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Assessing the benefits of using foliar N on oilseed rape

by
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CONTENTS

1. ABSTRACT

The specific objectives of this project were to:

1. understand whether late foliar N gives any yield advantage over and above optimal amounts of soil applied N such as ammonium nitrate.
2. identify the optimum timing and rate of foliar N.
3. quantify the efficiency with which foliar N is used by the crop
4. develop guidelines for the best use of late foliar N.

Field experiments were set up in 2008/09 and 2009/10 near ADAS Rosemaund, Herefordshire, and near ADAS High Mowthorpe, North Yorkshire. Each of the four experiments investigated six rates of soil applied N (ammonium nitrate) ranging from 0 to 280 or 320 kg N/ha with each treatment followed by zero or 40 kg/ha of foliar N applied as Nufol 20 (20% N) at the end of flowering. Each experiment also investigated five rates of foliar N ranging from 0 to 120 kg N/ha and five timings of foliar N from mid-flowering to two weeks after the end of flowering.

Foliar N at 40 kg N/ha increased the gross output by, on average, 0.20 t/ha across all experiments (range of 0 to 0.40 t/ha). This increase in gross output was achieved despite a reduction in the percentage oil content in the seed by an average of 0.9%. The gross output response was the same regardless of whether it followed sub-optimal or super-optimal rates of soil applied N, indicating that foliar N can increase yields over-and-above that achieved from optimal amounts of soil applied N. Similar yield responses were observed for foliar N applications between mid-flowering and two weeks after the end of flowering, which may indicate that foliar N could be combined with a fungicide spray during flowering. A foliar N rate of 40 kg/ha was found to be the maximum rate that should be used. Foliar N was usually taken up with a high efficiency of 70 to 100% and the resulting increase in post-harvest N residues was modest. It is recommended that foliar N should not be applied when the temperature is above 18°C. Yield responses were quite variable and further work is needed to identify environmental and crop factors that cause this variation. If minimal crop damage from applying foliar N is assumed then it may be concluded that, across a number of fields and seasons, applying foliar N at 40 kg N/ha will generally return a profit as long as the ratio of fertiliser cost (£ per kg of elemental N) to oilseed rape price (£/kg) is less than 3.0 when foliar N costs between £0.50 and £0.75 per kg of N, or the cost:price ratio is less than 3.5 when foliar N costs £0.80 to £1.00 per kg of N.

2. SUMMARY

2.1. Introduction

The benefits of foliar N applied to oilseed rape during flowering or early pod development as a means for increasing yield have been promoted by several sources within the agricultural industry. For example, yield responses to foliar urea applied at the end of petal fall of 0.5 to 1.6 t/ha have been reported in the popular farming press. At the time of writing this report the authors found no other independent information on the response of oilseed rape to late foliar N.

A key question is whether foliar N gives a yield benefit following optimal amounts of soil-applied N (e.g. ammonium nitrate). It is possible that the responses to foliar N that have been observed have occurred because the crops did not receive sufficient soil applied N before flowering. It is also not known at which growth stage foliar N should be applied, what the optimal rate is, or what type of crop may respond most. It will be important to understand whether foliar applied N could act as a substitute for late applications of soil applied N at yellow bud or early flowering as these can be taken up less efficiently in dry conditions and are difficult to apply to tall crops. The efficiency with which oilseed rape uses foliar N has not been measured and an understanding of this will be important for estimating the impact of foliar N use on N emissions to the air and water and its impact on the carbon footprint. Finally the impact of foliar applied N on seed protein has not been quantified which is important as it is usually inversely related to oil content.

2.1.1. Aim and objectives

Project Aim

To develop independent guidelines that describe how to make the best use of late foliar N applications on oilseed rape.

Specific Objectives

1. To understand whether late foliar N gives any yield advantage over and above optimal amounts of soil applied N such as ammonium nitrate.
2. To identify the optimum timing and rate of foliar N.
3. To quantify the efficiency with which foliar N is used by the crop
4. To develop guidelines for the best use of late foliar N.

2.2. Materials and methods

Field experiments were set up in 2008/09 and 2009/10 near ADAS Rosemaund (RM09 and RM10), Herefordshire, on a silty clay loam and near ADAS High Mowthorpe, North Yorkshire, on a silty clay loam (HM09 and HM10). The site codes (in brackets) are used in summary tables later in report. Experiments investigated six rates of soil applied N (ammonium nitrate) ranging from 0 to 280 or 320 kg N/ha, five rates of foliar N ranging from 0 to 120 kg N/ha (applied as Nufol 20, 20% N) applied at the end of flowering, five timings of foliar N from mid-flowering to two weeks after the end of flowering, and one rate of Omex Oilseed Extra (20 kg N/ha in 2008/09 and 40 kg N/ha in 2009/10). The rate of soil applied N required to achieve an optimum sized canopy at flowering was estimated using Canopy Management principles from measurements of soil mineral N and crop N in February. This soil applied N rate was either 160 or 200 kg N/ha and was followed by the foliar N rate and timing treatments. Each of the six soil applied N rates was followed by zero or 40 kg/ha of foliar N applied at the end of flowering. Foliar N was applied as Nufol 20 (20% N). A water volume of 100 l/ha was used for a foliar N rate of 20 kg N/ha, 200 l/ha for 40 kg N/ha, 400 l/ha for 80 kg N/ha and 600 l/ha for 120 kg N/ha. Soil mineral N levels and dates of fertiliser applications are described in Summary Table 1. Plots were 24m long x 3.5m wide and arranged in randomised blocks with all treatments replicated four times. Experiments were treated in spring with 75 kg/ha SO_3 as Kieserite to avoid sulphur limitation.

Measurements included: seed yield, oil content, leaf scorch, lodging, together with the biomass and N content of the seed, pod walls and stems. In 2010, thousand seed weight and seeds/m^2 were measured. Gross output was calculated to account for the combined economic effect of each treatment on seed yield and oil content using the equation below in which it is assumed that the oil bonus is 1.5% of the basic oilseed price for each additional percentage of oil content above a base level of 40%.

$$GrossOutput = 1.5\left(\frac{oilcontent - 40}{100}\right) * seedyield$$

Analysis of variance procedures within Genstat 12 (www.genstat.com) were used to calculate whether treatments were significantly different. Linear plus exponential N response curves were fitted to the seed yield and gross output data for each treatment and these were used to calculate the economic optimum N rate based on a breakeven ratio of 2.5:1.

Summary Table 1. Details of February SNS measurements, N rates and application dates for individual sites.

	HM09	RM09	HM10	RM10
Feb SMN (kg/ha)	14	19	32	24
Feb crop N (kg/ha)	65	37	50	58
Total SNS (kg/ha)	79	56	82	82
Soil appl N 1st split	16 March	05 March	23 March	11 March
Soil appl N 2nd split	7 April	19 March	21 April	30 March
Soil appl N 3rd split	21 April	08 April	11 May	19 April
Foliar N				
mid flower	10 May	22 April	19 May	14 May
mid flower +7d	21 May	29 April	27 May	21 May
end flower	4 June	24 May	11 June	2 June
end flower +7d	12 June	01 June	17 June	9 June
end flower +14d	21 June	08 June	25 June	16 June

SMN – soil mineral N, SNS – soil N supply (SMN + crop N)

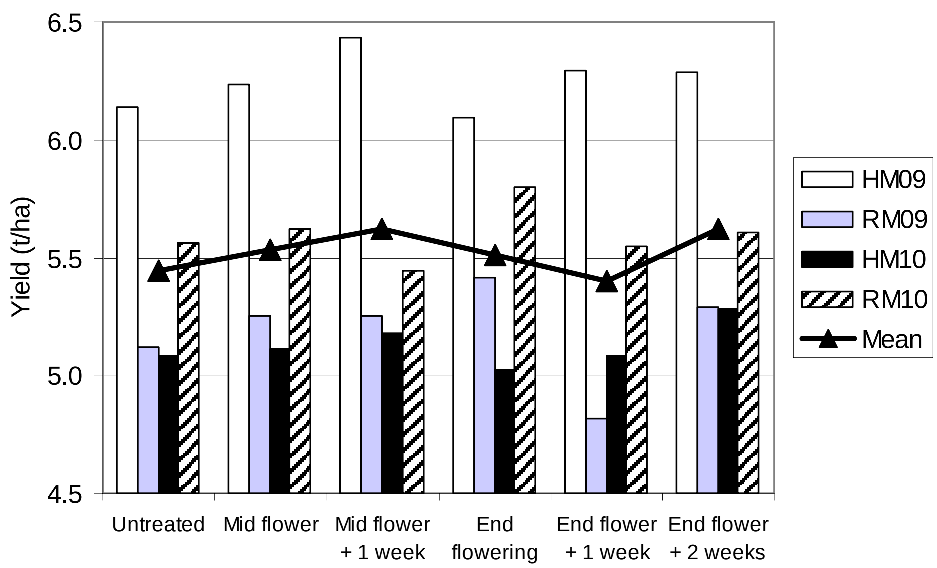
2.3. Results

2.3.1. Seed yield

The greatest yield responses resulted from increasing the soil applied N rate (ammonium nitrate) from zero to 80 or 100 kg N/ha, which increased yields by 1.42 t/ha on average. Increasing N rate by a further 80 to 100 kg N/ha increased yields by a further 0.65 t/ha on average. The economic optimum N rate for the soil applied N treatments without foliar N were 190 kg N/ha at HM09, 214 kg N/ha at RM09, 214 kg N/ha at RM10 and 174 kg N/ha at HM10. At these optimum N rates the seed yield was 6.11 t/ha at HM09, 5.12 t/ha at RM09, 5.09 t/ha at HM10 and 5.45 t/ha at RM10.

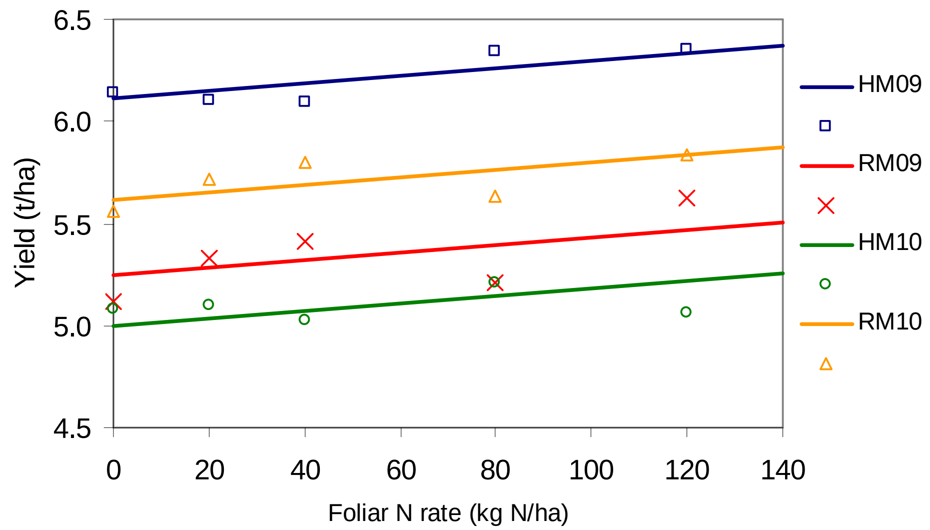
At HM09 the effect of foliar N applied at the end of flowering at 40 kg/ha interacted with the soil applied N rate ($P<0.05$) because the greatest yield increase of 0.72 t/ha was observed following a soil applied N rate of 80 kg/ha and smaller yield responses of up to 0.47 t/ha were observed following the other soil applied N rates. Foliar N increased yield by 0.24 t/ha on average across all soil applied N treatments at HM09. At RM10, a similar interaction was observed ($P=0.058$) to HM09 where the greatest yield response of 1.25 t/ha was observed in the absence of any soil applied N, with smaller yield responses of up to 0.32 t/ha following greater soil applied N rates. The average response to foliar N at RM10 was 0.41 t/ha. At RM09, there was no interaction between the soil applied and foliar N treatments and the average response to foliar N was 0.26 t/ha. At HM10, foliar N did not significantly affect yield.

The effect of foliar N timing between mid flowering and two weeks after flowering was investigated by applying a rate of 40 kg N/ha following a soil applied N rate of 160 kg N/ha at HM09, HM10 and RM10 and following 200 kg N/ha at RM09. There was no significant difference in yield response following the application of foliar N at the different timings at any site except RM09. The significant result at this site was due to a low yield following the 4th foliar N timing (7 days after end of flowering). This effect might be explained by warm weather on the day of application and the following day (max 26°C and 25°C respectively). At the same site, the other foliar N applications were applied on days with maximum temperatures no higher than 19°C. A cross site analysis revealed no consistent difference in the response of foliar N applied between mid flowering and two weeks after the end of flowering (Summary Figure 1), with an average yield response across all of the timing treatments of 0.11 t/ha.



Summary Figure 1. Effect of foliar N (40 kg N/ha) on yield, applied following soil applied N rates of 200 kg N/ha at RM09 and 160 kg N/ha at the other sites.

The effect of foliar N rate was investigated by applying rates of 0 to 120 kg N/ha at the end of flowering following a soil applied N rate of 160 kg N/ha at HM09, HM10 and RM10 and following 200 kg N/ha at RM09. At RM09, a foliar N rate of 120 kg N/ha increased yield by 0.5 t/ha ($P<0.05$), but lower foliar N rates had no significant effect. At the other sites there were no significant yield responses to foliar N applied at any rate (20 to 120 kg N/ha). A cross site analysis of variance revealed no consistent difference in the yield response to different rates of foliar N. The lack of significant effects from this dose response analysis, compared with the analysis for foliar N at 40 kg/ha, may be because the latter analysis was across several soil applied N rates which increased the amount of replication. Multiple linear regression analysis showed that the average yield increase per kg of foliar N was 0.002 t/ha and this was the same in each experiment (Summary Figure 2). Total Oilseed Extra applied at 20 kg N/ha at HM09 and RM09 and at 40 kg N/ha at HM10 and RM10 did not significantly increase yield following soil applied N rates of 160 or 200 kg N/ha; yield increases were up to 0.10 t/ha.



Summary Figure 2. Effect of foliar N rates on yield, applied at the end of flowering following soil applied N rates of 200 kg N/ha at RM09 and 160 kg N/ha at the other sites.

2.3.2. Oil content

Across all experiments increasing the soil applied N rate from 0 to 160 or 200 kg N/ha reduced oil content by 2.2% (Summary Table 2). Smaller reductions in oil content were observed when the N rate was increased above 160 or 200 kg N/ha.

Foliar N applied at the end of flowering at a rate of 40 kg N/ha significantly reduced oil content at HM09, RM09 and RM10 (Summary Table 2). At RM09 there was a significant interaction between foliar N and the soil applied N treatment because foliar N reduced oil content more at lower soil applied N rates than at high N rates. A cross site analysis showed a significant interaction between the foliar N and soil applied N treatments ($P<0.01$), and no interaction between site, foliar N and soil applied N, indicating that the interaction between foliar N and soil applied N was consistent across sites. Across sites, foliar N reduced oil content by 1.6% to 1.8% at soil applied N rates between zero and 160 to 200 kg N/ha, by 0.4% at soil applied N rates of 200 or 240 kg N/ha with no effect at greater soil applied N rates. In 2010, additional oil measurements were carried out on the foliar N rates at 20, 80 and 120 kg N/ha. These showed a negative linear relationship between increasing foliar N rate (0 to 120 kg/ha) and oil content with each additional kilogram of foliar N reducing oil percentage by 0.0324% at HM10 and by 0.0254% at RM10.

Summary Table 2. Oil content (%) for the factorially combined soil applied N and foliar N treatments.

Soil applied N rate (kg/ha)	Foliar N (kg/ha)	† Foliar N timing	HM09	RM09	HM10	RM10	Mean
0	0	0	53.0	49.0	48.5	49.3	49.9
80 or 100	0	0	52.5	48.2	46.0	48.6	48.8
160 or 200	0	0	50.3	46.4	46.5	47.4	47.6
200 or 240	0	0	49.2	46.0	44.7	46.1	46.5
240 or 280	0	0	49.1	45.1	45.0	45.6	46.2
0	40	3	51.7	47.3	46.8	47.0	48.2
80 or 100	40	3	49.8	47.2	44.4	46.7	47.0
160 or 200	40	3	50.0	45.7	43.0	45.3	46.0
200 or 240	40	3	49.7	44.7	44.8	45.4	46.2
240 or 280	40	3	48.4	46.2	45.7	45.0	46.3
Mean without Foliar N			50.8	46.9	46.2	47.4	47.8
Mean with 40 kg/ha of Foliar N			50.0	46.2	45.0	45.9	46.9
Grand Mean			50.4	46.6	45.6	46.6	47.4
	Soil appl	P Value	<0.001	<0.001	NS	<0.001	
	Soil appl	SED	0.59	0.41	1.26	0.59	
Foliar N		P Value	<0.05	<0.01	NS	<0.001	
Foliar N		SED	0.37	0.26	0.71	0.38	
Soil applied N x Foliar N		P Value	NS	<0.05	NS	NS	
Soil applied N x Foliar N		SED	0.83	0.59	1.71	0.84	

† Foliar N timings: 3 – end of flowering

2.3.3. Gross output (seed yield adjusted for oil content)

Gross output is the combined economic effect of seed yield and oil content as described in section 2.1. Increasing soil applied N increased gross output at all sites (Summary Table 3), however the increases in gross output were not as great as for seed yield because increasing soil applied N rate also reduced oil content.

Foliar N applied at the end of flowering at a rate of 40 kg N/ha significantly increased gross output at HM09, RM09 and RM10 (Summary Table 3). At RM09 and RM10 the average gross output increase to foliar N was 0.27 t/ha and 0.40 t/ha respectively. At HM09, there was a significant interaction between the foliar N and soil applied N treatments because foliar N increased yield by 0.62 t/ha at 80 kg N/ha, and by 0.44 t/ha at 200 kg N/ha, but had no effect at zero and the other soil applied N rates. Across all soil applied N rates the foliar N treatment increased gross output by 0.15 t/ha at HM09. Foliar N had no significant effect on gross output at HM10. A cross site analysis showed that the interaction between the soil applied N and foliar N treatments was not significant at the 95% level of confidence (P=0.087). A foliar N rate of 40 kg/ha applied at the end of flowering increased gross output by 0.20 t/ha across all sites and soil applied N rates of 0 to 240 or 280 kg/ha. However it should be recognised that there was also a highly significant 3-way interaction between site, soil applied N and foliar N treatments which showed that the effects of foliar N were not consistent between experiments.

Summary Table 3. Gross output (t/ha) for the factorially combined soil applied N and foliar N treatments.

Soil applied N rate (kg/ha)	Foliar N (kg/ha)	† Foliar N timing	HM09	RM09	HM10	RM10	Mean
0	0	0	5.08	2.57	3.65	4.30	3.90
80 or 100	0	0	6.11	4.62	4.91	6.00	5.41
160 or 200	0	0	7.08	5.31	5.58	6.17	6.04
200 or 240	0	0	6.93	5.34	5.46	6.09	5.96
240 or 280	0	0	7.09	5.22	5.60	6.01	5.98
0	40	3	4.86	2.89	3.73	5.57	4.26
80 or 100	40	3	6.73	5.06	5.00	6.20	5.75
160 or 200	40	3	7.01	5.52	5.25	6.26	6.01
200 or 240	40	3	7.37	5.38	5.49	6.29	6.13
240 or 280	40	3	7.09	5.57	5.68	6.24	6.14
Mean without Foliar N			6.46	4.61	5.04	5.71	5.46
Mean with 40 kg/ha of Foliar N			6.61	4.88	5.03	6.11	5.66
Grand Mean			6.47	4.66	4.96	5.88	5.49
	Soil appl	P Value	<0.001	<0.001	<0.001	<0.001	
	Soil appl	SED	0.111	0.128	0.116	0.224	
Foliar N		P Value	<0.05	<0.01	NS	<0.01	
Foliar N		SED	0.070	0.810	0.073	0.143	
Soil applied N x Foliar N		P Value	<0.01	NS	NS	0.073	
Soil applied N x Foliar N		SED	0.157	0.181	0.164	0.317	

† Foliar N timings: 3 – end of flowering

The use of foliar N did not affect the economic optimum soil applied N rate for gross output at HM09, RM09 or HM10. At HM09 and RM09 the N response data supported fitting parallel curves to the soil applied N and foliar N treatments. At HM10, a single response curve was shown to explain most variation because the foliar N treatment did not significantly affect yield at this site. At RM10, the N response data supported fitting non-parallel response curves to the soil applied N and foliar N treatments because foliar N caused a steeper response to the soil applied N treatments. The economic optimum soil applied N rates for gross output were 175 kg N/ha at HM09, 184 kg N/ha at RM09 and 237 kg N/ha at HM10. At RM10 the optimum soil applied N rate was 111 kg N/ha without foliar N and 84 kg N/ha with foliar N.

In 2010, additional measurements of oil content at the full range of foliar N doses enabled the effect of foliar N rate on gross output to be calculated. The maximum gross output occurred with a foliar N rate of 0 kg/ha at HM10 and 40 kg/ha at RM10. When the average oil response to foliar N across HM10 and RM10 was used to estimate the effect of foliar N rate on gross output across all four sites, then the greatest gross output increase occurred at a foliar N rate of 20 kg N/ha, with a smaller increase at 40 kg N/ha and reductions at 80 and 120 kg/ha.

2.3.4. N uptake

Foliar N applied at 40 kg N/ha at the end of flowering increased total N uptake by 42 kg N/ha at HM09 ($P<0.05$), 28 kg N/ha at RM09 ($P<0.001$), 37 kg N/ha at RM10, with no effect at HM10. The uptake efficiency of foliar N therefore ranged from 0 to over 100%, with an average across sites of 67%. At HM09, RM09 and RM10 foliar N increased N uptake by increasing the amount of N in the seed and pod wall (kg N/ha), which in turn resulted from increases in the biomass and N concentration of the seeds and pod walls. The reduction in the percentage of oil in the seed in response to foliar N was caused by a greater increase in protein yield (t/ha) than in oil yield (t/ha) which effectively diluted the oil content in the seed. On average, the increase in the N content of the crop residues following harvest as a result of 40 kg/ha of foliar N was 12 kg N/ha.

2.4. Discussion

Foliar N applied at the end of flowering at a rate of 40 kg N/ha increased seed yield by 0.41 t/ha at RM10, 0.26 t/ha at RM09, 0.24 t/ha at HM09 and had no significant effect at HM10. There was a tendency for foliar N to increase yield more when following nil or sub-optimal amounts of soil applied N. The economic benefits from increased seed yield from foliar N were reduced by a reduction in the percentage of oil within the seed of approximately 1%. The combined effects of foliar N on seed yield and oil concentration have been estimated in terms of the effect on gross output which takes account of the economic penalty of any reduction in oil concentration. Foliar N applied at the end of flowering at a rate of 40 kg N/ha increased gross output by 0.20 t/ha across sites, with a range of 0 to 0.40 t/ha between sites. The discovery that a similar response to foliar N occurs following a wide range of soil applied N rates, including super-optimal rates, indicates that foliar N can be used to increase yield to levels over-and-above those that can be achieved using optimal amounts of soil applied N at earlier timings.

The dose response study indicated that foliar N rates of 20 kg/ha and 40 kg/ha both gave a positive gross output response, with 80 and 120 kg N/ha giving negative responses. However, the yield responses at 20 kg/ha were not statistically significant, whereas the yield responses to 40 kg/ha were significant. Based on statistical significance this study can conclude that a foliar N rate of 40 kg/ha is the maximum rate that should be used.

This study has demonstrated that there can be quite large variation in the yield response to foliar N, particularly between sites, but also within the same field when applications were made on different days. There was no evidence that the growth stage at which foliar N was applied explained the variation and environmental or crop factors are the most likely cause of the variation. Regression analysis showed a weak negative correlation between the yield response and the air temperature at application with most yield losses occurring when the air temperature was 19^{o}C or more. Neither soil wetness, overhead conditions (sun or cloud), relative humidity nor time of day affected the size of the yield response. More research is required to quantify the effect of temperature on the yield response and to identify whether there are other environmental or crop factors which affect the yield response.

This study has indicated that late foliar N could give a greater yield response than soil applied N at yellow bud or early flowering (particularly in dry conditions). However, it should be emphasised that the foliar N yield responses also occurred following optimal or super-optimal rates of soil applied N which indicates that foliar N should be used as a treatment for increasing yields over-and-above those that can be achieved using earlier applications of soil applied N, rather than as a substitute for soil applied N. If conditions are predicted to be dry then it may be best to apply N to the soil earlier.

The unpredictable variation in yield response to foliar N means that it is difficult to carry out a reliable cost-benefit analysis. The full report describes several cost-benefit scenarios which use different assumptions about the gross output response to foliar N, the cost of foliar N, the price of oilseed rape, the cost of applying foliar N and yield losses caused by travelling through the crop. These analyses showed that the cost effectiveness of foliar N depended strongly on the assumptions used and decisions on whether it will be profitable should be calculated for each individual situation.

If an average gross output response to foliar N at 40 kg N/ha of 0.20 t/ha is assumed then the resulting cost benefit analysis is described in Summary Table 4. Yield losses from travelling through the crop are unlikely to be significant given that the majority of crops are desiccated anyway and many receive a fungicide spray during flowering. As a general guide when the fertiliser N cost is between £0.50 and £0.75 per kg of N then for foliar N to be profitable the ratio of fertiliser cost (£ per kg of elemental N): oilseed rape price (£/kg) must be less than 3.0. When the fertiliser N cost is between £0.80 and £1.00 per kg of N then for foliar N to be profitable the ratio of fertiliser cost: oilseed rape price must be less than 3.5.

Summary Table 4. Effect of foliar N cost and oilseed rape price on the gross margin over cost (£/ha) of using foliar N at 40 kg N/ha, assuming it increases gross output by 0.20 t/ha

Oilseed rape price (£/t)	**Cost of foliar N (£/kg)**					
	0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1**
160	-1	-5	-9	-13	-17	-21
200	7	3	-1	-5	-9	-13
240	15	11	7	3	-1	-5
280	23	19	15	11	7	3
320	31	27	23	19	15	11
360	39	35	31	27	23	19
400	47	43	39	35	31	27
440	55	51	47	43	39	35

Cost of applying foliar N of £13/ha included within costs

2.5. Conclusions

- Guidance for using foliar N arising from this study includes:
    - When the foliar N cost is between £0.50 and £0.75 per kg of N then the ratio of fertiliser cost (£ per kg of elemental N) to oilseed rape price (£/kg) must be less than 3.0. When the foliar N cost is between £0.80 and £1.00 per kg of N then the ratio must be less than 3.5. Assuming application causes minimal crop damage.
    - Foliar N rates should not exceed 40 kg N/ha.
    - Apply any time between mid-flowering and 2 weeks after the end of flowering
    - Avoid applications when the air temperature is above 18^{o}C.
- Foliar N at 40 kg/ha significantly increased seed yield in 3 out of 4 experiments, but also significantly reduced the percentage oil content in the seed by an average of 0.9%.
- The reduction in oil content resulted in smaller responses in gross output compared with seed yield following foliar N. Gross output responses ranged from zero to 0.40 t/ha and averaged 0.20 t/ha across the experimental sites. The gross output response was the same regardless of whether it followed sub-optimal or super-optimal rates of soil applied N, indicating that foliar N can increase yields over-and-above that achieved from optimal soil applied N.
- Similar yield responses were observed for foliar N applications between mid-flowering and two weeks after the end of flowering. This indicates that foliar N could be combined with a sclerotinia spray. Further work should investigate whether foliar N could increase yield from applications at early flowering.
- Based on statistical significance this study can conclude that a foliar N rate of 40 kg/ha is the maximum rate that should be used, but further work is required to test whether it may be more economic to use less than 40 kg N/ha.
- Foliar N was taken up with an efficiency of 70 to 100% at the three sites where it increased yield significantly, with zero uptake at the unresponsive site.
- The effect of foliar N at 40 kg N/ha on post-harvest N residues was modest, giving an average increase of 12 kg N/ha.
- Variation in yield responses were observed, a modest amount of which was explained by temperature because many of the zero or negative responses occurred when foliar N was applied at 19^{o}C or more. Further work is needed to identify environmental and crop factors that cause variation in yield response.

3. TECHNICAL DETAIL

3.1. Introduction

The benefits of foliar N applied to oilseed rape during flowering or early pod development as a means for increasing yield are being promoted by several sources within the agricultural industry. For example, yield responses to foliar urea applied at the end of petal fall of 0.5 to 1.6 t/ha have been reported in the popular farming press. However, a study in the Czech Republic in 1999 observed no benefit from foliar N (Yang-Yuen *et al*., 1999). At the time of writing this report the authors found no other independent information on the response of oilseed rape to late foliar N.

A key question is whether foliar N gives a yield benefit following optimal amounts of soil-applied N (e.g. ammonium nitrate). It is possible that the responses to foliar N that have been observed have occurred because the crops did not receive sufficient soil applied N before flowering. It is also not known at which growth stage foliar N should be applied, what the optimal rate is, or what type of crop may respond most. The efficiency with which oilseed rape uses foliar N has not been measured, which will be important for estimating the impact of foliar N use on N emissions to the air and water and its impact on the carbon footprint. Finally the impact of foliar applied N on seed protein has not been quantified which is important as it is usually inversely related to oil content.

Recent research funded by HGCA and Growhow UK Ltd (HGCA Project Report 447; Berry and Spink, 2009) has shown that crops with a high yield potential have a greater requirement for N. An extra 30 kg of ammonium nitrate was required for each additional 0.5 t/ha of yield above 3.5 t/ha. It was shown that extra ammonium nitrate should be applied as late as possible in order to prevent the production of an over-large canopy at flowering, which would cause fewer seeds to be set and lower yield potential. However, ammonium nitrate applications cannot be delayed too much because the rate at which oilseed rape takes up N from the soil decreases after flowering. This means the last ammonium nitrate split should not be made later than early flowering and the amount that can be applied in the final application is limited due to the time needed for its uptake.

If foliar N can be shown to increase yield as efficiently, or more efficiently, as earlier soil applied N then it could be used to supply some or all of the additional N requirement of high yield potential crops without some of the potential problems associated with using late applied soil applied N, such as the risk of dry weather and difficulty achieving an even spread pattern in tall crops. If this project proves that the crop can use foliar N efficiently to increase yield then this will help growers to justify its use in fertiliser programmes. This may be of particular importance within nitrate vulnerable zones (NVZs) as growers sometimes cannot use foliar N as they would exceed their N Max limit.

3.1.1. Aim and objectives

Project Aim

To develop independent guidelines that describe how to make the best use of late foliar N applications on oilseed rape.

Specific Objectives

1. Understand whether late foliar N gives any yield advantage over and above optimal applications of soil applied N such as ammonium nitrate.
2. Identify the optimum timing and rate of foliar N.
3. Quantify the efficiency with which foliar N is used by the crop
4. Develop guidelines for the best use of late foliar N.

3.2. Experimental design, materials and methods

3.2.1. Experiments and treatments

Field experiments were set up in 2008/09 and 2009/10 near ADAS Rosemaund (RM09 and RM10), Herefordshire, on a silty clay loam and near ADAS High Mowthorpe, North Yorkshire, on a silty clay loam (HM09 and HM10). Experiments investigated 6 rates of ammonium nitrate prills ranging from 0 to 280 or 320 kg N/ha, 5 rates of foliar N ranging from 0 to 120 kg N/ha (applied as Nufol 20, 20% N) at the end of flowering, 5 timings of foliar N from mid-flowering to two weeks after the end of flowering, and one rate of Omex Oilseed Extra at a rate of 20 kg N/ha in 2008/9 and 40 kg N/ha in 2009/10. Oilseed Extra contains N and other nutrients including sulphur, magnesium, manganese, molybdenum and copper.

Table 1 shows details of treatments and timings used in one of the experiments; other site seasons used similar treatments, the only differences being in the soil applied N rates, which were determined after measurement of soil and crop N in February, and the rate of Oilseed Extra, which was increased to 40 kg N/ha in 2009/10 following a change in the rate recommended by the manufacturer.

Table 1. Details of treatments and timings at High Mowthorpe in 2008/09.

Treatment	Soil applied N rate (kg N/ha)			Foliar N rate (kg N/ha)				
	Early March, before stem ext	Late March / April, 2-3 weeks after 1st split	Yellow bud / early flower	Mid Flower (main raceme GS 4,9)	Mid Flower plus 7 days	End of petal fall	End petal fall plus 7 days	End petal fall plus 14 days
1	0	0	0	0	0	0	0	0
2	35	45	0	0	0	0	0	0
3	70	90	0	0	0	0	0	0
4	70	90	40	0	0	0	0	0
5	70	90	80	0	0	0	0	0
6	70	90	120	0	0	0	0	0
7	0	0	0	0	0	40	0	0
8	35	45	0	0	0	40	0	0
9	70	90	0	0	0	40	0	0
10	70	90	40	0	0	40	0	0
11	70	90	80	0	0	40	0	0
12	70	90	120	0	0	40	0	0
13	70	90	0	40	0	0	0	0
14	70	90	0	0	40	0	0	0
15	70	90	0	0	0	0	40	0
16	70	90	0	0	0	0	0	40
17	70	90	0	0	0	20	0	0
18	70	90	0	0	0	80	0	0
19	70	90	0	0	0	120	0	0
20	70	90	0	0	0	Oilseed Extra 20	0	0

The soil applied N rates used in treatments 3, 9 and 13-20 were intended to be at the rate required to achieve a yield of 3.5 t/ha according to 'Canopy Management Principles' (Table 2). Canopy Management involves applying sufficient N for the crop to achieve an optimum green area index (GAI) of 3.5 units at flowering, which has been shown to be sufficient to achieve a yield of around 3.5 t/ha (HGCA Report 447). The crop must take up 50 kg N/ha to build each unit of GAI, which means that the crop must take up 175 kg N/ha to achieve the optimum GAI of 3.5. Canopy Management principles assume that any N that the crop has taken up by the end of winter remains in the crop until flowering and therefore contributes to the production of the optimum GAI. It was also assumed that oilseed rape takes up 100% of the soil mineral N measured in the soil in February and 60% of any fertiliser N applied. This N was applied in two similar sized splits; 1) early March before stem extension and 2) at the green bud stage (GS3,5-3,6) which was usually 2-3 weeks after the first split (see Table 2 for application dates). The experiments at High Mowthorpe in 2008/9, High Mowthorpe 2009/10 and Rosemaund 2009/10 were each estimated to require 160 kg N/ha to achieve a yield of 3.5 t/ha because each all of these sites had a similar soil N supply (SNS) (combined soil mineral N plus crop N measured in February) of 79-92 kg N/ha (Table 2). The site at Rosemaund 2008/9 had a smaller SNS of 56 kg N/ha and therefore required 200 kg N/ha to achieve 3.5 t/ha (Table 2). An example of how the rate of N required to achieve 3.5 t/ha is described below.

Example: In February the amount of N in the soil was 50 kg N/ha and the amount of N in the crop was 50 kg N/ha. It is assumed that by flowering the crop will contain all of this soil and crop N (100 kg N/ha). This means it will be 75 kg N/ha short of the amount required for the optimum GAI. At 60% efficiency, 125 kg of fertiliser N must be applied to make up this shortfall.

Crops with a greater yield potential require additional N equating to 30 kg N/ha per additional 0.5 t/ha that potential yield is above 3.5 t/ha. Fields at Rosemaund and High Mowthorpe were chosen that had a yield potential of at least 4.5 t/ha. This additional N was applied between yellow bud and early flowering (Treatments 4-6 and 10-12) as ammonium nitrate (see Table 2 for application dates).

Foliar N was applied as Nufol 20 (20% N). A water volume of 100 l/ha was used for a foliar N rate of 20 kg N/ha, 200 l/ha for 40 kg N/ha, 400 l/ha for 80 kg N/ha and 600 l/ha for 120 kg N/ha. A CO_2 knapsack sprayer was used with Green nozzles (LD 015 F110) with medium spray for foliar N rates of 20 and 40 kg N/ha and Red nozzles (LD04 F110) with coarse spray for foliar N rates of 80 and 120 kg N/ha. A spray pressure of 2.5 - 2.8 bar was used for all applications.

Table 2. Details of February SNS measurements, N rates and application dates for individual sites.

	HM09	RM09	HM10	RM10
Feb SMN (kg/ha)	14	19	32	24
Feb crop N (kg/ha)	65	37	50	58
Total SNS (kg/ha)	79	56	82	82
N rate used in trts 3, 9 & 13-20 (kg/ha)	160	200	160	160
Soil appl N 1st split	16 March	05 March	23 March	11 March
Soil appl N 2nd split	7 April	19 March	21 April	30 March
Soil appl N 3rd split	21 April	08 April	11 May	19 April
Foliar N				
mid flower	10 May	22 April	19 May	14 May
mid flower +7d	21 May	29 April	27 May	21 May
end flower	4 June	24 May	11 June	2 June
end flower +7d	12 June	01 June	17 June	9 June
end flower +14d	21 June	08 June	25 June	16 June

SMN – soil mineral N, SNS – soil N supply (SMN + crop N)

Foliar N treatment applications were made in a range of environmental conditions including sunny and overcast days, 9°C to 26°C, 51% to 75% relative humidity, wet and dry soil conditions and early morning or late evening (Table 3).

Application timings included mid-flowering (GS4,5), mid-flowering plus 7 days, end of petal fall, end of petal fall plus 7 days and end of petal fall plus 14 days. Care was taken to avoid applying foliar N treatments in hot sunny conditions and applications were usually made in the morning or evening. Dates of foliar N applications are given in Table 2.

Plots were 24m long x 3.5m wide and arranged in randomised blocks, with each treatment replicated four times. Experiments were treated in spring with 75 kg/ha SO_3 as Kieserite to avoid sulphur limitation. Varieties used were Castille at RM09, Vision at RM10 and Ovation at HM09 and HM10. Interference by weeds, pests and diseases was minimised using robust programmes of herbicides, fungicides, insecticides and molluscicides. As a result there was little or no pressure from pests and diseases.

Table 3. Environmental conditions when foliar N was applied.

	Soil conditions	Overhead conditions	Temperature (°C) at the time of application	Relative humidity (%)	Time of application start
HM09					
Mid flower	Wet	Overcast	11	70	07.45
Mid flower +7d	Dry	Sunny	15	65	18.45
End flower	Dry	Overcast	9	76	10.00
End flower +7d	Wet	Sunny	17	60	18.30
End flower +14d	Damp	sunny	18	69	16.30
RM09					
Mid flower	Dry	Sunny	16	Not recorded	10.45
Mid flower +7d	Damp	Sunny	13	Not recorded	11.15
End flower	Dry	Sunny	19	Not recorded	12.00
End flower +7d	Dry	Sunny	26	Not recorded	10.40
End flower +14d	Damp	Overcast	14	Not recorded	11.45
HM10					
Mid flower	Dry	Overcast	17	75	19.45
Mid flower +7d	Dry	Sunny	12	55	19.00
End flower	Damp	Overcast	19	60	18.30
End flower +7d	Damp	Sunny	21	56	16.30
End flower +14d	Dry	Overcast	22	55	17.15
RM10					
Mid flower	Dry	Overcast	12	59	11.30
Mid flower +7d	Dry	Sunny	23	58	10.45
End flower	Damp	Overcast	17	53	10.45
End flower +7d	Damp	Overcast	21	74	15.15
End flower +14d	Dry	Sunny	20	51	10.30

3.2.2. Measurements

Soil mineral N to 90 cm and crop N were measured in February in all site seasons, to enable determination of appropriate rates of soil applied N. Twenty soil samples were taken from the trial area and these were bulked and tested for nitrate and ammonium-N by NRM labs using standard procedures. Crop samples were taken from a 1m x 1m area in one plot of each replicate. The dry weight of the plant sample was taken and the N concentration of the tissue determined by NRM labs.

Phytotoxicity (scorch) was measured in all treatments 7-14 days after N applications using a 0 to 9 scale where 0 indicated zero scorch and 9 very severe scorch.

Crop samples were taken from a 1m x 1m area 10-14 days before harvest from treatments 1-5 and 7-11. The samples were separated into stems, pod walls and seed and the dry weights and N content of each fraction determined to allow calculation of the crop biomass (t/ha) and crop N content (kg N/ha) of the stems, pod walls and seed, and fertiliser N uptake efficiency.

Immediately before harvest, lodging and % pod shatter were assessed on all plots.

Yield was determined for all treatments using a small plot combine from an area of at least 30m^2 avoiding plot edges and the moisture content measured. The seed oil content was measured on treatments 1-5 and 7-11 and thousand seed weight was measured on treatments 1-5 and 7-11 in 2010.

3.2.3. Statistical analysis

Analysis of variance procedures within Genstat 12 (www.genstat.com) were used to calculate whether treatments were significantly different. Linear plus exponential N response curves were fitted to the seed yield and gross output data for each N treatment of the form

$$Y = A + BR^N + CN \qquad \text{Equation 1}$$

where *Y* is the seed yield (t/ha), *A, B, C* and *R* are constants. Each linear plus exponential function was fitted using a stepwise process within Genstat 12 involving the following steps: i) fitting a common curve to the soil applied and soil applied with foliar N treatments, ii) fitting separate parallel curves for each soil applied and soil applied with foliar N treatment, iii) fitting separate curves for each soil applied and soil applied with foliar N treatment by allowing parameters *A*, *B* and *C* all to vary, and iv) fitting separate curves for each treatment by allowing all parameters to vary. The sums of squares explained at each stage was calculated, and a test was made of the improvement in fit over the previous model. If there was no significant improvement between two stages, then the previous model was taken as the best description of the data. In general, fitting at stage (ii) was most satisfactory and the economic N rate (N_{OPT}) was determined from the fitted linear plus exponential parameters as follows;

$$N_{OPT} = \frac{[\ln(k/1000 - C) - \ln(B(\ln R))]}{\ln R} \qquad \text{Equation 2}$$

where *k* is the breakeven price ratio between fertiliser N (p/kg) and grain (p/kg). A breakeven ratio of 2.5 was used in this study because this is used as a standard for fertiliser recommendations in the Defra RB209 Fertiliser Recommendation handbook. The yield at the optimum N rate (Y_{OPT}) was calculated from the fitted parameters using equation 1.

The oil premium was calculated as 1.5% of the basic oilseed rape price for each percentage point that the oil content was above 40%. When the oil content was less than 40% the same formula was used to calculate the price penalty. Gross output was calculated to account for the combined effect of treatment effects on seed yield and oil content using Equation 3.

$$GrossOutput = 1.5\left(\frac{oilcontent - 40}{100}\right) * seedyield \qquad \text{Equation 3}$$

3.3. Results

3.3.1. Seed yield

Effects of soil applied N (ammonium nitrate)

The greatest yield responses resulted from increasing the soil applied N rate (ammonium nitrate) from zero to 80 or 100 kg N/ha (Table 4), which increased yields by 1.42 t/ha on average. Increasing N rate by a further 80 to 100 kg N/ha increased yields by a further 0.65 t/ha on average. No significant yield increases were observed from applying more than 160 kg N/ha at HM09, HM10 or RM10, or 200 kg N/ha at RM09. The economic optimum N rate for the soil applied N treatments were 190 kg N/ha at HM09, 214 kg N/ha at RM09, 214 kg N/ha at RM10 and 174 kg N/ha at HM10. At these optimum N rates the seed yield was 6.11 t/ha at HM09, 5.12 t/ha at RM09, 5.09 t/ha at HM10 and 5.45 t/ha at RM10.

Table 4. Seed yield (t/ha) for all treatments.

Soil applied N rate (kg/ha)	Foliar N (kg/ha)	† Foliar N timing	HM09	RM09	HM10	RM10	Mean
0	0	0	4.25	2.40	3.23	3.78	3.43
80 or 100	0	0	5.14	4.35	4.51	5.31	4.85
160 or 200	0	0	6.14	5.12	5.08	5.56	5.50
200 or 240	0	0	6.09	5.19	5.10	5.58	5.51
240 or 280	0	0	6.24	5.15	5.20	5.54	5.55
280 or 320	0	0	6.01	5.47	5.20	5.74	5.63
0	40	3	4.14	2.77	3.38	5.03	3.86
80 or 100	40	3	5.86	4.85	4.68	5.63	5.29
160 or 200	40	3	6.09	5.41	5.03	5.80	5.62
200 or 240	40	3	6.43	5.35	5.12	5.81	5.72
240 or 280	40	3	6.29	5.45	5.23	5.81	5.73
280 or 320	40	3	6.48	5.38	5.18	5.89	5.77
160 or 200	40	1	6.24	5.26	5.11	5.62	5.59
160 or 200	40	2	6.43	5.25	5.18	5.44	5.61
160 or 200	40	4	6.29	4.82	5.08	5.55	5.46
160 or 200	40	5	6.29	5.29	5.28	5.61	5.64
160 or 200	20	3	6.11	5.33	5.10	5.72	5.60
160 or 200	80	3	6.35	5.21	5.21	5.63	5.63
160 or 200	120	3	6.36	5.62	5.07	5.84	5.76
160 or 200	Oilseed Extra	3	6.18	5.22	5.16	5.39	5.51
		Mean	5.97	4.95	4.91	5.52	5.36
	SED		0.145	0.217	0.094	0.232	
	LSD		0.293	0.439	0.189	0.469	
	P Value		<0.001	<0.001	<0.001	<0.001	

† Foliar N timings: 1 – Mid-flowering, 2 – 1 week after mid-flowering, 3 – end of flowering, 4 – 1 week after end of flowering, 5 – 2 weeks after end of flowering.

Foliar N effects at different soil applied N rates

At HM09 the effect of foliar N at 40 kg/ha interacted with the soil applied N rate (P<0.05; Table 5) because the greatest yield increase of 0.72 t/ha was observed following a soil applied N rate of 80 kg/ha and smaller yield responses of up to 0.47 t/ha were observed following the other soil applied N rates. Foliar N increased yield by 0.24 t/ha on average across all soil applied N treatments at HM09. At RM10, a similar interaction was observed (P=0.058) to HM09 where the greatest yield response of 1.25 t/ha was observed in the absence of any soil applied N, with smaller yield responses of up to 0.32 t/ha following greater soil applied N rates (Figure 1). The average response to foliar N at RM10 was 0.41 t/ha. At RM09, there was no interaction between the soil applied and foliar N rate treatments and the average response to foliar N was 0.26 t/ha. At HM10, foliar N did not significantly affect yield at any of the soil applied N rates.

Table 5. Seed yield (t/ha) for the factorially combined soil applied N and foliar N treatments.

Soil applied N rate (kg/ha)	Foliar N (kg/ha)	† Foliar N timing	HM09	RM09	HM10	RM10	Mean
0	0	0	4.25	2.40	3.23	3.78	3.43
80 or 100	0	0	5.14	4.35	4.51	5.31	4.85
160 or 200	0	0	6.14	5.12	5.08	5.56	5.50
200 or 240	0	0	6.09	5.19	5.10	5.58	5.51
240 or 280	0	0	6.24	5.15	5.20	5.54	5.55
280 or 320	0	0	6.01	5.47	5.20	5.74	5.63
0	40	3	4.14	2.77	3.38	5.03	3.86
80 or 100	40	3	5.86	4.85	4.68	5.63	5.29
160 or 200	40	3	6.09	5.41	5.03	5.80	5.62
200 or 240	40	3	6.43	5.35	5.12	5.81	5.72
240 or 280	40	3	6.29	5.45	5.23	5.81	5.73
280 or 320	40	3	6.48	5.38	5.18	5.89	5.77
Mean without Foliar N			5.64	4.61	4.72	5.25	5.08
Mean with 40 kg/ha of Foliar N			5.88	4.87	4.77	5.66	5.33
Grand Mean			5.76	4.74	4.75	5.46	5.21
	Soil app	P Value	<0.001	<0.001	<0.001	<0.001	
	Soil app	SED	0.119	0.117	0.076	0.191	
	Foliar N	P Value	<0.001	<0.001	NS	<0.001	
	Foliar N	SED	0.068	0.070	0.040	0.110	
Soil applied N x Foliar N		P Value	0.010	NS	NS	0.058	
Soil applied N x Foliar N		SED	0.168	0.165	0.107	0.270	

† Foliar N timings: 3 – end of flowering

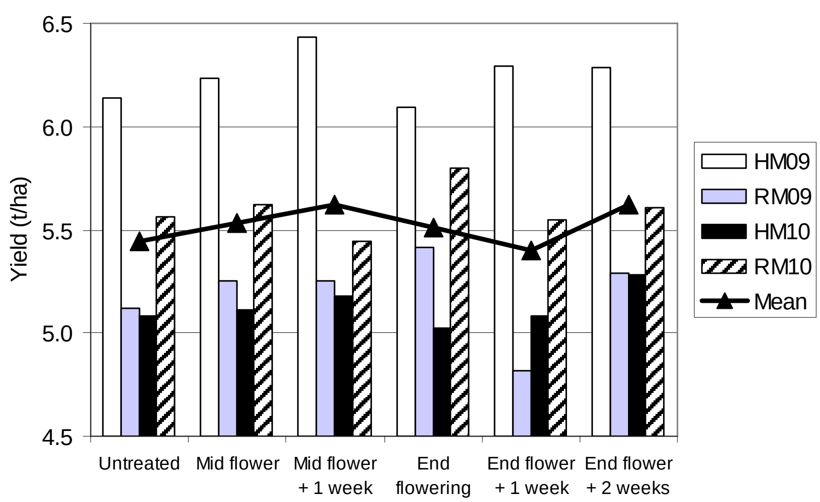


Figure 1. Effect of foliar N (40 kg N/ha) on yield, applied following soil applied N rates of 200 kg N/ha at RM09 and 160 kg N/ha at the other sites.

In 2010, additional measurements were made of the components of yield (thousand seed weight (TSW) and seeds/m^2). At HM10, increasing the soil applied N rate from 0 to 80 kg N/ha significantly reduced the TSW ($P<0.01$; Table 6). Applying more than 80 kg N/ha of soil applied N had little effect on TSW. Applying foliar N at 40 kg N/ha increased the TSW from 5.02 to 5.18 g ($P<0.01$) across a range of soil applied N rates (Table 6). There was an interaction between foliar N and soil applied N rate because foliar N had little effect following soil applied N rates of 200 and 240 kg N/ha. However, foliar N had a significant effect when following 0 or 280 kg N/ha which indicates that the effect of foliar N was not necessarily confined to when it followed low rates of soil applied N. Increasing soil applied N from 0 to 160 kg N/ha significantly increased seeds/m^2 ($P<0.001$), with no further increases above 160 kg N/ha. Foliar N caused a slight reduction in seeds/m^2 ($P = 0.056$). The counteracting effects of foliar N on TSW and seeds/m^2 explain why there was no yield response to foliar N at this site.

At RM10, the soil applied N rate treatment had no effect on TSW and foliar N applied at 40 kg N/ha increased TSW from 5.80 to 6.01 g ($P<0.01$) across all of the soil applied N rates (Table 6). The effects of the soil applied N and foliar N treatments on seeds/m^2 interacted ($P<0.05$). Foliar N increased seeds/m^2 following zero soil applied N, but had no effect following soil applied N rates of 80 kg N/ha or more. Without any foliar N, seeds/m^2 were increased by soil applied N rates up to 160 kg N/ha. With foliar N, seeds/m^2 were increased by soil applied N rates of up to just 80 kg N/ha. The significant yield increase at this site appeared to be due to a combination of greater seeds/m^2 and greater individual seed weight.

Across HM10 and RM10, the more consistently positive effects of foliar N on seed size, compared with seed number, indicate that foliar N increased yield by increasing either the rate or/and duration of seed filling. This may indicate that crops with a large sink size (more seeds/m^2), which require more resources to fill all the seeds, will benefit most from foliar N.

Table 6. Thousand seed weight (TSW) and seeds per metre squared for the factorially combined soil applied N and foliar N treatments in HM10 and RM10.

Soil applied N rate (kg/ha)	Foliar N (kg/ha)	† Foliar N timing	HM10 TSW (g)	HM10 Seeds/m^2	RM10 TSW (g)	RM10 Seeds/m^2
0	0	0	5.06	58148	6.04	57126
80 or 100	0	0	4.84	84699	5.59	86281
160 or 200	0	0	4.94	93735	5.40	94319
200 or 240	0	0	5.09	91066	5.98	85047
240 or 280	0	0	5.10	92801	5.83	86788
280 or 320	0	0	5.09	93016	5.96	87857
0	40	3	5.40	57015	6.01	76741
80 or 100	40	3	5.14	82908	5.89	87208
160 or 200	40	3	5.06	90413	6.06	87139
200 or 240	40	3	5.03	92672	5.76	91866
240 or 280	40	3	5.14	92708	6.22	85208
280 or 320	40	3	5.30	88972	6.11	87931
Mean without Foliar N			5.02	85577	5.80	82903
Mean with 40 kg/ha of Foliar N			5.18	84115	6.01	86015
Grand Mean			5.10	84846	5.90	84459
	Soil app	P Value	<0.01	<0.001	NS	<0.001
	Soil app	SED	0.046	1252.8	0.180	3597.6
	Foliar N	P Value	<0.01	0.056	0.054	NS
	Foliar N	SED	0.027	723.3	0.104	2077.1
Soil applied N x Foliar N		P Value	<0.05	NS	NS	<0.05
Soil applied N x Foliar N		SED	0.065	1771.8	0.255	5087.8

† Foliar N timings: 3 – end of flowering

Effects of foliar N at different application timings

The effect of foliar N timing was investigated by applying a rate of 40 kg N/ha following a soil applied N rate of 160 kg N/ha at HM09, HM10 and RM10 and following 200 kg N/ha at RM09. There was no significant effect of foliar N timing on seed yield at any site except RM09. The significant result at this site was due to a low yield following the 4th foliar N timing (7 days after end of flowering). This effect might be explained by warm weather on the day of application and the following day (max 26°C and 25°C respectively). At the same site, the other foliar N applications were applied on days with maximum temperatures no higher than 19^{o}C. A cross site analysis revealed no consistent difference in the response of foliar N applied between mid flowering and two weeks after the end of flowering (Figure 1), with an average yield response across all of the timing treatments of 0.11 t/ha.

Foliar N rate

The effect of foliar N rate was investigated by applying a rates of 0 to 120 kg N/ha at the end of flowering following a soil applied N rate of 160 kg N/ha at HM09, HM10 and RM10 and following 200 kg N/ha at RM09. At RM09, a foliar N rate of 120 kg N/ha increased yield by 0.5 t/ha ($P<0.05$), but lower foliar N rates had no significant effect. At the other sites there were no significant yield responses to foliar N applied at any rate (20 to 120 kg N/ha) (Table 4). A cross site analysis of variance revealed no consistent difference in the yield response to different rates of foliar N. The lack of significant effects from this analysis, compared with the analysis across soil applied N rates (Table 5) may be at least partly explained by fewer degrees of freedom. Multiple linear regression analysis showed that the average yield increase per kg of foliar N was 0.002 t/ha and this was the same in each experiment (Figure 2). Total Oilseed Extra applied at 20 kg N/ha at HM09 and RM09 and at 40 kg N/ha at HM10 and RM10 did not significantly increase yield following soil applied N rates of 160 or 200 kg N/ha, with yield increases of up to 0.10 t/ha.

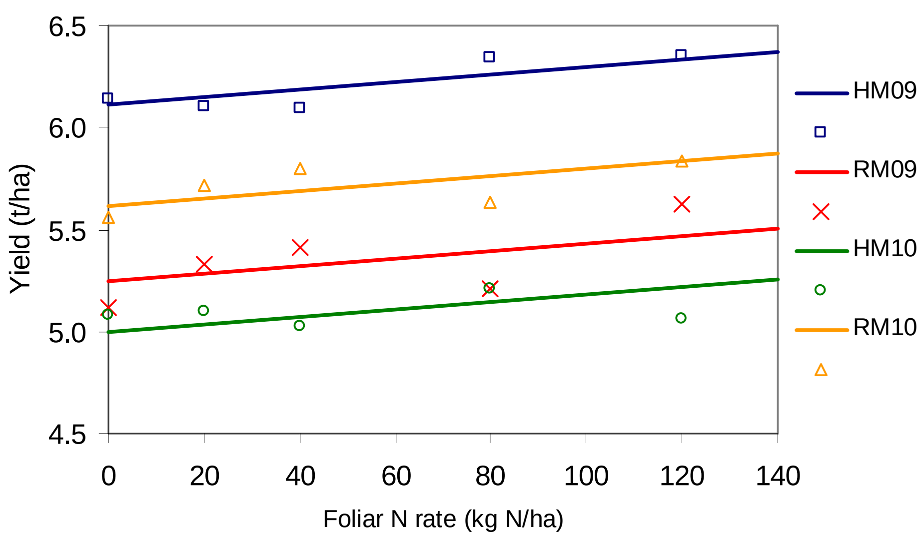


Figure 2. Effect of foliar N rates on yield, applied at the end of flowering following soil applied N rates of 200 kg N/ha at RM09 and 160 kg N/ha at the other sites.

3.3.2. Oil content

Increasing the soil applied N rate from 0 to 160 or 200 kg N/ha significantly reduced the oil content at HM09, RM09 and RM10 ($P<0.001$; Table 7). Across all experiments increasing the soil applied N rate from 0 to 160 or 200 kg N/ha reduced oil content by 2.2%. Smaller reductions in oil content were observed when the N rate was increased above 160 or 200 kg N/ha.

Table 7. Oil content (%) for the factorially combined soil applied N and foliar N treatments.

Soil applied N rate (kg/ha)	Foliar N (kg/ha)	† Foliar N timing	HM09	RM09	HM10	RM10	Mean
0	0	0	53.0	49.0	48.5	49.3	49.9
80 or 100	0	0	52.5	48.2	46.0	48.6	48.8
160 or 200	0	0	50.3	46.4	46.5	47.4	47.6
200 or 240	0	0	49.2	46.0	44.7	46.1	46.5
240 or 280	0	0	49.1	45.1	45.0	45.6	46.2
0	40	3	51.7	47.3	46.8	47.0	48.2
80 or 100	40	3	49.8	47.2	44.4	46.7	47.0
160 or 200	40	3	50.0	45.7	43.0	45.3	46.0
200 or 240	40	3	49.7	44.7	44.8	45.4	46.2
240 or 280	40	3	48.4	46.2	45.7	45.0	46.3
Mean without Foliar N			50.8	46.9	46.2	47.4	47.8
Mean with 40 kg/ha of Foliar N			50.0	46.2	45.0	45.9	46.9
Grand Mean			50.4	46.6	45.6	46.6	47.4
	Soil appl	P Value	<0.001	<0.001	NS	<0.001	
	Soil appl	SED	0.59	0.41	1.26	0.59	
Foliar N		P Value	<0.05	<0.01	NS	<0.001	
Foliar N		SED	0.37	0.26	0.71	0.38	
Soil applied N x Foliar N		P Value	NS	<0.05	NS	NS	
Soil applied N x Foliar N		SED	0.83	0.59	1.71	0.84	

† Foliar N timings: 3 – end of flowering

Foliar N applied at the end of flowering at a rate of 40 kg N/ha significantly reduced oil content at HM09, RM09 and RM10. At RM09 there was a significant interaction between foliar N and the soil applied N treatment because foliar N reduced oil content more at lower soil applied N rates than at high N rates. A cross site analysis showed a significant interaction between the foliar N and soil applied N treatments ($P<0.01$), and no interaction between site, foliar N and soil applied N, indicating that the interaction between foliar N and soil applied N was consistent across sites. Across sites, foliar N reduced oil content by 1.6% to 1.8% at soil applied N rates between zero and 160 to 200 kg N/ha, by 0.4% at soil applied N rates of 200 or 240 kg N/ha with no effect at greater soil applied N rates. In 2010, additional oil measurements were carried out on the foliar N rates at 20, 80 and 120 kg N/ha. These showed a negative linear relationship between increasing foliar N rate (0 to 120 kg/ha) and oil content with each additional kilogram of foliar N reducing oil percentage by 0.0324 at HM10 and by 0.0254 at RM10.

3.3.3. Gross output (yield adjusted for oil content)

Gross output is the combined effect of seed yield and oil content using equation 3 (section 3.2.3). Increasing soil applied N increased gross output at all sites (Table 8), however the increases in gross output were not as great as for seed yield (Table 5) because increasing soil applied N rate also reduced oil content (Table 7).

Table 8. Gross output (t/ha) for the factorially combined soil applied N and foliar N treatments.

Soil applied N rate (kg/ha)	Foliar N (kg/ha)	† Foliar N timing	HM09	RM09	HM10	RM10	Mean
0	0	0	5.08	2.57	3.65	4.30	3.90
80 or 100	0	0	6.11	4.62	4.91	6.00	5.41
160 or 200	0	0	7.08	5.31	5.58	6.17	6.04
200 or 240	0	0	6.93	5.34	5.46	6.09	5.96
240 or 280	0	0	7.09	5.22	5.60	6.01	5.98
0	40	3	4.86	2.89	3.73	5.57	4.26
80 or 100	40	3	6.73	5.06	5.00	6.20	5.75
160 or 200	40	3	7.01	5.52	5.25	6.26	6.01
200 or 240	40	3	7.37	5.38	5.49	6.29	6.13
240 or 280	40	3	7.09	5.57	5.68	6.24	6.14
Mean without Foliar N			6.46	4.61	5.04	5.71	5.46
Mean with 40 kg/ha of Foliar N			6.61	4.88	5.03	6.11	5.66
Grand Mean			6.47	4.66	4.96	5.88	5.49
	Soil appl	P Value	<0.001	<0.001	<0.001	<0.001	
	Soil appl	SED	0.111	0.128	0.116	0.224	
Foliar N		P Value	<0.05	<0.01	NS	<0.01	
Foliar N		SED	0.070	0.810	0.073	0.143	
Soil applied N x Foliar N		P Value	<0.01	NS	NS	0.073	
Soil applied N x Foliar N		SED	0.157	0.181	0.164	0.317	

† Foliar N timings: 3 – end of flowering

Foliar N applied at the end of flowering at a rate of 40 kg N/ha significantly increased gross output at HM09, RM09 and RM10. At RM09 and RM10 the average gross output increase to foliar N was 0.27 t/ha and 0.40 t/ha respectively. At HM09, there was a significant interaction between the foliar N and soil applied N treatments because foliar N increased yield by 0.62 t/ha at 80 kg N/ha, and by 0.44 t/ha at 200 kg N/ha, but had no effect at zero and the other soil applied N rates. Across all soil applied N rates the foliar N treatment increased gross output by 0.15 t/ha at HM09. Foliar N had no effect on gross output at HM10. A cross site analysis showed that the interaction between the soil applied N and foliar N treatments was not significant at the 95% level of confidence (P= 0.087).

There was also a highly significant 3-way interaction between site, soil applied N and foliar N treatments which showed that the N treatment effects were not consistent between experiments.

The use of foliar N did not affect the economic optimum soil applied N rate at HM09, RM09 or HM10. At HM09 and RM09 the N response data supported fitting parallel curves to the soil applied N and foliar N treatments (Figure 3). At HM10, a single response curve was shown to explain most variation because the foliar N treatment did not significantly affect yield at this site. At RM10, the N response data supported fitting non-parallel response curves to the soil applied N and foliar N treatments because foliar N caused a steeper response to the soil applied N treatments. The economic optimum soil applied N rates were 175 kg N/ha at HM09, 184 kg N/ha at RM09 and 237 kg N/ha at HM10. At RM10 the optimum soil applied N rate was 111 kg N/ha without foliar N and 84 kg N/ha with foliar N.

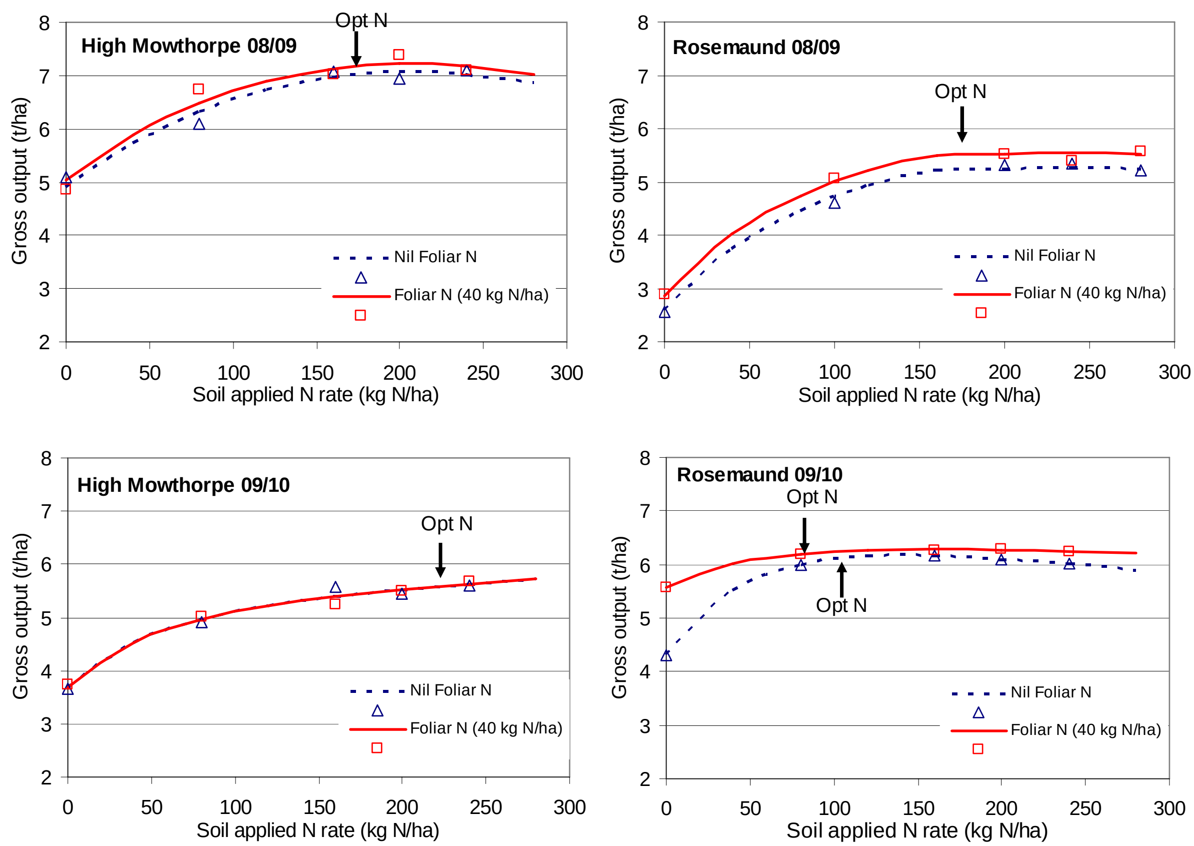


Figure 3. Gross output response to soil applied N and foliar N at each site: fitted curves and mean data points. Statistics support the fitting of parallel curves for treatments with and without foliar N in 2008/09, a single curve for both treatments for High Mowthorpe 2009/10 and non-parallel curves for Rosemaund 2009/10. Opt N denoted the economic optimum N rate at breakeven ratio 2.5:1.

In 2010, additional measurements of oil content at the full range of foliar N doses enabled the effect of foliar N on gross output to be calculated. The maximum gross output occurred with a foliar N rate of 0 kg/ha at HM10 (Figure 4) and 40 kg/ha at RM10 (Figure 5). However, the effect of increasing foliar N from 0 to 120 kg N/ha did not significantly affect gross output at either site. When the average oil response to foliar N across HM10 and RM10 was used to estimate the effect of foliar N rate on gross output across all four sites, then the greatest gross output response occurred at a foliar N rate of 20 kg N/ha, with a smaller response at 40 kg N/ha and gross output losses at 80 and 120 kg/ha (Figure 6).

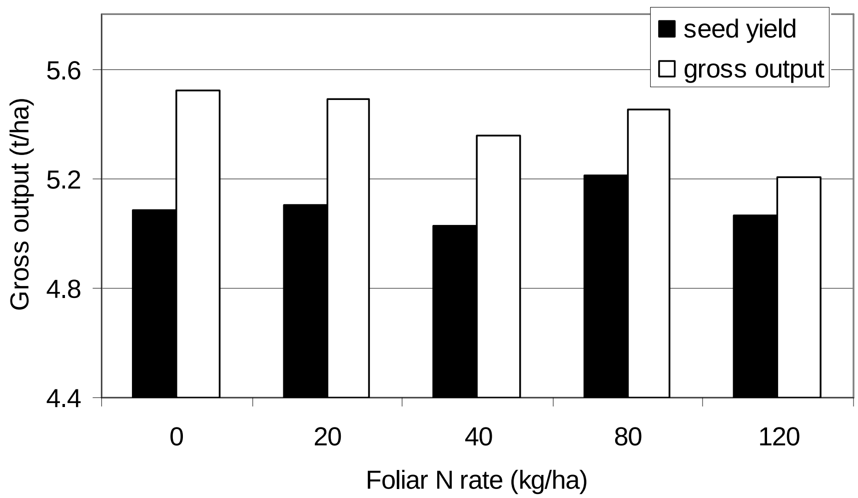


Figure 4. Effect of foliar N rates on seed yield and gross output, applied at the end of flowering following soil applied N rates of 160 kg N/ha at HM10.

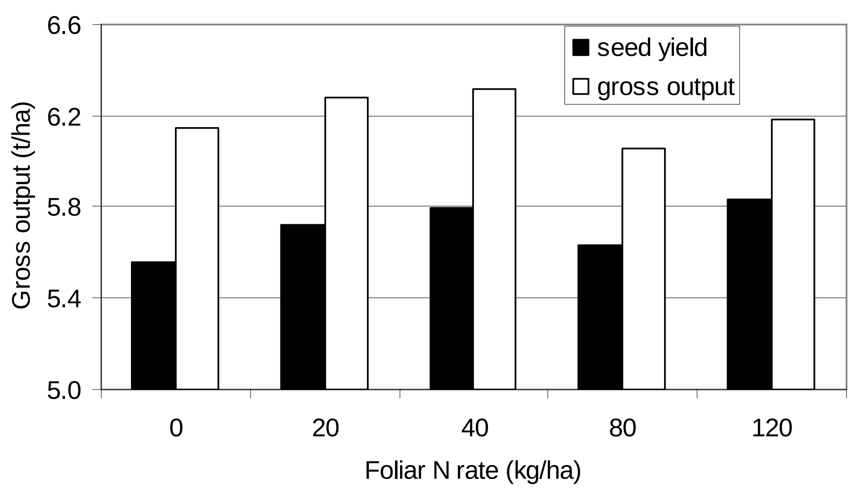


Figure 5. Effect of foliar N rates on seed yield and gross output, applied at the end of flowering following soil applied N rates of 160 kg N/ha at RM10.

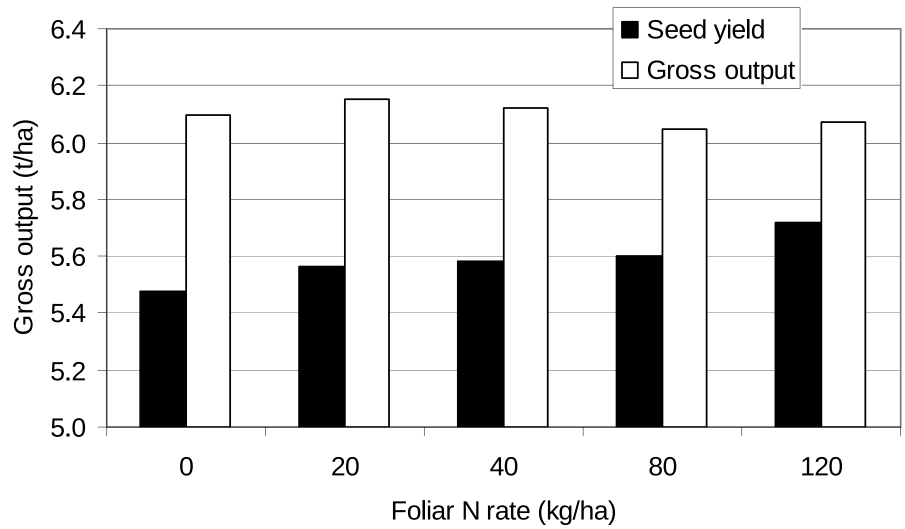


Figure 6. Effect of foliar N rates on seed yield and gross output, applied at the end of flowering following soil applied N rates of 160 kg N/ha. Average seed yield data across HM09, RM09, HM10, RM10 and average oil response data across HM10 and RM10.

3.3.4. N uptake

Increasing the rate of soil applied N significantly increased the biomass, N content and N yield of seed, stems and pod walls in all site seasons (Tables 9 to 12). Increasing the soil applied N rate from 0 to 240 or 280 kg N/ha increased the total N taken up at harvest from 217 kg N/ha to 482 kg N/ha at HM09, from 86 kg N/ha to 242 kg N/ha at RM09, from 156 kg N/ha to 295 kg N/ha at HM10 and from 174 to 266 kg N/ha at RM10 (averaged across foliar N rates). Foliar N applied at 40 kg N/ha at the end of flowering increased total N uptake by 42 kg N/ha at HM09 ($P<0.05$), 28 kg N/ha at RM09 ($P<0.001$), 37 kg N/ha at RM10, with no effect at HM10. The uptake efficiency of foliar N therefore ranged from 0 to over 100%, with an average across sites of 67%.

At HM09, RM09 and RM10 foliar N increased N uptake by increasing the amount of N in the seed and pod wall (kg N/ha). At RM09 and RM10 the greatest contribution to the increased N uptake came from the increase in seed N content, and pod wall N contributed most to the increase in N at HM09. The increase in seed N and pod wall N came from approximately equal increases in seed or pod wall biomass and seed or pod wall N concentration. Foliar N generally had no effect on stem biomass and the concentration of N in the stem tissue, apart from at RM10 where foliar N increased stem biomass by 0.78 t/ha ($P<0.05$).

Across all sites, and soil applied N rates, foliar N applied at 40 kg N/ha increased seed N% by 0.17% (2.86% to 3.03%). This will result in an average increase in seed protein due to foliar N of 1.06% (17.87 to 18.93%) (1 kg of N = 6.25 kg protein). The average reduction in oil content across the same soil applied N rates and sites was 0.90% (47.8% to 46.9%) (Table 6). The average seed yield increase at 100% dry matter across the same soil applied N rates and sites was 0.24 t/ha (4.50 to 4.74 t/ha). This means that the foliar N increased oil yield (tonnes of oil per hectare) by 0.072 t/ha (2.154 to 2.224 t/ha) and increased total seed protein yield by 0.093 t/ha (0.804 to 0.897 t/ha). The reduction in the percentage of oil in the seed was therefore caused by a greater increase in protein yield (t/ha) than in oil yield (t/ha) which effectively diluted the oil content in the seed. It is clear that the increase in oil and protein yields do not add up to the total increase in seed yield, which indicates that foliar N must also have increased other components of the seed (e.g. fibre).

Table 9. Biomass and N uptake measured at maturity at High Mowthorpe in 2008/09.

Soil applied N rate (kg/ha)	Foliar N (kg/ha)	Biomass (t/ha dry weight)				N content (%)			N yield (kg/ha)			
		Seed	Stem	Pod wall	Total	Seed	Stem	Pod wall	Seed	Stem	Pod wall	Total
0	0	3.87	6.01	6.65	16.53	2.471	0.558	1.085	95.6	33.4	74.1	203.0
80	0	4.68	7.76	9.53	21.97	2.674	0.555	1.156	124.8	43.1	109.5	277.5
160	0	5.58	8.07	10.97	24.62	2.804	0.869	1.244	156.7	70.1	136.0	362.8
200	0	5.54	8.77	11.15	25.46	2.935	1.134	1.651	162.6	98.2	184.0	444.8
240	0	5.68	8.37	10.91	24.96	2.970	1.040	1.536	168.6	89.7	168.7	427.1
0	40	3.77	6.22	7.16	17.15	2.593	0.561	1.400	97.7	34.4	99.7	231.7
80	40	5.33	8.01	9.89	23.24	2.912	0.688	1.226	155.1	55.1	121.1	331.3
160	40	5.54	6.78	11.23	23.56	2.979	0.955	1.375	165.2	65.7	151.9	382.7
200	40	5.85	8.33	10.59	24.77	3.002	1.203	1.569	175.7	99.8	165.4	441.0
240	40	5.73	9.41	13.49	28.63	3.111	1.364	1.632	178.2	132.4	226.8	537.4
Mean without Foliar N		5.07	7.80	9.84	22.71	2.771	0.831	1.334	141.7	66.9	134.5	343.0
Mean with 40 kg/ha Foliar N		5.25	7.75	10.47	23.47	2.919	0.954	1.440	154.4	77.5	153.0	384.8
Grand Mean		5.16	7.78	10.16	23.09	2.845	0.893	1.387	148.1	72.2	143.8	363.9
Soil applied N SED		0.081 ***	0.579 ***	0.787 ***	1.201 ***	0.057 ***	0.101 ***	0.103 ***	3.088 ***	12.14 ***	17.85 ***	28.52 ***
Foliar N SED		0.051 **	0.366	0.498	0.759	0.036 ***	0.064	0.065	1.953 ***	7.68	11.29	18.04 *
Soil applied N x Foliar N SED		0.115 ***	0.819	1.113	1.698	0.080	0.143	0.146	4.367 **	17.17	25.25	40.34

*** denotes statistical significance at P<0.001, ** at P<0.01 and * at P<0.05.

Table 10. Biomass and N uptake measured at maturity at Rosemaund in 2008/09.

Soil applied N rate (kg/ha)	Foliar N (kg/ha)	Biomass (t/ha dry weight)				N content (%)			N yield (kg/ha)			
		Seed	Stem	Pod wall	Total	Seed	Stem	Pod wall	Seed	Stem	Pod wall	Total
0	0	2.18	2.69	2.06	6.85	2.423	0.586	0.559	52.9	16.6	11.0	78.9
100	0	3.96	4.35	3.72	12.03	2.363	0.554	0.666	93.6	24.0	24.7	142.3
200	0	4.66	4.09	3.87	12.62	2.820	0.959	0.878	131.3	39.3	34.2	204.7
240	0	4.72	4.69	4.12	13.52	2.865	0.767	0.838	135.2	35.6	34.5	205.3
280	0	4.68	4.22	3.84	12.74	2.970	1.053	0.888	139.1	44.3	34.3	217.7
0	40	2.52	2.22	2.18	6.92	2.578	0.652	0.606	65.0	14.3	13.0	92.3
100	40	4.41	4.65	3.57	12.63	2.615	0.509	0.668	115.4	23.2	23.8	162.4
200	40	4.92	4.48	4.42	13.82	2.943	0.801	1.018	144.9	35.9	45.5	226.3
240	40	4.87	4.33	4.44	13.64	2.988	1.122	1.067	145.5	49.9	48.3	243.6
280	40	4.96	4.52	4.48	14.15	3.105	1.104	1.255	153.7	50.2	57.2	266.0
Mean without Foliar N		4.04	4.01	3.52	11.55	2.688	0.784	0.766	110.4	32.0	27.7	169.8
Mean with 40 kg/ha Foliar N		4.34	4.04	3.82	12.23	2.846	0.838	0.923	124.9	34.7	37.6	198.1
Grand Mean		4.19	4.03	3.67	11.89	2.767	0.811	0.845	117.7	33.4	32.7	184.0
Soil applied N SED		0.104 ***	0.307 ***	0.185 ***	0.467 ***	0.032 ***	0.078 ***	0.087 ***	2.576 ***	4.22 ***	5.02 ***	9.13 ***
Foliar N SED		0.066 ***	0.194	0.117 *	0.295 *	0.021 ***	0.049	0.055 **	1.629 ***	2.67	3.18 **	5.77 ***
Soil applied N x Foliar N SED		0.147	0.434	0.261	0.661	0.046	0.111*	0.123	3.643	5.96	7.10	12.91

*** denotes statistical significance at P<0.001, ** at P<0.01 and * at P<0.05.

Table 11. Biomass and N uptake measured at maturity at High Mowthorpe in 2009/10.

Soil applied N rate (kg/ha)	Foliar N (kg/ha)	Biomass (t/ha dry weight)				N content (%)			N yield (kg/ha)			
		Seed	Stem	Pod wall	Total	Seed	Stem	Pod wall	Seed	Stem	Pod wall	Total
0	0	2.94	5.74	4.23	12.9	2.52	0.621	1.10	74.0	35.4	46.9	156
80	0	4.10	5.55	5.37	15.0	2.74	0.702	1.29	112.7	38.3	69.2	220
160	0	4.63	6.44	6.40	17.5	3.15	1.126	1.65	145.8	72.3	105.3	324
200	0	4.64	6.48	6.58	17.7	3.24	0.897	1.55	150.5	58.5	102.6	312
240	0	4.73	5.49	6.02	16.2	3.37	0.929	1.35	159.8	51.3	82.0	293
0	40	3.08	4.49	4.02	11.6	2.73	0.618	1.07	84.3	27.8	43.1	155
80	40	4.26	5.60	5.26	15.1	3.03	0.723	1.23	129.1	40.5	65.7	235
160	40	4.57	7.09	6.75	18.4	3.27	1.083	1.64	149.7	77.7	110.5	338
200	40	4.66	5.74	5.85	16.2	3.39	0.932	1.38	157.9	53.7	82.9	294
240	40	4.76	5.38	5.53	15.7	3.37	1.081	1.44	160.4	58.3	79.7	298
Mean without Foliar N		4.21	5.94	5.72	15.9	3.01	0.855	1.39	128.5	51.2	81.2	261
Mean with 40 kg/ha Foliar N		4.27	5.66	5.48	15.4	3.16	0.877	1.35	136.3	51.6	76.4	264
Grand Mean		4.24	5.80	5.60	15.6	3.08	0.871	1.37	132.4	51.4	78.8	263
Soil applied N SED		0.073 ***	0.420 **	0.470 ***	0.83 ***	0.038 ***	0.080***	0.119 ***	2.84 ***	7.09 ***	11.78 ***	17.8 ***
Foliar N SED		0.046	0.266	0.297	0.52	0.024***	0.050	0.075	1.80***	4.48	7.45	11.2
Soil applied N x Foliar N SED		0.103	0.595	0.664	1.17	0.054*	0.113	0.169	4.02	10.03	16.66	25.1

*** denotes statistical significance at P<0.001, ** at P<0.01 and * at P<0.05.

Table 12. Biomass and N uptake measured at maturity at Rosemaund in 2009/10.

Soil applied N rate (kg/ha)	Foliar N (kg/ha)	Biomass (t/ha dry weight)				N content (%)			N yield (kg/ha)			
		Seed	Stem	Pod wall	Total	Seed	Stem	Pod wall	Seed	Stem	Pod wall	Total
0	0	3.44	3.52	2.72	9.7	2.64	0.50	0.58	90.7	17.7	16.0	124
80	0	4.83	5.33	4.31	14.5	2.74	0.55	0.81	132.5	29.6	36.2	198
160	0	5.06	4.98	4.38	14.4	3.03	0.69	0.78	153.4	34.1	34.6	222
200	0	5.08	4.62	3.89	13.6	3.15	0.72	0.92	159.7	34.0	36.8	231
240	0	5.04	5.22	5.40	15.7	3.29	0.71	1.05	166.3	37.5	57.0	261
0	40	4.58	5.26	5.77	15.6	3.03	0.50	1.02	138.5	25.8	61.1	225
80	40	5.13	5.49	4.24	14.9	3.07	0.52	0.69	157.2	28.3	29.3	215
160	40	5.28	6.01	5.64	16.9	3.20	0.67	0.92	168.9	40.7	52.0	262
200	40	5.29	5.80	3.84	14.9	3.27	0.66	0.89	173.2	39.5	34.3	247
240	40	5.28	5.00	4.87	15.2	3.39	0.78	1.05	179.3	38.9	52.5	271
Mean without Foliar N		4.69	4.73	4.14	13.6	2.97	0.63	0.83	140.5	30.6	36.1	207
Mean with 40 kg/ha Foliar N		5.11	5.51	4.87	15.5	3.19	0.62	0.91	163.4	34.6	45.8	244
Grand Mean		4.90	5.12	4.51	14.5	3.08	0.62	0.87	152.0	32.6	41.0	226
Soil applied N SED		0.175***	0.533	0.499	0.96*	0.050***	0.044***	0.084*	5.83***	4.98*	8.06	13.2***
Foliar N SED		0.111***	0.337*	0.316*	0.60*	0.032***	0.028	0.053	3.69***	3.15	5.10	8.4***
Soil applied N x Foliar N SED		0.247	0.754	0.706**	1.35*	0.071*	0.062	0.119*	8.25*	7.05	11.40*	18.7**

*** denotes statistical significance at P<0.001, ** at P<0.01 and * at P<0.05.

3.3.5. Phytotoxicity, lodging and pod shatter

Following 40 kg/ha foliar N, the average level of leaf scorch 7-14 days after application across all foliar N timings and soil applied N treatments was 0.7% at HM09, 1.5% at HM10, nil at RM10 and a score of 0.7 out of nine at RM09 (where a different scoring system was used) (Table 13). There were no significant differences in the level of scorch following different soil applied N treatments, although there was an indication of more scorch following greater applications of soil applied N (Table 13). At HM10, applying foliar N at 40 kg N/ha one week after the end of flowering significantly increased the level of scorch compared with other timings (Table 13). The temperature during the application of this treatment was slightly greater than for the preceding treatments at 21°C, but 1°C less than the following treatment (Table 3). There were no differences in leaf scorch between the foliar N timings at the other sites. Increasing foliar N rate to 80 kg N/ha or 120 kg N/ha significantly increased levels of scorch at HM09, RM09 and HM10. When foliar N was applied at 120 kg N/ha the level of leaf scorch was 11% at HM09, 2% at RM09 and 15% at HM10. No leaf scorch was observed at RM10 and no scorch was observed on the pods at any of the sites. No lodging or pod shatter was observed in any of the experiments.

Table 13. Leaf scorch due to foliar N applications, assessed 7-14 days after application in all site seasons (1-9 scale used in RM09 and % leaf area in all other site seasons).

Treatment	Soil applied N rate (kg/ha)	Foliar N (kg/ha)	† Foliar N timing	HM09	RM09	HM10	RM10
3	160 or 200	0	0	0.0	0.0	0.0	0.0
7	0	40	3	0.0	1.3	0.0	0.0
8	80 or 100	40	3	0.0	1.0	1.7	0.0
9	160 or 200	40	3	0.0	1.0	2.0	0.0
10	200 or 240	40	3	0.5	1.3	1.7	0.0
11	240 or 280	40	3	0.3	1.0	2.0	0.0
12	280 or 320	40	3	1.3	1.0	2.3	0.0
13	160 or 200	40	1	0.5	0.0	0.0	0.0
14	160 or 200	40	2	0.5	0.0	0.0	0.0
15	160 or 200	40	4	2.5	0.0	4.3	0.0
16	160 or 200	40	5	1.3	0.0	1.0	0.0
17	160 or 200	20	3	0.8	1.0	0.3	0.0
18	160 or 200	80	3	6.8	1.3	10.0	0.0
19	160 or 200	120	3	11.3	2.0	15.0	0.0
20	160 or 200	Oilseed Extra	3	0.0	1.0	6.3	0.0
mean							
SED				***1.01	***0.14	***0.39	NA

*** denotes significance at P<0.001, ** at P<0.01 and * at P<0.05.

† Foliar N timings: 1 – Mid-flowering, 2 – 1 week after mid-flowering, 3 – end of flowering, 4 – 1 week after end of flowering, 5 – 2 weeks after end of flowering.

3.4. Discussion

Foliar N applied at the end of flowering at a rate of 40 kg N/ha increased seed yield by 0.41 t/ha at RM10, 0.26 t/ha at RM09, 0.24 t/ha at RM09 and had no significant effect at HM10. There was a tendency for foliar N to increase yield more when following nil or sub-optimal amounts of soil applied N. The benefits from increased seed yield from foliar N were usually reduced by a reduction in the percentage of oil within the seed of approximately 1%. The reduction in oil concentration occurred via a dilution effect after the foliar N had increased protein yield more than oil yield. The combined effects of foliar N on seed yield and oil concentration have been estimated in terms of the effect on gross output which takes account of the economic penalty of any reduction in oil concentration. Foliar N applied at the end of flowering at a rate of 40 kg N/ha increased gross output by 0.40 t/ha at RM10, 0.27 t/ha at RM09, 0.15 t/ha at HM09 and had no effect at HM10. The average gross output response across all sites was 0.20 t/ha. It should be noted that the average gross output responses were calculated across the first five soil applied N rates, whereas the seed yield responses were calculated across all six soil applied N rates. A cross site analysis revealed that the response was the same following soil applied N rates ranging from zero to 240 or 280 kg N/ha, as there was no significant interaction at the 95% level of confidence. However there was an interaction at the 90% level of confidence which indicated that there was a greater response following zero soil applied N compared with greater N rates. If the response to foliar N is calculated following the soil applied N rates above zero then the average gross output increases is only reduced by a modest amount to 0.16 t/ha. For the purposes of the economic analysis described below the conclusions drawn from the statistical analysis at the 95% level of confidence will be used which gave an average gross output increase across sites of 0.20 t/ha. The discovery that the response to foliar N occurs following a wide range of soil applied N rates, including super-optimal rates, indicates that foliar N can be used to increase yield to levels over-and-above those that can be achieved using optimal amounts of soil applied N at earlier timings.

This study has demonstrated that there can be large variability for the yield response to foliar N, particularly between sites, but also within the same field when applications were made on different days. There was no consistent effect of applying foliar N at different growth stages ranging from mid-flowering to two weeks after the end of flowering. Significant yield responses were also seen for all four of the experimental crops from at least one foliar N treatment. It therefore seems likely that the variation in yield response was mainly caused by environmental factors, although differences between the crops (e.g. canopy size) cannot be ruled out. Linear regression analysis was used to investigate whether any of the environmental factors at the time of application described in Table 3 affected the yield response for the foliar N treatment applied at 40 kg N/ha between mid flowering and two weeks after flowering. This showed that neither soil wetness, sun or cloud, relative humidity or time of day affected the size of the yield response. There was a weak negative correlation between the air temperature at application and the yield response (Figure 7).

Six out of 19 tests showed a negative or neutral yield response to foliar N, of which five occurred when the temperature at application was 19°C or more. More research is required to quantify the effect of temperature on the yield response, but this analysis indicates that applications should be avoided when the temperature is 19°C or above. It is clear that temperature only explains a small part of the variation in yield response and further research will be required to identify whether there are other environmental or crop factors which affect the yield response. One area that may be investigated is whether foliar N may reduce the seeds/m^2 in certain situations, as foliar N caused a slight reduction in seeds/m^2 at the site with no yield response. Other areas for investigation could be levels of water stress and effects on disease.

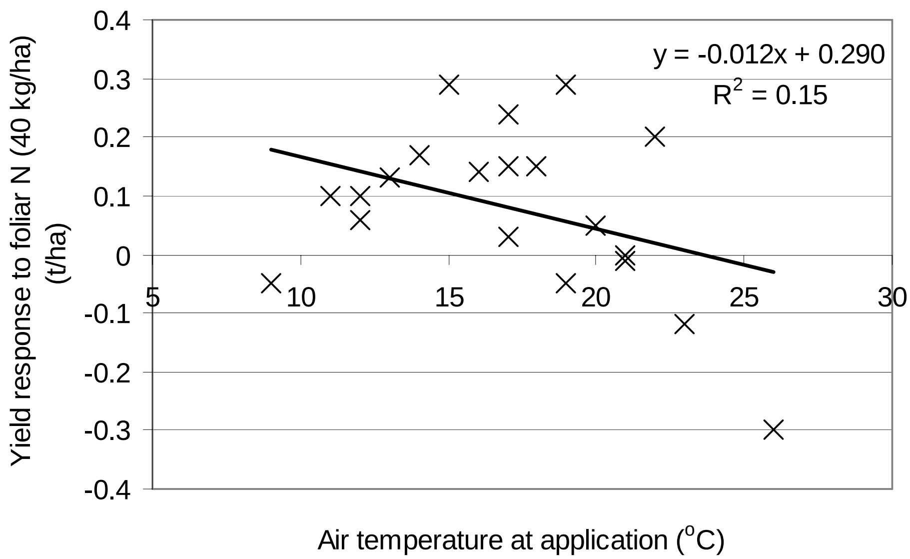


Figure 7. Correlation between the yield response to foliar N applied at 40 kg N/ha and the air temperature at the time of application. Data includes applications between mid-flowering and 2 weeks after the end of flowering for each experiment (HM09, RM09, HM10, RM10).

The unpredictable variation in yield response to foliar N means that it is difficult to carry out a cost-benefit analysis. Table 14 describes how the gross margin over costs change with different oilseed rape prices and foliar N costs. It was assumed that foliar N was applied at a rate of 40 kg N/ha, the cost of an application was £13/ha (Nix, 2009) and the gross output response was 0.20 t/ha (the average response found within this study). The dose response study indicated that, across all sites, using a foliar N rate of 20 kg/ha would give the greatest gross output response with a slightly smaller gross output response to 40 kg N/ha and negative gross output responses for foliar N rates above 40 kg N/ha. The cost-benefit analysis described below is based on the statistically significant gross output response to foliar N applied at 40 kg/ha because it was measured following a wider range of soil applied N rates than the response to foliar N at 20 kg N/ha and therefore is a more robust estimate. Foliar N at 40 kg N/ha is also generally regarded as the industry standard rate. It should be recognised however that a greater gross margin may sometimes be possible following a foliar N rate of 20 kg N/ha.

The cost-benefit analysis for a gross output yield response to foliar N at 40 kg N/ha is described in Figure 7. As a general guide this analysis shows that when the fertiliser N cost is between £0.50 and £0.75 per kg of N then for foliar N to be profitable the ratio of fertiliser cost (£ per kg of elemental N): oilseed rape price (£/kg) must be less than 3.0. When the fertiliser N cost is between £0.80 and £1.00 per kg of N then for foliar N to be profitable the ratio of fertiliser cost: oilseed rape price must be less than 3.5. For example, when foliar N costs £0.8/kg then oilseed rape prices must be at least £225/t to make a profit.

Table 15 illustrates a similar cost-benefit analysis to that described in Table 14, but this time the yield response is assumed to be just 0.15 t/ha (the same as at HM09). In this scenario when foliar N costs £0.8/kg then oilseed rape prices must be at least £300/t to make a profit. Table 16 shows the cost-benefit analysis for a yield response of 0.40 t/ha (as achieved in RM10) and this shows that when foliar N costs £0.8/kg then oilseed rape prices may be as low as £120/t and a profit would still be achieved.

The cost-benefit analysis described above does not take account of possible yield losses which may arise from travelling through the crop during or after flowering. Yield losses from travelling through the crop have been estimated at 0.8% for travelling through the crop at mid-flowering, end of flowering or at the time of desiccation, and 1.4% for the end of flowering followed by time of desiccation (Ogilvy, 1989). These losses were for a self-propelled sprayer on narrow wheels (23 cm wide) with a ground clearance of 90cm. Using a tractor mounted sprayer with a ground clearance of 60 cm and similar width tyres resulted in losses of 0.8% at mid-flowering and time of desiccation, 2.0% at end of flowering and 2.3% at end of flowering followed by the time of desiccation. If it is assumed that the majority of crops are desiccated then an additional pass through the crop at the end of flowering may be estimated to increase losses by 0.6% for a sprayer with 90cm clearance or by 1.5% for a sprayer with 60cm clearance. The losses associated with a foliar N spray at the end of flowering may be negligible for a high clearance sprayer if a sclerotinia spray has been applied during early flowering. It should be recognised that the foliar N timing treatments gave similar yield responses to foliar N when applied any time between mid-flowering and two weeks after the end of flowering. This indicates that the foliar N application could be combined with a fungicide for controlling sclerotinia which would spread the yield damage costs and the application costs. If the yield losses from a foliar N spray at the end of flowering are 0.6% (high clearance sprayer, desiccant and no sclerotinia spray) then the cost benefit analysis for the average gross output response of 0.20 t/ha described in Table 14 changes to the analysis described in Table 17. The effect of this level of yield loss would be to increase the oilseed rape price at which foliar N paid for itself (assuming a cost of £0.8/kg of N) from £225/t to £255/t.

Table 14. Effect of foliar N cost and oilseed rape price on the gross margin over cost (£/ha) of using foliar N at 40 kg/ha and assuming a gross output increase of 0.20 t/ha

Oilseed rape price (£/t)	Cost of foliar N (£/kg)					
	0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1**
160	-1	-5	-9	-13	-17	-21
200	7	3	-1	-5	-9	-13
240	15	11	7	3	-1	-5
280	23	19	15	11	7	3
320	31	27	23	19	15	11
360	39	35	31	27	23	19
400	47	43	39	35	31	27
440	55	51	47	43	39	35

Cost of applying foliar N of £13/ha included within costs

Table 15. Effect of foliar N cost and oilseed rape price on the gross margin over cost (£/ha) of using foliar N at 40 kg/ha and assuming a gross output increase of 0.15 t/ha

Oilseed rape price (£/t)	Cost of foliar N (£/kg)					
	0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1**
160	-9	-13	-17	-21	-25	-29
200	-3	-7	-11	-15	-19	-23
240	3	-1	-5	-9	-13	-17
280	9	5	1	-3	-7	-11
320	15	11	7	3	-1	-5
360	21	17	13	9	5	1
400	27	23	19	15	11	7
440	33	29	25	21	17	13

Cost of applying foliar N of £13/ha included within costs

Table 16. Effect of foliar N cost and oilseed rape price on the gross margin over cost (£/ha) of using foliar N at 40 kg/ha and assuming a gross output increase of 0.40 t/ha

Oilseed rape price (£/t)	Cost of foliar N (£/kg)					
	0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1**
160	31	27	23	19	15	11
200	47	43	39	35	31	27
240	63	59	55	51	47	43
280	79	75	71	67	63	59
320	95	91	87	83	79	75
360	111	107	103	99	95	91
400	127	123	119	115	111	107
440	143	139	135	131	127	123

Cost of applying foliar N of £13/ha included within costs

Table 17. Effect of foliar N cost and oilseed rape price on the gross margin over cost (£/ha) of using foliar N at 40 kg N/ha and assuming it increases gross output by 0.20 t/ha and yield losses of 0.6% from an additional pass through the crop.

Oilseed rape price (£/t)	Cost of foliar N (£/kg)					
	0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1**
160	-5	-9	-13	-17	-21	-25
200	2	-2	-6	-10	-14	-18
240	9	5	1	-3	-7	-11
280	16	12	8	4	0	-4
320	23	19	15	11	7	3
360	30	26	22	18	14	10
400	37	33	29	25	21	17
440	44	40	36	32	28	24

Cost of applying foliar N of £13/ha included within costs

Canopy management principles for N applications recommend that crops with a yield potential of 3.5 t/ha or more receive additional N compared with that required to build an optimum sized canopy by flowering. This N should be applied at yellow bud or early flowering in order to minimise the risk of building on over-large canopy. In dry years there is a risk that this later applied N will be taken up less efficiently. This study investigated whether foliar N could be a reliable substitute for a late dose of soil applied N applied at yellow bud or early flowering. This study indicated that foliar N at 40 kg N/ha applied at the end of flowering generally did give a greater yield response than ammonium nitrate applied at yellow bud or early flowering. Conditions were very dry in the spring of 2010, and N was applied quite late at HM10 (one week before mid-flowering), both of which may have reduced uptake efficiency of late soil applied N in this year. This indicates that foliar N could be used if conditions were predicted to be too dry for soil applied N to be taken up efficiently. However, it should be emphasised that the foliar N yield responses also occurred following optimal or super-optimal rates of soil applied N which indicates that foliar N should be used as a treatment for increasing yields over-and-above those that can be achieved using earlier applications of soil applied N, rather than as a substitute for soil applied N. Therefore if conditions are predicted to be dry then it may be best to apply N to the soil earlier.

Foliar N was taken up with an efficiency of 70% to 100% at the three sites where foliar N significantly increased yield. There was no significant increase in total N uptake by the crop at the site without a significant yield response. Across all four experimental sites the efficiency with which foliar N was taken up was 67%. This is significantly greater then the uptake N efficiency of foliar applied to wheat after flowering. This suggests that oilseed rape pods and upper stems may be relatively efficient at absorbing foliar N and consequently there may be less gaseous loss due to volatilisation following foliar applications to oilseed rape compared with wheat. Foliar N generally resulted in more N taken up into the seed and pod wall with significant increases in seed N observed more commonly than significant increases in pod wall N. Across all sites following a foliar N rate of 40 kg/ha, approximately 36% of the foliar N was taken up into the seed, 30% into the pod walls and stems and 34% lost as gaseous emissions. This indicates that the additional amount of N in crop residues following harvest was modest at 12 kg N/ha. Only a proportion of this would be vulnerable to leaching during the following winter due to the relatively high C:N ratio of pod walls which will reduce the rate of mineralisation of these tissues. This observation may be important regarding the inclusion of foliar N in the N-Max limits for NVZs. Currently some growers do not use foliar N because doing so would result in exceedance of the N-Max limit, however this results indicate that foliar N may cause a small increase in the risk of nitrate leaching.

3.5. Conclusions

- Guidance for using foliar N arising from this study include;
    - When the foliar N cost is between £0.50 and £0.75 per kg of N then the ratio of fertiliser cost (£ per kg of elemental N): oilseed rape price (£/kg) must be less than 3.0. When the foliar N cost is between £0.80 and £1.00 per kg of N then the ratio must be less than 3.5.
    - Foliar N rates should not exceed 40 kg N/ha.
    - Apply any time between mid-flowering and two weeks after the end of flowering
    - Avoid applications when the air temperature is above 18^{o}C.
- Foliar N applied at 40 kg N/ha at the end of flowering significantly increased seed yield in 3 out of 4 experiments. The seed yield response following a wide range of soil applied N rates ranged from 0.06 to 0.41 t/ha.
- The yield increases occurred at sub-optimal, optimal and super-optimal levels of soil-applied N, hence are likely to have arisen by a separate mechanism.
- Foliar N at 40 kg N/ha significantly reduced the percentage oil content in the seed by an average of 0.9%. This was caused because foliar N increased seed protein (%N x 6.25) by 1.1%, which displaced the oil.
- The reduction in oil content resulted in smaller responses in gross output compared with seed yield following foliar N. Gross output responses ranged from zero to 0.40 t/ha and averaged 0.20 t/ha across the experimental sites. The gross output response was the same regardless of whether it followed sub-optimal or super-optimal rates of soil applied N.
- The yield response to foliar N resulted mostly from increases in individual seed size, but an increase in seeds/m^2 did occur at one site.
- Similar yield responses were observed for foliar N applications between mid-flowering and two weeks after the end of flowering.

- The dose response study indicated that a foliar N rate of 20 kg/ha gave a similar gross output response to a foliar N rate of 40 kg/ha, with greater foliar N rates giving neutral or negative responses. The best conclusion from this study is that a foliar N rate of 40 kg/ha is the maximum that should be used.
- Foliar N was taken up with an efficiency of 70 to 100% at the three sites where it increased yield significantly, with 8% uptake at the unresponsive site.
- The effect of foliar N at 40 kg N/ha on post-harvest N residues was modest, giving an average increase of 12 kg N/ha.
- Some of the variation in effectiveness of foliar N was caused by temperature with a greater frequency of small or negative responses when foliar N was applied at 19^{o}C or more. Variation in yield response could not be explained by relative humidity, overhead conditions or time of application.
- It may be possible to combine foliar N with fungicide sprays during flowering to minimise crop damage from extra wheel passes.

3.6. Recommendations for further work

- Understand what causes the variation in yield response to foliar N by investigating the responses across a greater range of environmental and crop conditions. For example crops with greater sink sizes (seeds/m^2) may respond more to foliar N, whether or not foliar N has any disease control effects must be understood, and the impact of drought stress maybe important. This will enable more precise guidelines for when to apply foliar N to be developed and will enable a more accurate cost-benefit analysis.
- Investigate whether foliar N can give yield benefits when applied before mid-flowering and whether greater rates could be used at this time. If earlier yield responses can be shown then this might enable increased efficiency over-and-above soil-applied N, and would give greater scope for mixing with fungicide sprays.
- Investigate whether the optimum foliar N rate is less than 40 kg/ha by assessing the dose response at more N rates between 0 and 40 kg/ha.

3.7. References

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