. Optimum yields varied from 5·8 to 9·9 t/ha, with a mean for all sites of 7·3 t/ha (S.E. ± 0·34).

Mean differences for all sites between the single and divided dressings were +0·08 t/ha and −0·04 t/ha for the early and late timings respectively, both within 1% of the mean yield for the single timing. Statistically significant ($P < 0{\cdot}05$) yield differences due to N timing occurred at five individual sites (Table 2); compared with the single N application, the early dressing reduced yield by 0·3 t/ha at Site 4 despite slightly less lodging (Table 3). In contrast, early N gave a yield increase of 0·57 t/ha at Site 10, associated with significantly less lodging. Compared to the single dressing, late N increased yield by 0·26 t/ha at Site 13, the only non-lodging site, but reduced yield at three other sites; by 0·41 t/ha at Site 2, by 0·53 t/ha at Site 10, where late N significantly increased the amount of lodging, and by 0·38 t/ha at Site 11 with slightly more lodging. Only Site 11 showed a significant interaction between amount and timing of N on yield, due to a yield reduction where a total amount of 80 kg/ha N was all applied at GS35–37.

Grain N concentration and offtake

Fitted values for minimum and maximum N concentration in grain, also the corresponding amounts of applied N, are summarized in Table 4. Small amounts of N decreased grain N concentrations at the majority of sites but, as amounts of applied N were increased, there were marked increases in grain N concentrations at all sites where data fits were obtained. Mean values for all sites of minimum and maximum concentrations of grain N were 1·62% (range 1·42–1·91%) and 2·14% (range 1·83–2·38%) respectively. Mean amounts of fertilizer N giving these minimum and maximum values were 26 (range 0–55) and 216 (range 115–240) kg/ha respectively.

Table 2. *Mean grain yields* (*t/ha, 85% DM*) *for* (*i*) *total rate and* (*ii*) *timing of applied N, with fitted N optima* (N_{opt}, *kg/ha*) *and corresponding yield* (Y_{opt}, *t/ha, 85% DM*)

Year and site code	(i) N rate† (kg/ha)										(ii) Timing‡			
	0	40	80	120	160	200	240	S.E.§ (D.F.)	N_{opt} (S.E.)	Y_{opt}	Single	Early	Late	S.E. (D.F.)
1984														
1	8·41	9·03	9·83	10·07	9·77	9·32	—	0·112 (11)*	95 (5·3)	9·91	9·67	—	9·83	0·079 (11)
2	5·84	7·09	7·65	7·56	7·39	7·53	7·21	0·106 (14)	109 (4·7)	7·62	7·62	7·57	7·21	0·082(14)*
3	3·37	4·72	5·59	6·37	6·71	6·33	5·99	0·168 (14)*	140 (7·2)	6·40	6·15	6·19	6·26	0·130 (14)
4	5·27	7·89	8·37	8·81	8·78	8·46	8·48	0·105 (14)*	131 (3·7)	8·84	8·74	8·42	8·58	0·081 (14)*
1985														
5	5·70	6·50	6·47	6·33	5·65	5·69	5·73	0·198 (14)*	59 (35·4)	6·29	5·92	6·08	5·92	0·153 (14)
6	3·60	5·57	6·11	5·93	5·36	4·16	4·11	0·150 (14)*	87 (4·3)	5·97	5·00	5·23	5·17	0·116 (14)
1986														
7	5·44	7·37	8·21	8·74	8·91	8·81	—	0·066 (11)*	144 (4·6)	8·86	8·58	8·72	8·70	0·057 (11)
8	4·62	6·10	5·82	5·77	5·66	6·07	—	0·204 (11)	99 (18·9)	5·83	5·71	5·96	5·82	0·176 (11)
9	5·31	6·66	6·76	7·22	7·01	7·39	7·36	0·185 (14)	146 (16·9)	7·21	7·35	6·90	7·19	0·144 (14)
1987														
10	4·39	5·53	6·37	8·23	8·47	7·81	—	0·224 (11)*	143 (62·0)	7·86	7·71	8·28	7·18	0·194 (11)*
11	5·05	6·88	7·55	8·05	8·13	8·09	8·03	0·122 (14)*	145 (7·9)	8·15	8·17	7·97	7·77	0·094 (14)*
12	6·40	6·49	6·34	5·76	4·98	4·83	4·74	0·202(14)*	0 (—)	6·40	5·21	5·54	5·23	0·156 (14)
1988														
13	2·72	4·05	4·73	5·47	5·81	6·08	—	0·071 (11)*	202 (20·9)	6·09	5·37	5·47	5·73	0·062 (11)*
14	3·13	5·19	6·21	7·09	7·19	7·30	—	0·077 (11)*	163 (9·5)	7·26	6·87	7·07	6·91	0·067 (11)

* $P < 0·05$.
† yields at each N rate from 80 to 200/240 kg/ha are meaned across timings.
‡ yields are means of the 80–200/240 kg/ha N rates.
§ S.E. for 80, 120, 160, 200 and, where applied, 240 kg/ha N rates.

Table 3. *Mean crop lodging prior to harvest* (%, *plot area*) *for* (*i*) *total rate and* (*ii*) *timing of applied N*, *with fitted rates of applied N* (*kg/ha*) *at the start* (N_{L0}) *and fifty percent* (N_{L50}) *of crop lodging*

Year and site code	(i) N rate† (kg/ha)								Applied N at		(ii) Timing‡			
	0	40	80	120	160	200	240	S.E.§ (D.F.)	N_{L0}	N_{L50}	Single	Early	Late	S.E. (D.F.)
1984														
1‖	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2‖	—	—	—	—	—	—	—	—	—	—	—	—	—	—
3	0	0	0	18	48	73	78	2·3 (14*)	82	152	49	37	41	1·8 (14)*
4	0	0	8	38	52	78	78	4·0 (14)*	50	150	55	49	49	3·2 (14)
1985														
5	0	10	25	43	52	68	65	4·0 (14)*	49	149	49	46	57	3·0 (14)
6	0	0	12	40	58	82	85	4·9 (14)*	47	142	56	52	58	3·7 (14)
1986														
7	0	0	20	52	70	73	—	2·8 (11)*	41	124	56	46	59	2·4 (11)*
8	0	0	15	32	35	42	—	3·9 (11)*	33	217	31	28	34	3·3 (11)
9	0	10	23	52	85	90	88	2·7 (14)*	14	113	65	68	70	2·1 (14)
1987														
10	0	0	0	1	19	59	—	2·9 (11)*	120	191	22	2	36	2·5 (11)*
11	0	0	18	48	55	63	65	6·2 (14)*	29	153	51	38	61	4·8 (14)*
12	10	20	58	93	100	100	100	1·8 (14)*	0	73	91	91	89	1·4 (14)
1988														
13	0	0	0	0	0	0	—	—	—	—	0	0	0	—
14	0	0	0	42	30	64	—	5·0 (11)*	r95	173	29	19	26	4·3 (11)

* = $P < 0{\cdot}05$.
† yields at each N rate from 80 to 200/240 kg/ha are meaned across timings.
‡ yields are means of the 80–200/240 kg/ha N rates.
§ S.E. for 80, 120, 160, 200 and, where applied, 240 kg/ha N rates.
‖ Lodging occurred but plot scores were not recorded.

Table 4. *Fitted values for minimum and maximum grain N concentrations* (%, *DM basis*) *and corresponding rates of applied N* (*kg/ha*)

Year and site code	Minimum		Maximum	
	%N	Applied N	%N	Applied N
1984				
1*	—	—	—	—
2	1·73	Nil	2·09	170
3	1·48	31	2·38	240
4	1·62	25	2·26	240
1985				
5	1·70	55	2·34	240
6	1·72	51	2·31	240
1986				
7	1·42	38	1·85	115
8	n.f.†	—	n.f.	—
9	1·64	0	1·99	240
1987				
10	1·49	0	2·11	240
11	1·56	40	1·93	190
12	1·91	0	2·23	200
1988				
13	1·67	28	2·32	240
14	1·53	40	1·83	240

* Grain N was not measured.
† n.f., no fit.

The mean response in grain N concentration between minimum and maximum values was 0·12% N (range 0·06–0·22) for each 40 kg/ha N applied.

Timing of applied N usually showed very little effect on grain N concentration at each site, with a mean of 1·94% (range 1·66–2·15) for a single dressing, compared with 1·91% (range 1·56–2·12) from an early dressing of 40 kg/ha N and 1·96% (range 1·71–2·11) after a late dressing of 80 kg/ha N. The only statistically significant ($P < 0·05$) effect at individual sites was a reduction in grain N concentration at sites 3 and 14 when N was applied as an early divided, instead of a single dressing.

Apparent recovery of the optimum amount of applied N in grain (ARN_{opt}) ranged from 13 to 57% (mean 39%) and it increased with the degree of yield response ($Y_{opt} - Y_0$) to applied N ($ARN_{opt} = 6·80 + 11·3\ (Y_{opt} - Y_0)$, $r = 0·719$ (13 paired values)).

Lodging

The percentage of crop area lodged always increased significantly ($P < 0·05$) with increasing amount of applied N, except at Site 13 where there was no lodging (Table 3). Some lodging occurred at Site 12 even without N fertilizer, because of a large soil N supply. The optimum amount of fertilizer N decreased as overall site lodging increased ($N_{opt} = 195 - 1·63 \times$ %lodging, $r = 0·691$ (12 paired values)). The average N_{L0} was 51 kg/ha N (range 20–120) for the 11 sites where lodging incidence was recorded. N_{L0} was correlated with soil N_{min} at the seven sites where soil N supply was measured in the spring ($N_{L0} = 101 - 0·894 \times N_{min}$, $r = 0·794$ (7 paired values)). The average N_{L50} was 149 kg/ha N (range 73–217) and nine of the 11 sites had < 50% lodging at the optimum amount of N. The average amount of fertilizer N between the start of lodging and 50% lodging ($N_{L50} - N_{L0}$) was 89 kg/ha (range 70–124) at 10 of the 11 sites; the major exception was Site 8, where the main N dressing was applied late and, as a result, ($N_{L50} - N_{L0}$) was 184 kg/ha.

Surprisingly, early divided N reduced the mean percentage lodging across sites from 49% for a single N dressing to 43%, whereas late N increased lodging to 53%. The timing of applied N significantly ($P < 0·05$) affected the amount of lodging at Sites 3, 7, 10 and 11, where early N caused less lodging. Late N did not consistently influence the extent of lodging at these four sites. A significant interaction between amount and timing of N on lodging only occurred at Sites 3 and 10, where early N caused less lodging from the largest amounts of total N application.

Mean grain weight

Fitted mean grain weights at nil N and at the 'startpoint' (single line regressions, with or without the nil N value) or 'breakpoint' (two-line function fits) for the regression fits used to describe the data are given in Table 5, together with the corresponding amount of applied N at the 'start/breakpoint' and the rate at which mean grain weight changed with applied N. Mean grain weight decreased with increasing amounts of applied N at each site, although the decreases were very slight at Sites 2, 3, 5, 8 and 13. Actual reductions in mean grain weight with increasing amounts of N > 80 kg/ha were statistically significant ($P < 0·05$) at seven sites. The mean value for fitted mean grain weight at N_{opt} was 32·0 mg (range 27·1–37·8); across all sites the mean rate of decrease in mean grain weight with applied N was 0·60 mg/grain (range 0·12–1·44) for each 40 kg/ha N applied.

Timing effects on mean grain weight were generally small at each site; mean grain weight was never changed by > 1·4 or 1·3 mg with early or late N dressings, respectively, compared to the single timing. Timing differences were, however, statistically significant ($P < 0·05$) at five sites; early N reduced mean grain weight at Site 7 but increased it at Site 12. Late N reduced mean grain weight at Sites 5 and 10 but increased it at Site 2. Amount and timing of N only showed a significant interaction on mean grain weight at Site 12, where reductions in mean grain weight with applied N tended to be greatest with single dressing.

Table 5. *Fitted mean grain weight (mg/grain, 85% DM basis) at nil applied N and the 'start' (single line fit) or 'breakpoint' (two line regression fit), with the corresponding rate of applied N (kg/ha); fitted decrease in mean grain weight (MGW) with applied N (mg/grain per 40 kg/ha N) and the variance accounted for (%) by regression*

Year and site code	Fitted mean grain weight at		N rate at start/breakpoint	Change in MGW with applied N	Percentage variance accounted for
	Nil N	Start/breakpoint			
1984					
1	29·2	29·2	0	−0·88	61·4
2	30·3	30·3	0	−0·24	19·3
3	27·5	27·0	200	−0·12	27·0
4	34·6	29·4	200	−1·04	76·6
1985					
5	34·2	34·1	40	−0·16	5·0
6	29·2	28·7	40	−0·44	51·3
1986					
7	33·1	29·3	107	−1·44	—
8	28·0	27·9	40	−0·16	—
9	36·5	36·0	40	−0·48	25·3
1987					
10	35·3	34·5	40	−0·80	48·4
11	38·3	38·3	0	−0·84	48·7
12	37·8	37·8	0	−1·00	57·8
1988					
13	37·8	37·5	40	−0·32	16·4
14	35·1	35·1	0	−0·56	41·7

Nitrogen harvest index (NHI) and fertile shoot numbers

Total crop N in grain and straw at harvest was measured for each treatment at Sites 3 and 4 only, to determine NHI. As found with other cereals, larger amounts of N fertilizer reduced NHI significantly ($P < 0{\cdot}05$) at Site 4. Late N consistently increased NHI significantly ($P < 0{\cdot}05$) at Site 3, and early N reduced NHI at Site 4, compared with the single N dressing.

Fertile shoot counts were only recorded at Sites 1, 2 and 6. Shoot numbers increased with applied N, although differences between N amounts > 80 kg/ha were only statistically significant ($P < 0{\cdot}05$) at Site 2. Timing treatments had no significant effect. An average of 37·3 grains per shoot was calculated for these three sites from the yields, mean grain weights and fertile shoot counts, with a maximum range of only 6·4 grains per shoot from the effects of applied N.

DISCUSSION

N requirement and its predictability

Oats provide an effective 'break' crop in a cereals rotation against the soil-borne fungus 'take-all' (*Gaeumannomyces graminis*) and associated yield benefits for the following wheat crops (Bennett 1989; Hornby & Bateman 1991). Lodging risk is, however, an important factor in oat production, and the

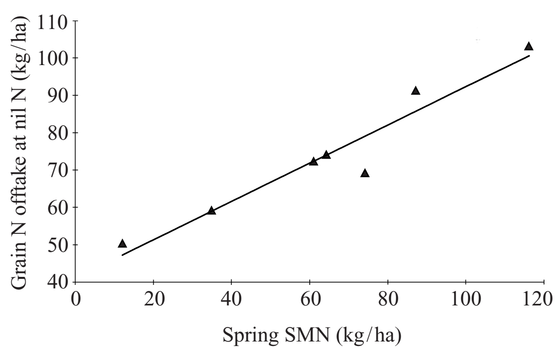

Fig. 2. Effect of spring soil mineral N (kg/ha, 0–90 cm) on grain N offtake at nil applied N ($N_{oft0} = 41{\cdot}0 + 0{\cdot}514$ SMN, $r = 0{\cdot}963$).

accurate prediction of N requirement, allowing for soil N supply, will minimize the risk of major crop lodging which could reduce yield and grain quality. Grain N offtake at nil N was highly correlated with spring soil N_{min}, which was taken as a direct measure of soil N supply, at the seven sites where both variables were measured and has thus been taken more generally as a good measure of soil N supply (Fig. 2). Some sites had a larger soil N supply than originally anticipated from previous cropping information; on further investigation, the main causes of unexpectedly greater N fertility proved to be the recent use of organic manures (Site 5) or the ploughing

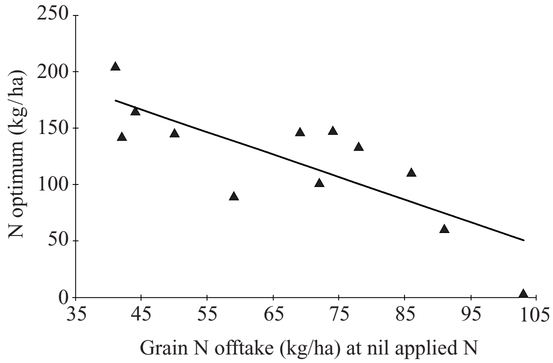

Fig. 3. Relationship between optimum amount of fertilizer N and N offtake in the grain at nil applied N ($N_{opt} = 256 - 2{\cdot}0\ N_{oft}$, $r = 0{\cdot}773$).

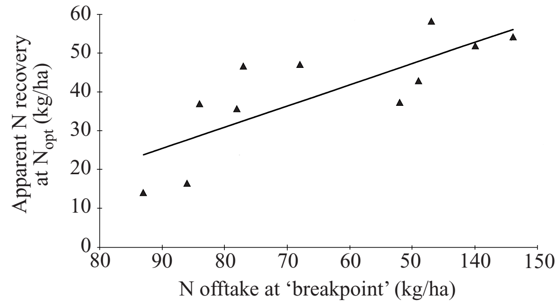

Fig. 4. Relationship between apparent recovery in the grain at the optimum amount of applied N and the N offtake in grain at the fitted 'break point' for N offtake ($ARN_{opt} = -23{\cdot}6 + 0{\cdot}545$ grain N offtake at 'break point', $r = 0{\cdot}757$).

out of a grass ley within the previous 3 years (Sites 2 and 12).

Mean yields in these experiments compared well with the national average for oats and were unrelated to the extent of lodging at each site. N optima varied widely but were not related to yield at N_{opt}, although these two variables have been shown to have some degree of correlation in other cereals (Sylvester-Bradley *et al.* 1987). Grain N offtake at nil N, as an indirect measure of soil N supply, accounted for 60% of the variance in N_{opt} (Fig. 3). Soil N_{min} did not give a significant correlation with N_{opt}, only accounting for 47% of the variance in N_{opt} ($P = 0{\cdot}09$), although it was only measured at seven of the 14 sites; subsequent mineralization of soil N during the spring and summer may partly explain the poorer correlation of soil N_{min} with N_{opt}. The results from this series of experiments have confirmed that, as with other crops (Sylvester-Bradley *et al.* 1987), soil N supply is an important predictor of fertilizer N requirement. Detailed examination of field histories will usually identify the soil N fertility status and where soil N supply is predicted as large, for example in mixed rotations, soil N_{min} testing will provide a useful guide to this aspect of N requirement.

Lodging, as well as N_{opt}, was related to soil N supply and it was not clear from the results whether the extent of site lodging limited the potential yield response to applied N and hence N_{opt}. Except for Site 9, those sites which lodged more severely with applied N showed a sharper downturn in yield with large amounts of N, compared with non-lodged or moderately lodged crops. Standard errors for N_{opt} were small at the majority of sites, where N_{opt} was well defined because of a downturn in yield with increasing N, but were moderate or large at Sites 5, 8, 9, 10 and 13, due to the pattern of yield response.

Apparent N recovery in the grain at N_{opt} tended to be less than in other cereal experiments (Bloom *et al.* 1988) and varied appreciably between sites. Recovery was related to the amount of yield response and also to the resulting grain N offtake from applied N at the 'breakpoint' illustrated in Fig. 1(*c*) (Fig. 4). Efficiency of fertilizer N use was consequently better at the more yield-responsive sites. Site yields were satisfactory despite the relatively poor N recoveries, assuming that the measured N harvest index at Sites 3 and 4 of *c.* 0·8 is typical for oats.

Although the main factor affecting variation in N_{opt} in these experiments appeared to be soil N supply, the soil N fertility at most sites was relatively low. Even at low N fertility (N Index 0; Anon. 1985), the amount of lodging which usually occurred at N_{opt} would have reduced speed of combining at harvest and increased the risk of crop losses due to sprouting or shedding of ripe grain during wet weather. The N recommendation for oats grown on mineral soils with low fertility was 100 kg/ha at the start of these experiments (Anon. 1985). This amount of N, which is less than the average N_{opt} (119 kg/ha) in this series of experiments, would in practice have lessened the risk of significant lodging but would also have led to a financial loss in grain yield. The results suggested that the N recommendation could be increased by 10–20 kg/ha, provided that appropriate measures are taken to control lodging by choice of cultivar and the use of a plant growth regulator. The two main cultivars of winter oats at the time of these experiments, Pennal and Peniarth, have since been superseded by new cultivars with better standing ability and yield potential (Anon. 1998), which are less likely to lodge when 110–120 kg/ha N is applied to low-N fertility sites. R. Green (unpublished) obtained an average and economic yield response of 0·36 t/ha when the amount of N application to the cultivars Pennal, Bulwark or Image was increased from 100 to 140 kg/ha at five sites in south-east England during 1985–88, even though the percentage lodging increased by an average of 36%.

Both the early and late divided N dressings gave, on average, almost the same yield as the single timing, despite significant but inconsistent timing effects from early N at two sites and from late N at three sites. Otherwise, yield differences at individual sites from divided N dressings were small, up to 0·2 t/ha, compared with a single N dressing and did not show any clear trends. The yield results suggest no agronomic advantage from applying a divided, rather than single, dressing to winter oats. Early N is, however, recommended on winter wheat and winter barley, because yield benefits are more likely in these crops on low N fertility soils (Anon. 1985). Sylvester-Bradley *et al.* (1984) found that applying part of the total N amount as a late split dressing of 40–50 kg/ha N at flag leaf emergence or later often reduced the yield of winter wheat.

Lodging

Leitch & Hayes (1989) showed that the increased susceptibility of oats to lodging at larger amounts of N was the result of longer stems of less weight per unit length having to support larger panicles. Crop lodging can create difficult harvest conditions and, depending on the stage at which lodging starts, reduce yield and quality. Despite overall treatment with a plant growth regulator, lodging occurred with increasing amounts of applied N at all sites except for Site 13, where N fertility was very low and BYDV infection had partially stunted the crop. Lodging was so severe at a further two sites in the wet summer of 1985 that they could not be harvested. Such unreliability is probably not representative of the UK as a whole. Although drilling date was not a factor in the experimental design, the overall amount of lodging at each site tended to be less with later drilling dates, an effect also noted by Hayes (1989).

The extent of site lodging at harvest increased with grain N offtake at nil N (as an estimate of soil N supply) (Fig. 5). Coincidentally, N_{opt} was also correlated with site lodging, which accounted for 53% of the variance in N_{opt}, as well as with soil N supply. However, multiple regression of N_{opt} on site lodging and soil N supply gave little improvement in correlation compared with the single regressions, accounting for 65% of the variance in N_{opt}. This suggests that lodging, expressed as a site mean, was not a major influence on N_{opt}, as no relationship was found between the amount of lodging which occurred at 120 kg/ha of applied N and N_{opt}. The average amount of N supplied from soil plus fertilizer, needed to cause the start of crop lodging, was 120 kg/ha (range 88–170).

Optimum yields were unrelated to lodging, whether defined as the overall site mean or as the mean percentage lodging at 120 kg/ha N. The lack of correlation between yield and lodging suggests either that lodging mostly happened late in the season or that crops recovered after initial lodging. The onset of lodging was not recorded at each site, but would have been influenced by seasonal factors such as strong winds or heavy rainfall during June–August. Early lodging will limit light distribution within the canopy and have a more detrimental effect on the crop than lodging later in the season.

Lodging is the failure of a complex plant/soil support system at its weakest point (Easson *et al.* 1990); the origin of lodging can be above ground, as stem failure, or below ground due to root failure, normally when the soil surface is wet and roots have pulled through the soil. Lodging origin was recorded at Site 11 as stem failure, which is likely to be the more common lodging mechanism in oats. Timing of applied N had been expected to influence lodging; early N in cereals encourages greater tiller survival and should increase the risk of subsequent lodging, whereas late N ought to have produced fewer, and so shorter and sturdier, stems less prone to lodging. Average differences in lodging due to timing were small but significant and contrary to expectations. Compared with a single N dressing, early N reduced the amount of lodging at nine of the 11 recorded sites, although the mean reduction from 49 to 43% was largely influenced by Site 10, where early N application was delayed until late March; lodging differences between these two N timings were mostly small at the other sites. Late N consistently caused similar amounts of lodging as the single N dressing, with a slightly higher mean of 53%. However, N dressings at GS30–31 were applied after mid April at ten of the sites, according to crop development, and this delay in application may have mitigated lodging susceptibility from the single N dressing. Another possibility is that late N may have produced shorter stems with a subsequent larger leaf canopy, resulting in increased potential for rain capture and associated top-heaviness. Insufficient data were obtained on shoot densities to determine whether they influenced timing effects on lodging, although the shoot densities recorded at three sites were not significantly affected by N timing.

As early N rarely gave any yield benefit, the lodging results also suggest that a N requirement of 100–120 kg/ha could be applied as a single dressing at GS30–31 on soils with low N status. Late N divided dressings are not advocated from these results, as this timing did not give any yield or lodging benefits and, in dry summers, could lead to poorer efficiency of N use, yield loss and increased risk of nitrate leaching losses in the following winter.

Grain quality

The principal market sectors for oats are human food products and animal (including horse) feeds, although there is also a small outlet for industrial use (Loader 1991). Each sector has particular oat quality requirements, including good grain size, measured as specific

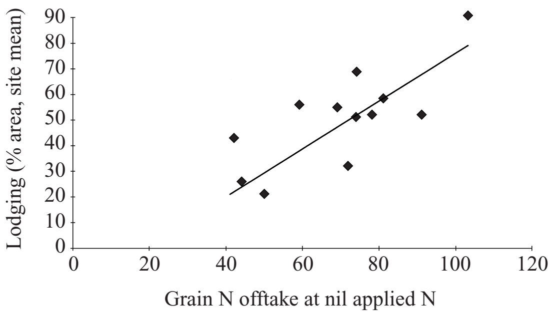

Fig. 5. Relationship between average amount of crop lodging at harvest and soil N supply (% crop lodging (site mean) = $-17{\cdot}4+0{\cdot}936\ N_{oft0}$, $r = 0{\cdot}762$).

weight, and, for animal feeds, adequate crude protein content (Loader 1991). However, oat quality is not classified, as milling and feed standards are set on an *ad hoc* basis according to season. Mean grain weight is considered to be a relatively unimportant quality factor for the oats market (Loader 1991). Treatment effects in these experiments on grain N and mean grain weight, as parameters for grain quality, thus have less agronomic significance than their effects on yield and lodging incidence. Oat oil has a range of potential uses and raising the level of oil (and protein) would increase the value and marketability of oat grain (Butler-Stoney & Valentine 1991). It is likely, however, that any decreases in grain oil concentrations that may occur with applied N would be small.

Grain N concentration, and hence protein content, always increased significantly with applied N. The average increase of 0·12 %N per 40 kg/ha applied N is similar to the typical grain N increases which are obtained for N dressings at GS30–31 on wheat (Sylvester-Bradley *et al*. 1987). Minimum concentrations of grain N were inversely related to yield response ($\%\text{Nmin} = 1{\cdot}84-0{\cdot}085\ (Y_{opt}-Y_0)$, $r = 0{\cdot}793$ (12 paired values)), due to N ‘dilution’ at low rates of applied N. Maximum concentrations of grain N were inversely related to Y_{opt}, which also suggests a ‘dilution’ effect, although this only accounted for 38 % of the variance in maximum N concentration ($\%\ N_{max} = 3{\cdot}0-0{\cdot}119\ Y_{opt}$, $P < 0{\cdot}05$). N timing affected grain N concentration, but the effects were very slight; early N, which would typically be expected to encourage vegetative growth, did tend to reduce grain N concentration. Late N, which is more likely to be taken up into the grain if there is adequate soil moisture, tended to increase grain N concentration, compared with the single N dressing. The grain results indicate that, as for yield and lodging effects, there is no advantage in using divided, rather than single dressings.

Changes in mean grain weight due to the amount and timing of N were small, although sometimes statistically significant, at individual sites. The average reduction in these experiments of 0·6 mg/grain for each 40 kg/ha N applied suggests that normal fertilizer N inputs will have little adverse effect on mean grain weight. Mean grain weight was not significantly related to the amount of lodging, which may also suggest that the onset of lodging tended to be relatively late in the season. Mean grain weight might be expected to be negatively correlated with fertile shoot density for soils of similar texture, but insufficient records of shoot densities were taken to test this hypothesis. These results show that appropriate agronomic adjustments to the amount and timing of fertilizer N for optimizing yield, albeit at the risk of some lodging in oat cultivars with only moderate standing ability, would not adversely affect the variables of grain quality which were measured in these experiments.

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