2. Nitrogen nutrition

2.1 Results

2.1.1 Residual Nitrogen

The effect of soil residual nitrogen on the response of wheat to plant population was examined at Sutton Bonington in 2001, 2002 and 2003.

In 2001 the differences in soil mineral nitrogen were created by applying 80 kg N/ha to the ResN1 plots in the previous autumn. This resulted in a difference between treatments of 55 kg N/ha in February (Figure 2.1). In subsequent years, differential N applications to the previous crop were used, resulting in a difference between treatments of 21 kg N/ha in 2002 and 17 kg N/ha in 2003 (Figure 2.1).

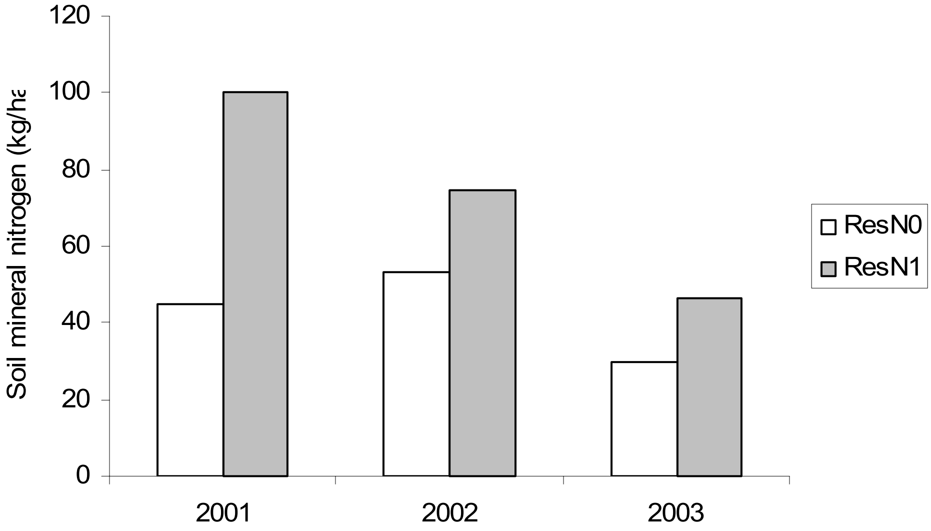

Figure 2.1 Soil mineral nitrogen (kg/ha) 0-90cm, measured in February.

In 2001 crops grown on high soil residual nitrogen (ResN1) had more shoots throughout the growing season (Figure 2.2a) with significant differences on 28 February (P=0.048), 25 May (P=0.008) and 20 June (P=0.042). Crops grown on high soil residual nitrogen had larger GAI (Figure 2.3a) and biomass (Figure 2.4a) throughout the growing season, but the difference was only significant on 3 April (GAI P=0.007, biomass P=0.047).

Throughout the 2002 season, there was a trend for ResN0 plots to have more shoots/m^2 than ResN1 and the difference was significant on 15 March (Figure 2.2b). Generally, there were no significant differences in GAI between residual nitrogen treatments (Figure 2.3b). However on 22 April the ResN0 plots had a significantly larger GAI than the ResN1 plots (P=0.013). Residual nitrogen had no significant effect on crop biomass (Figure 2.4b).

In 2003 due to relatively poor establishment and a dry spring limiting N uptake, the 2003 crop was much smaller than the previous two years reaching a GAI of just 4 at 320 seeds/m^2 (200 plants/m^2). Shoot numbers were equally low, reaching a maximum of 800/m^2 in 2003 compared with 1200-1400/m^2 in 2001 and 2002. ResN1 plots had larger GAI on 12 May (P=0.049) (Figure 2.3c), while shoot number (P=0.054) (Figure 2.2c) and biomass (P=0.076) (Figure 2.4c) on the same date, just missed the 5% statistical cut off point.

Figure 2.5 depicts the fractional interception by the different seed rate plots in the three experimental years (averaged across residual nitrogens) and confirms that in 2003 less of the available light was intercepted early in the season, and that there were larger differences between seed rates than in the previous years.

Across the three years, there was no interaction between seed rate and residual N for any of the parameters measured.

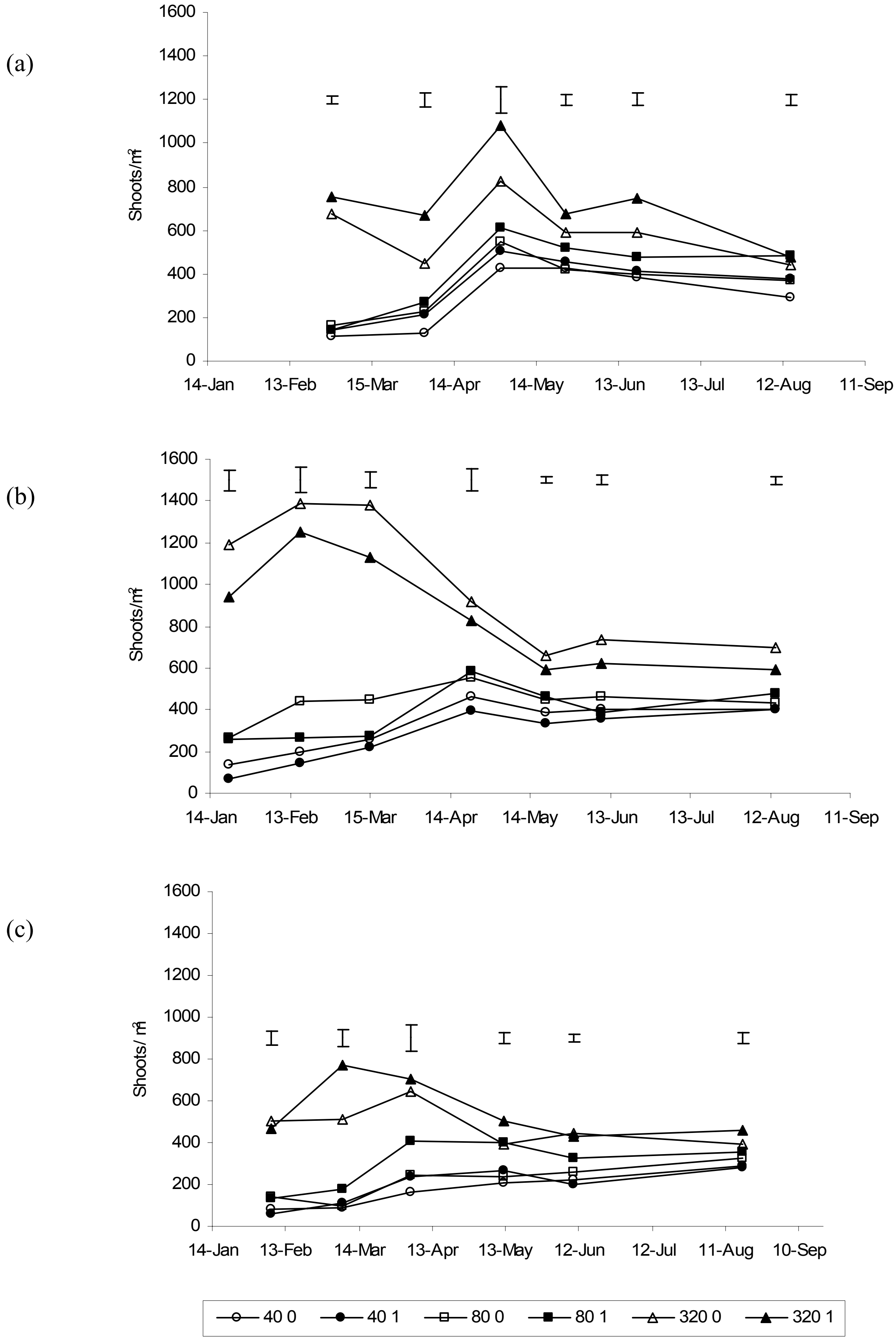

Figure 2.2. Effect of soil mineral nitrogen and seed rate on shoots/m^2 at Sutton Bonington (a) 2001 (b) 2002 (c) 2003. Bars depict SED, 8df.

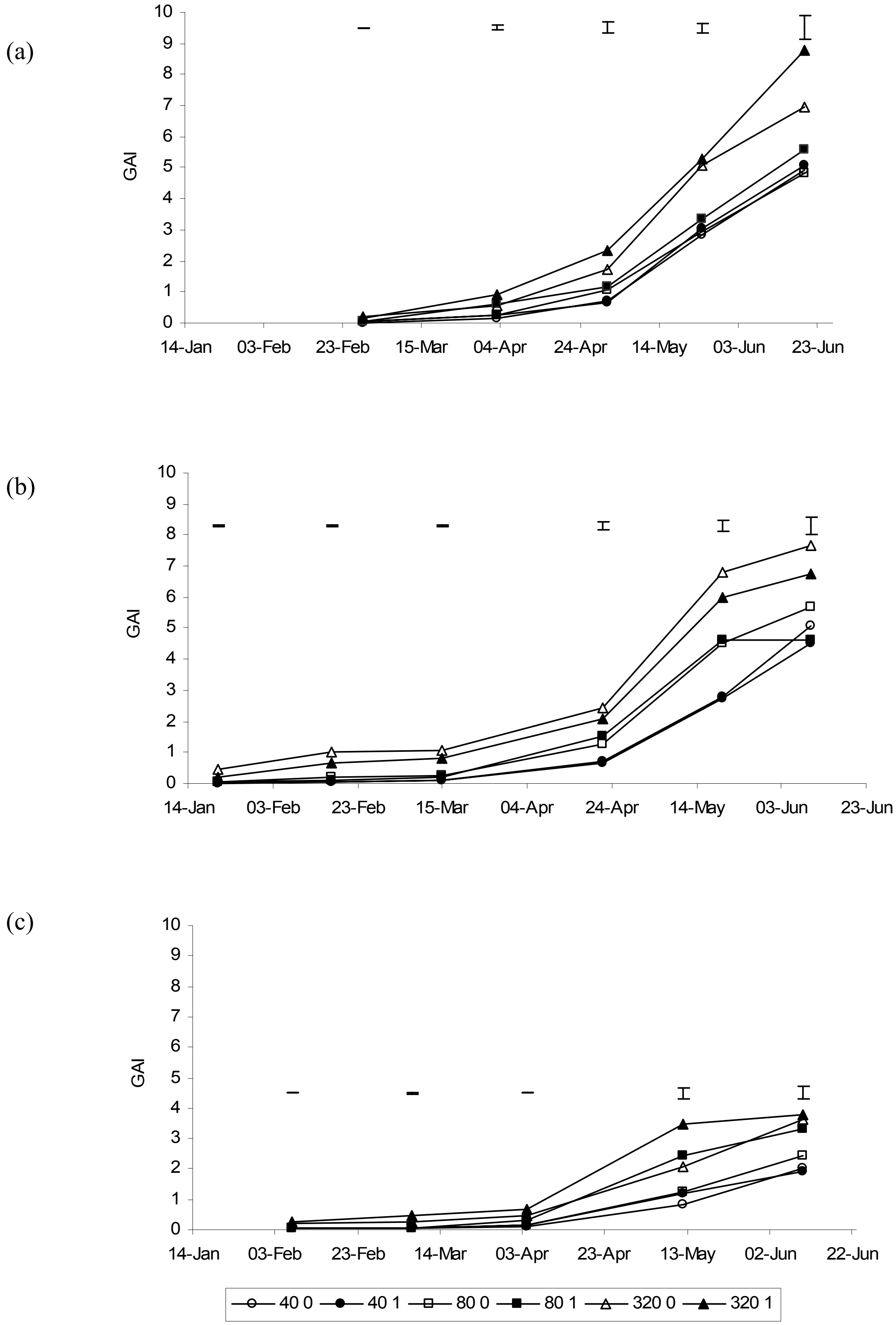

Figure 2.3. Effect of soil mineral nitrogen and seed rate on GAI at Sutton Bonington (a) 2001 (b) 2002 (c) 2003. Bars depict SED, 8df.

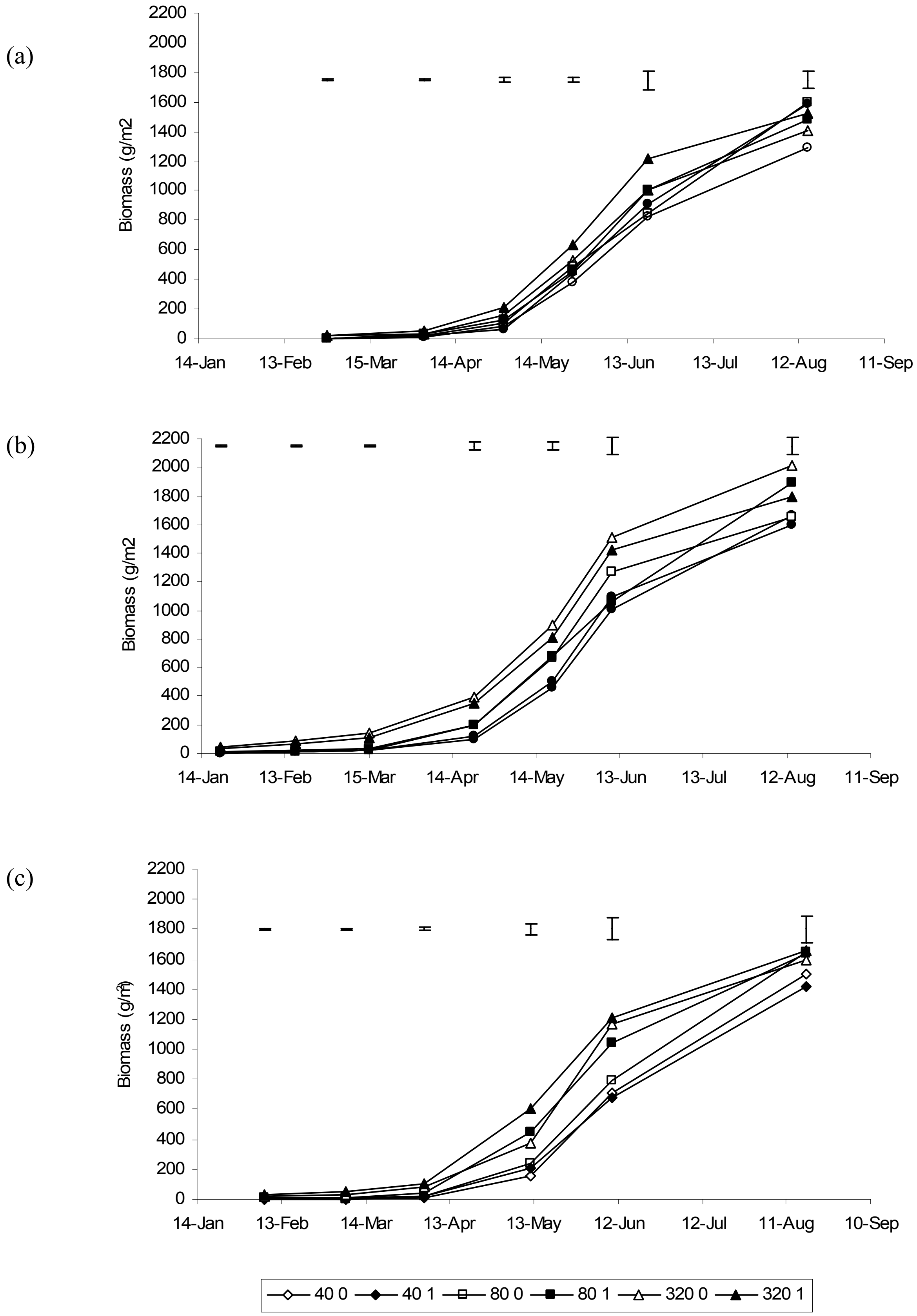

Figure 2.4. Effect of soil mineral nitrogen and seed rate on crop biomass at Sutton Bonington (a) 2001 (b) 2002 (c) 2003. Bars depict SED, 8df.

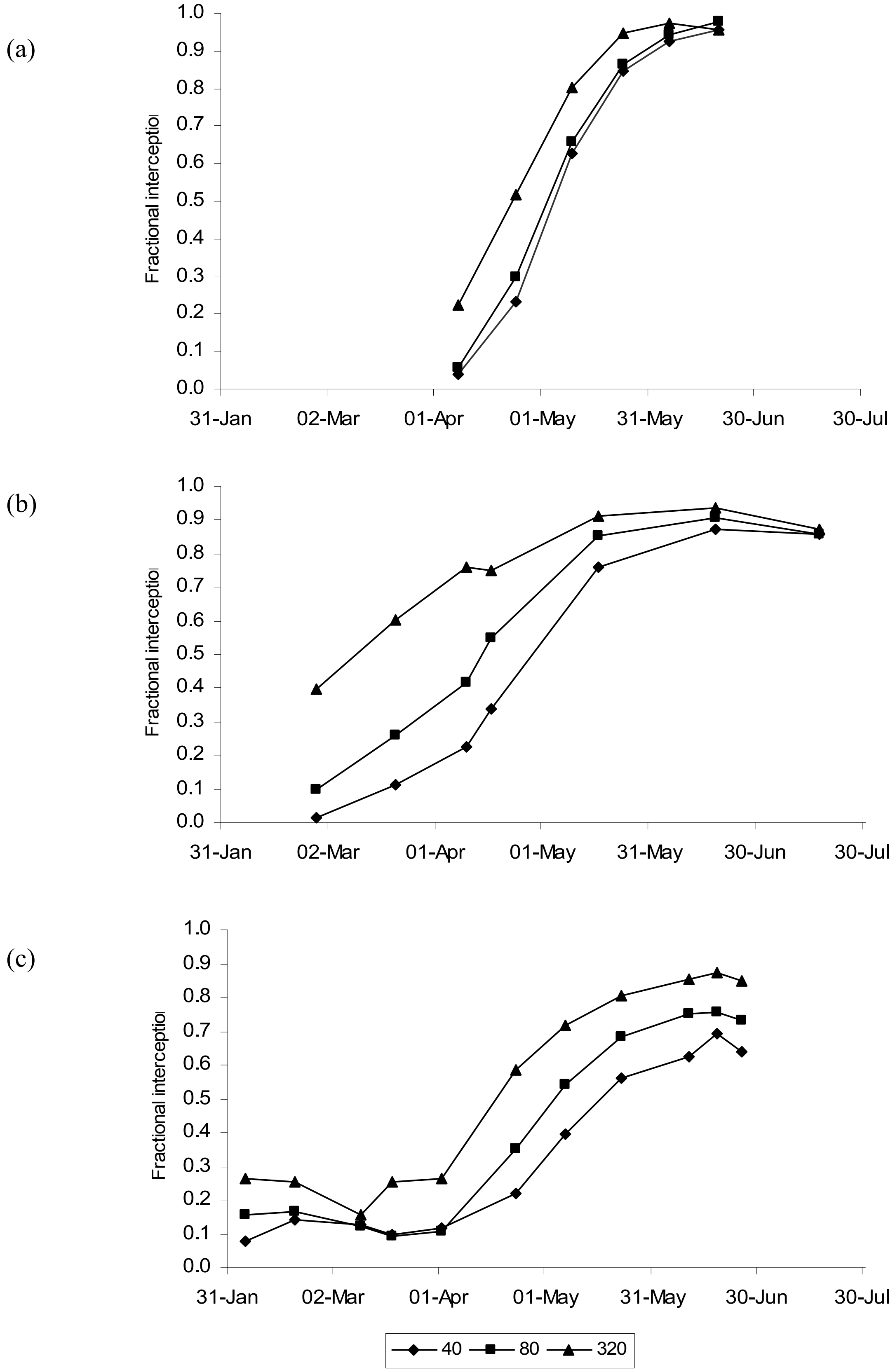

Figure 2.5 The effect of seed rate on fractional interception through the season.

In 2001, plots with high residual N (created by applying 80 kg/ha in the autumn) tended to produce a greater yield than low residual N plots (P=0.057) (Figure 2.6a). Severe lodging occurred following 80mm rain on 18 July 2001. A lodging assessment on 24 July (Table 2.1) showed that, as expected, lodging increased with seed rate (P<0.001). Surprisingly, there was less lodging in the ResN1 plots (P=0.005). There was also an interaction between residual nitrogen and seed rate (P<0.001): lodging increased more rapidly with increasing seed rate in the ResN0 plots. The ResN0 plots received more nitrogen in spring (to balance N nutrition between treatments), which may have created more lodging prone crops. It is therefore likely that the differences in yield between the residual nitrogen treatments were due to the differential lodging rather than N nutrition *per se*.

Table 2.1. Lodging index recorded on 24 July 2001, Sutton Bonington

	Seed rate					
Residual N	40	80	160	320	640	Mean
Res N0	21.3	42.0	61.8	71.7	85.3	56.4
Res N1	10.5	13.3	10.8	42.7	45.8	24.6
Mean	15.9	27.7	36.3	57.2	65.5	

	P	SED	df
Residual N	0.005	4.28	3
Seed rate	<0.001	4.34	72
Residual N * Seed rate	<0.001	6.96	18

In 2002 and 2003 the differences in soil mineral nitrogen between the residual nitrogen treatments were smaller than in 2001: 21 kg N/ha in February 2002 and 17 kg N/ha in February 2003 (Figure 2.1). In neither year did this result in a yield response. However, in 2003 there was an interaction between seed rate and soil residual nitrogen; plots with low residual nitrogen content produced a greater yield at the lower plant populations (P=0.012). At the higher plant populations, soil residual nitrogen had no effect on yield (Figure 2.6c). There were no significant interactions between residual nitrogen and timing of the first spring nitrogen application in any of the experiments.

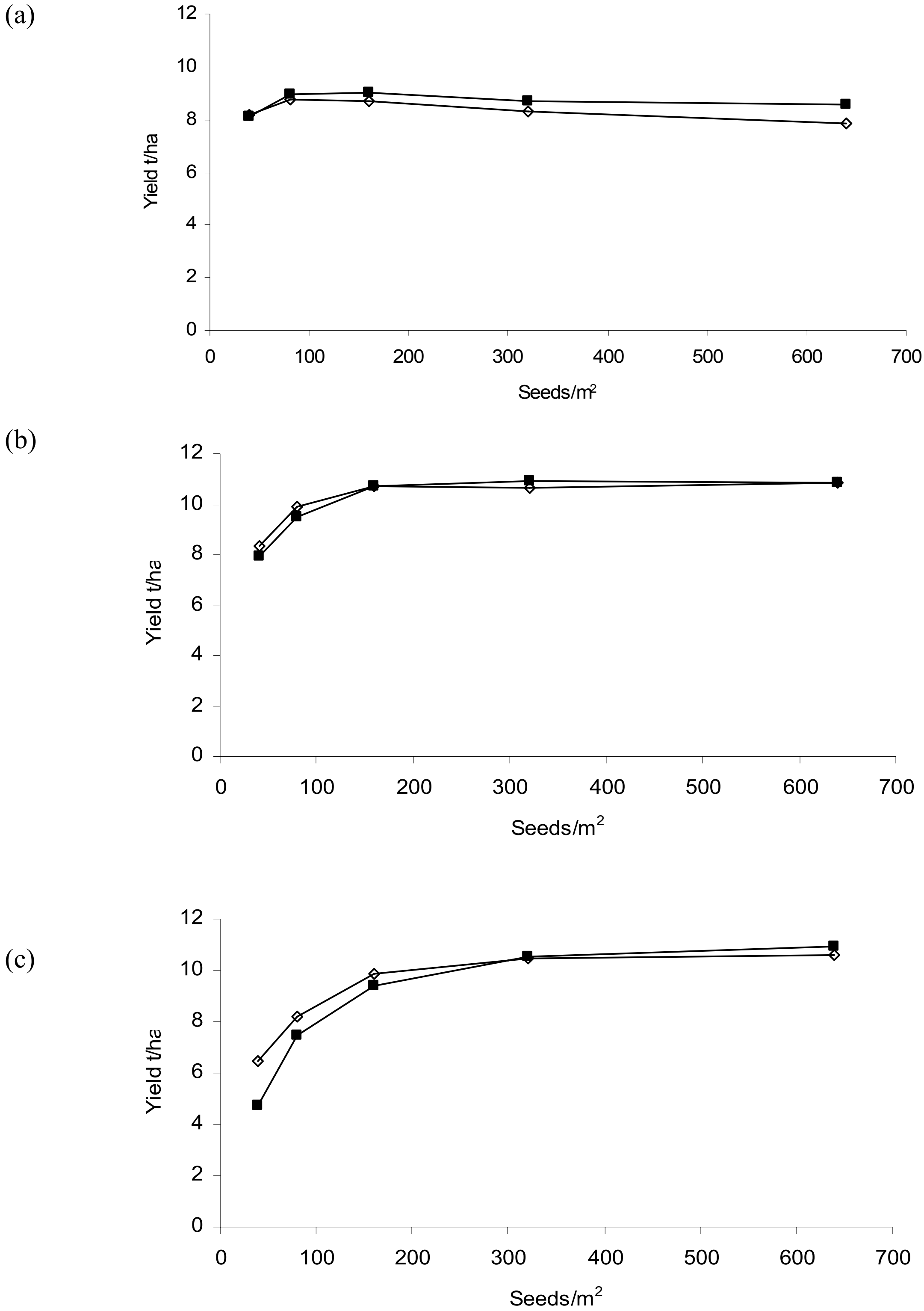

Figure 2.6. The effect of soil mineral nitrogen and seed rate on wheat yield at Sutton Bonington (a) 2001, (b) 2002, (c) 2003. ◊ResN0, ■ ResN1

2.1.2. Timing of early nitrogen application

Across seven site seasons, timing of early spring nitrogen had no significant effect on the yield of wheat (Table 2.2). This was surprising given the response of shoot production to the application of early nitrogen. Figure 2.7 shows the shoot production and survival for the three nitrogen timings at Sutton Bonington (averaged across seed rates). In 2001 and 2003 the early nitrogen timing produced three more shoots than the late timing at maximum shoot number and by harvest still retained one additional shoot per plant. At Bridgets in 2001, the pattern was very similar with differences of three shoots per plant at maximum shoot number and one at harvest (Figure 2.8a). At Sutton Bonington in 2002, there were no clear differences between treatments by harvest. At Aberdeen, data was only collected until mid June (shortly after maximum shoot number). These data also showed differences between treatments at this time, but the absolute differences were smaller than at Sutton Bonington and Bridgets at one shoot per plant in 2002 and 0.5 shoots per plant in 2003 (Figure 2.8 b,c). At Edinburgh in 2002, data was only collected until 5 February which is before the N timing treatments were applied (data not shown).

Table 2.2. Effect of timing of early nitrogen on wheat yield (t/ha).

	Site and year						
N timing	SB01	SB02	SB03	BR01	ED02	AB02	AB03
Early	8.6	10.1	8.5	8.8	9.0	7.9	6.8
Normal	8.7	9.9	8.4	8.7	8.9	7.7	6.5
Late	8.7	10.1	9.6	8.6	8.7	7.9	6.4
P	0.258	0.217	0.139	0.283	0.430	0.510	0.578
SED	0.114	0.145	0.599	0.080	0.178	0.169	0.450
df	12	8	8	6	6	6	6

The response, in terms of shoot production and survival, to early N application was greater at the lower plant populations. For example, Figures 2.9 & 2.10 show data from Bridgets and Sutton Bonington respectively in 2001. At Bridgets the crop sown at 40 seeds/m^2 with late applied N had, on average, 2.4 fewer shoots per plant at harvest, than when nitrogen was applied earlier. At Sutton Bonington the difference was 1.6 shoots per plant. Although the trend was similar, in terms of shoot production, at 80 seeds/m^2 the differences were smaller, while at 320 seeds/m^2 timing of early nitrogen had no apparent effect at either site.

In general, there was no interaction between seed rate and timing of early nitrogen resulting in a single optimum plant population being calculated across the three nitrogen timings (Table 2.3). The one exception was at ADAS Bridgets in 2001 (Figure 2.11) (P=0.034). In this experiment, low plant populations performed better when early nitrogen was applied, while higher plant populations, notably the 320 seed rate, performed worse in relation to the other treatments.

Table 2.3. Optimum plant populations for the seven site seasons, across all N timings.

	Site and year						
N timing	SB01	SB02	SB03	BR01	ED02	AB02	AB03
Single curve	63	95	$	118	119	217	127

N.B. For Bridgets the optimum populations for the different N timings were: early 84, normal 118, late 149

$ the optimum plant population for Sutton Bonington in 2003 could not be calculated across all N treatments – for ResN1 normal N timing it was 215 plants

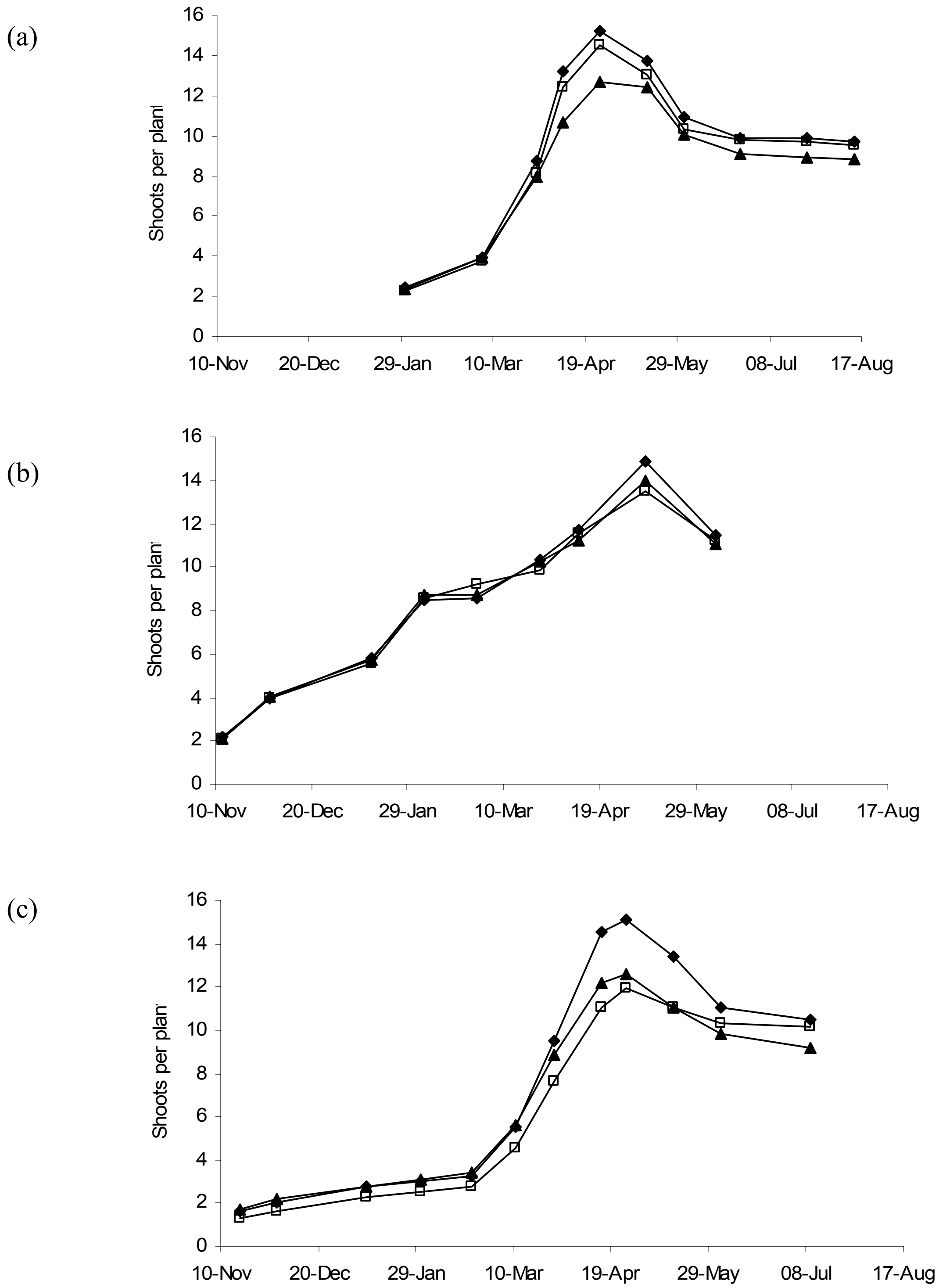

Figure 2.7. Shoot number per plant as affected by timing of early nitrogen at Sutton Bonington (a) 2001, (b) 2002, (c) 2003. ♦ early □ normal ▲late.

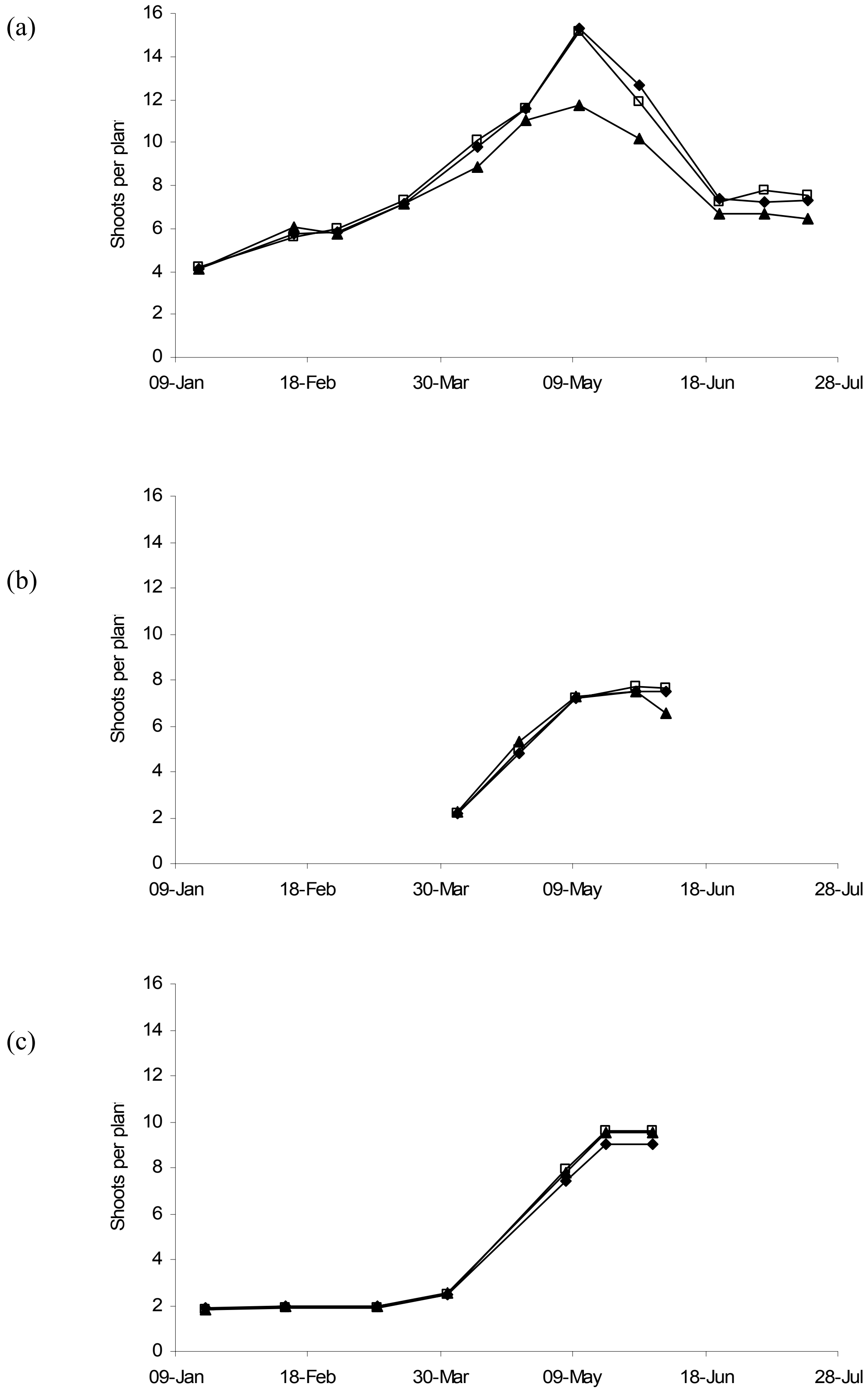

Figure 2.8. Shoot number per plant as affected by timing of early nitrogen at (a) Bridgets 2001, (b) Aberdeen 2002, (c) Aberdeen 2003. ♦ early □ normal ▲late.

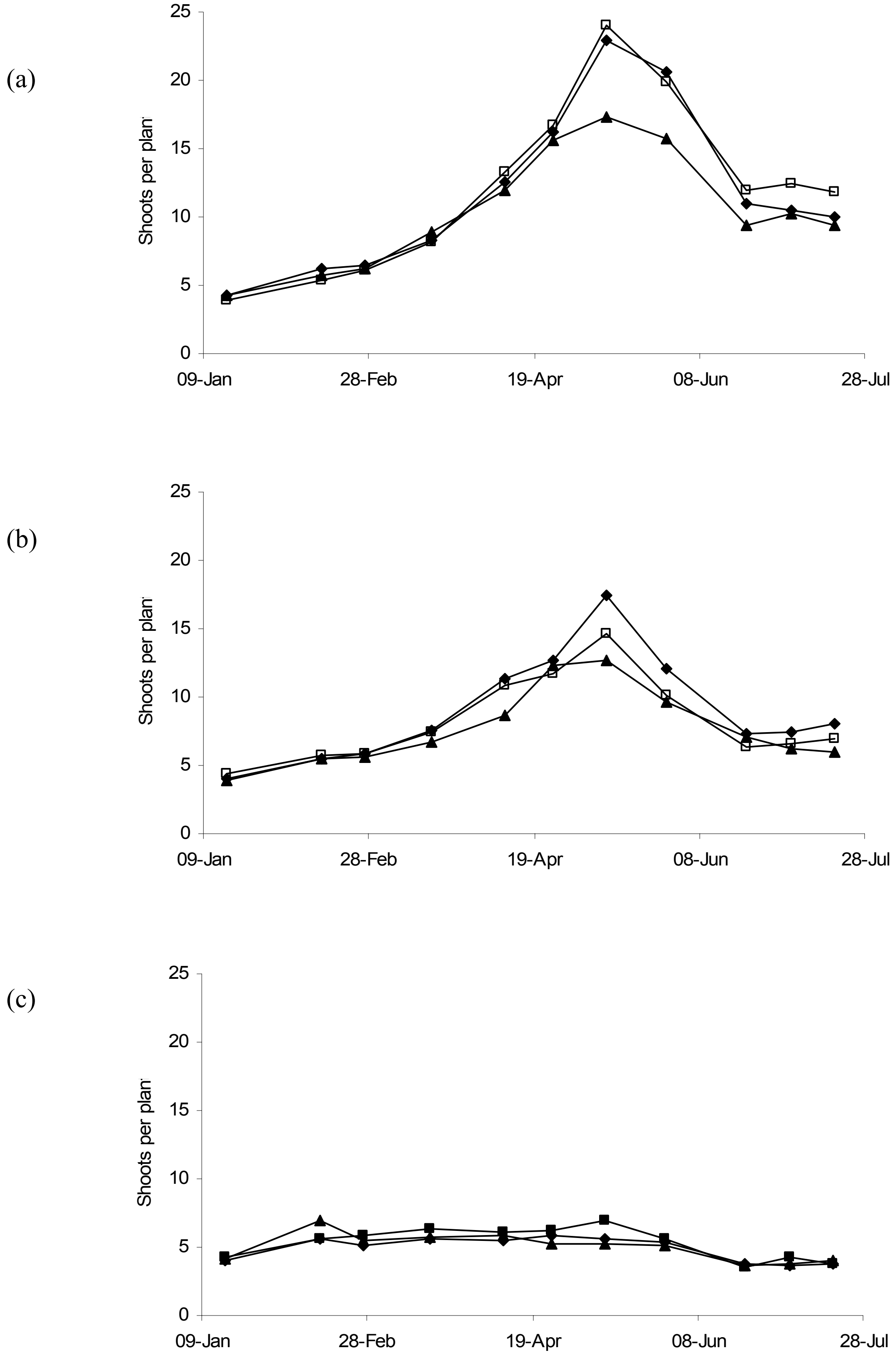

Figure 2.9. Response of wheat sown at different seed rates to timing of early nitrogen. ADAS Bridgets, 2001 (a) 40seeds/m2 (b) 80 seeds/m2 (c) 320 seeds/m2.

♦ early □ normal ▲late.

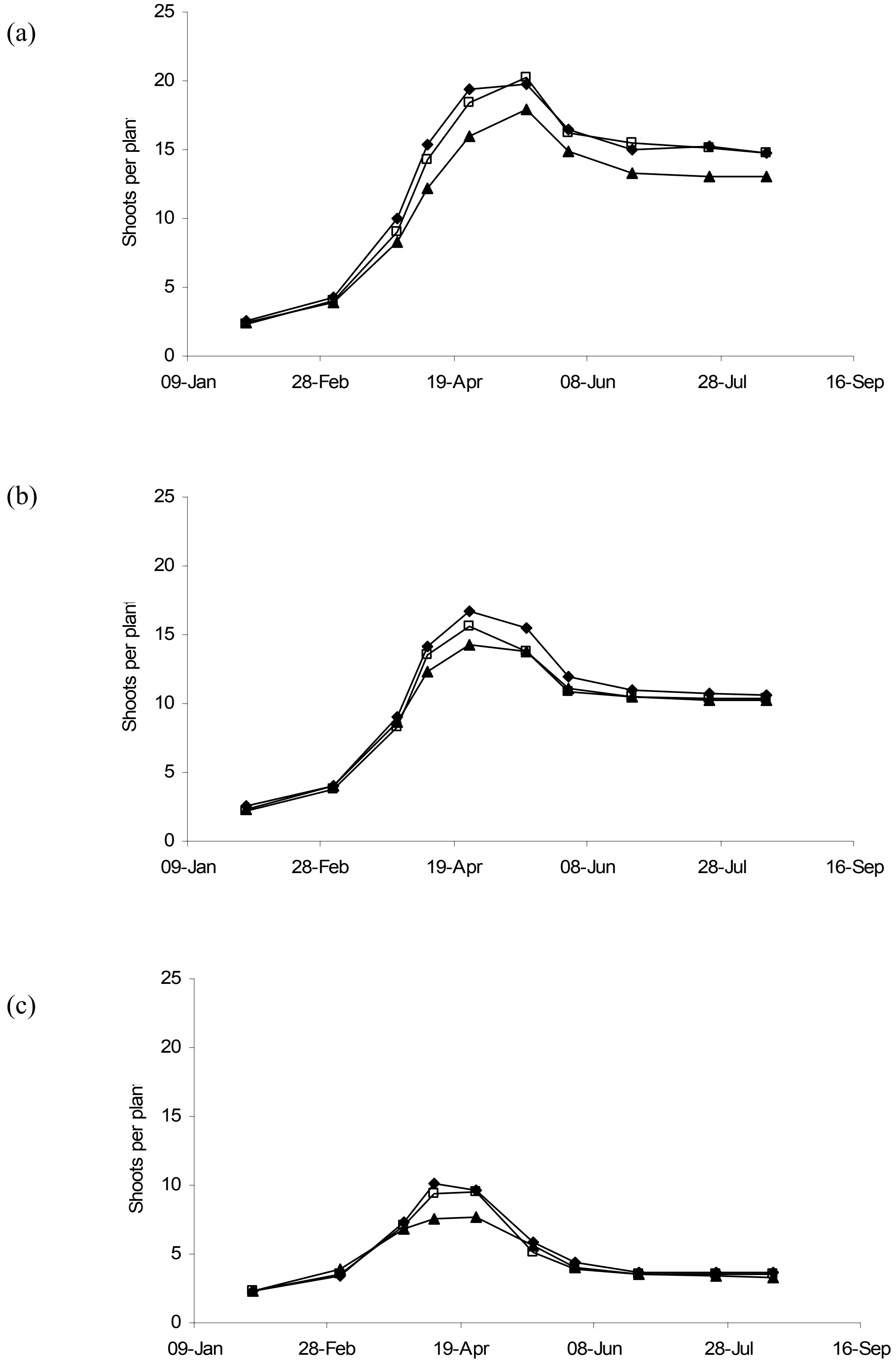

Figure 2.10. Response of wheat sown at different seed rates to timing of early nitrogen. Sutton Bonington, 2001 (a) 40seeds/m2 (b) 80 seeds/m2 (c) 320 seeds/m2. ♦ early □ normal ▲late.

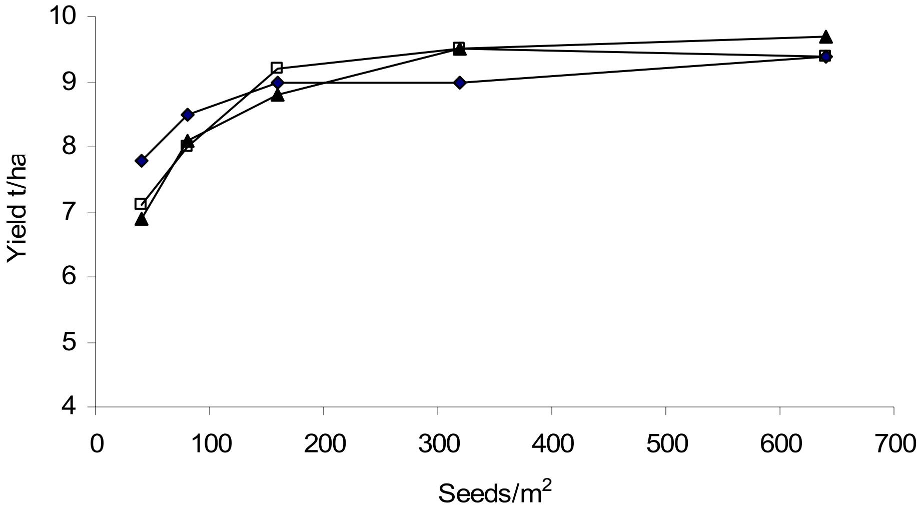

Figure 2.11. Interaction between seed rate and timing of early nitrogen: ♦ early □ normal ▲late. ADAS Bridgets 2001

2.2 Discussion

There was no consistent response to soil residual nitrogen across the three years of experiments. In 2001, the apparent increase in yield at the higher residual nitrogen level was due to differential lodging rather than nitrogen nutrition *per se*. In this year, high soil residual nitrogen was created by applying 80 kg N/ha as ammonium nitrate in the autumn. The spring nitrogen application was adjusted to 'balance' the amount of nitrogen available to all treatments, therefore the 'ResN0' plots received more spring nitrogen. It is hypothesised that this additional nitrogen in April led to more lodging prone crops. However, it is surprising that the additional 80kg/ha supplied in the autumn did not have a greater effect than the late spring application (Berry *et al.* 2000).

In 2002 there was no effect of soil mineral nitrogen on wheat yield, while in 2003 there was an interaction between seed rate and soil mineral nitrogen, with low seed rates performing better at ResN0 than ResN1. This is contrary to what might be expected; that low plant populations require more nitrogen to compensate by tillering. It should be noted that the difference between the two residual nitrogen treatments was only 17kg N/ha in February 2003, which taken in conjunction with the variable and protracted emergence in autumn 2002 leads to the suspicion that this may be a spurious result.

Although crops responded to early N application by producing more shoots per plant, and in many cases by retaining more shoots until harvest, there was no effect of N timing on grain yield. Only at one site/season (Bridgets, 2001) was there an interaction between seed rate and early N timing, with lower seed rates benefiting more than high seed rates. This would imply that soil mineral N was limiting at Bridgets, and that tillering was promoted by the early N application. However, this is not supported by the soil mineral nitrogen results which show that Bridgets had greater SMN in February, both in the topsoil (0-30cm) and in the 0-90cm profile, than all three seasons at Sutton Bonington (Table 2.4). Another potential reason is that the plant populations were unusually low at Bridgets, therefore early tiller production was more important. In fact, plant populations for the 40 & 80 seed rates were amongst the highest across all site seasons (Table 2.5). The timing of the nitrogen applications was also similar between Bridgets and Sutton Bonington (Table 2.6). Therefore, it is difficult to explain why an interaction between early N timing and seed rate should be observed only at Bridgets 2001.

Table 2.4 Soil mineral nitrogen (kg/ha) measured in February

	Site and year			
	SB01	SB02	SB03	BR01
0-30	17.3	15.5	10.5	55.9
30-60	15.6	21.2	9.7	16.3
60-90	12.1	16.3	9.4	6.9
0-90	45.0	53.0	29.6	79.1

Table 2.5 Spring plant populations (plants/m^2)

	Site and year						
Seed rate	SB01	SB02	SB03	BR01	ED02	AB02	AB03
40	25	20	19	36	31	24	24
80	58	41	34	57	70	54	41
320	235	229	221	193	264	236	189

Table 2.6 Time of early nitrogen application

	Site and year			
	SB01	SB02	SB03	BR01
Early	20 February	4 March	19 February	15 February
Normal	6 March	18 March	19 March	8 March
Late	2 April	9 April	9 April	29 March

2.3 Conclusion

Experiments conducted across seven site seasons do not generally support the hypothesis that crops with lower established plant populations require early spring nitrogen applications. Although these crops responded by producing and retaining more shoots there was no associated yield benefit (with the exception of Bridgets, 2001). However, previous work has shown that low seed rate plots are much less susceptible to lodging (Berry *et al*. 2000), and therefore the risk of applying early N, in terms of lodging is much less. Therefore, the first nitrogen application could be applied relatively early without the risk of lodging.

3. **Plant population : pest interactions**

3.1 Results

3.1.1 Slug Control

At Rosemaund in 2001 autumn establishment averaged 72%, with a range from 82% at the lowest seed rate (40 seeds/m^2) down to 67% at the 640 seeds/m^2 rate. There was no significant effect of slug control treatment on establishment but the untreated was consistently around 5% lower than the Secur treatment. (Table 3.1).

Established spring plant population mirrored almost exactly the autumn plant populations with little change in numbers indicating an absence of winter kill (Table 3.2).

Final ear number/m^2 was assessed immediately pre-harvest (Table 3.3). Ear numbers were slightly lower than the 600 per m^2 typically expected even at the highest seed rates,with the 640 seed rate only producing 560 ears/m^2 on average. There was no indication that the degree of slug control affected the crops compensatory ability through a leaf grazing effect as there was no effect of slug control or interaction with seed rate on final ear number, although there was a significant effect of seed rate.

Table 3.1 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Prophylactic - Secur seed treatment followed by slug pellets) on Autumn plant population, Rosemaund, 2001.

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	28.1	37.4	33.0	32.8
80 seeds/m^2	60.7	66.3	65.9	64.3
160 seeds/m^2	125.9	126.7	137.8	130.1
320 seeds/m^2	218.5	233.3	241.9	231.2
640 seeds/m^2	419.6	432.6	434.4	428.9
Mean	170.6	179.3	182.6	177.5

	p	LSD
Slug Treat	NS	NS
Seed rate	<0.001	15.36
Slug Treat * seed rate	NS	NS

Table 3.2 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on established Spring plant population Rosemaund, 2001.

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	23	26	31	26.7
80 seeds/m^2	60	53	64	59.0
160 seeds/m^2	119	134	122	125.0
320 seeds/m^2	205	233	249	229.0
640 seeds/m^2	409	404	451	421.3
Mean	163.2	170.0	183.4	172.2

	p	LSD
Slug Treat	NS	NS
Seed rate	<0.001	37.04
Slug Treat * seed rate	NS	NS

Table 3.3 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on final ear number/m^2, Rosemaund, 2001,

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	335.47	328.07	322.07	328.54
80 seeds/m^2	353.21	338.49	356.40	349.37
160 seeds/m^2	359.49	360.09	372.23	363.94
320 seeds/m^2	419.30	449.05	456.30	441.55
640 seeds/m^2	598.47	535.27	548.19	560.65
Mean	413.19	402.19	411.04	408.81

	p	LSD
Slug Treat	NS	-
Seed rate	<0.001	38.70
Slug Treat * seed rate	NS	-

Grain yield averaged 8.3 t/ha, however there was a significant effect of plant population with maximum yield of 9.04 t/ha being achieved on average from the 320 seeds/m^2 seed rate. Between 320 and 640 seeds/m^2 there was a slight but not statistically significant reduction of 0.25 t/ha, despite the absence of lodging. Below 320 seeds/m^2 yield also decreased, with the yield loss from sowing 40 seeds/m^2 being on average 1.7 t/ha (Table 3.4). There was a significant interaction between slug control and seed rate, which appeared to be due at least in part to a greater rate of yield loss at lower seed rates in the untreated than in either of the slug control treatments

The economic optimum, was estimated using an exponential-plus-linear fitted curve (Figure 3.1). A seed to grain price ratio of 3.75:1 was used and it was assumed that the curve would intersect at the origin, such that no seed equated to zero yield. This gave optimum seed rates of 142, 95 and 133 seeds/m^2 for the untreated, SFP and prophylactic slug treatments respectively. As all three slug control treatments had average spring establishment figures of close to 75% at 80 and 160 seeds/m^2 these seed rates equate to 106, 71 and 100 plants/m^2.

Table 3.4 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on grain yield (t/ha @ 85%) Rosemaund, 2001,

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	6.88	7.74	7.42	7.35
80 seeds/m^2	7.71	7.92	7.98	7.87
160 seeds/m^2	8.50	8.42	8.75	8.56
320 seeds/m^2	9.11	9.02	8.99	9.04
640 seeds/m^2	8.60	8.57	9.21	8.79
Mean	8.16	8.33	8.47	8.32

	p	LSD
Slug Treat	NS	NS
Seed rate	<0.001	0.276
Slug Treat * seed rate	0.042	0.719

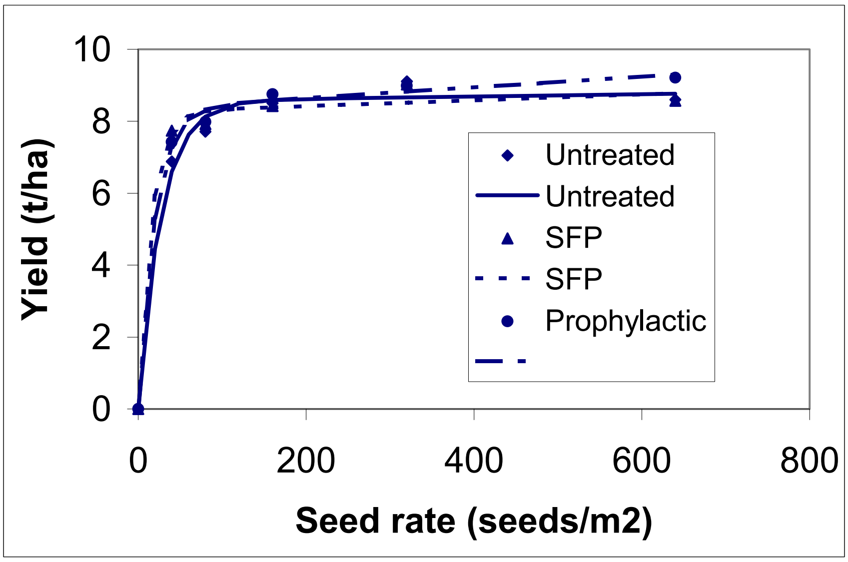

Figure 3.1 Effect of seed rate on yield fitted with exponential-plus-linear response curves, Rosemaund 2001.

As well as the effects on grain yield there were additional effects on grain quality in the form of grain size, which decreased significantly with increasing seed rate. There was an overall decline of 6.3g between 40 and 640 seeds/m^2, the effect was not due solely to effects at very low seed rates however, as between 160 and 640 seeds/m^2 there was a decline of 4.2g (Table 3.5).

Table 3.5 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on Thousand grain weight (g @ 85%) Rosemaund, 2001.

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	54.4	56.8	55.9	55.7
80 seeds/m^2	54.6	55.3	55.6	55.2
160 seeds/m^2	53.5	53.1	54.3	53.6
320 seeds/m^2	52.1	52.5	51.3	52.0
640 seeds/m^2	48.7	49.5	49.9	49.4
Mean	52.7	53.4	53.4	53.2

	p	LSD
Slug Treat	NS	NS
Seed rate	<0.001	1.262
Slug Treat * seed rate	NS	NS

At Edinburgh in 2001 the average establishment was lower than at Rosemaund at only 56% (Table 3.6). There was no real evidence of declining establishment with increasing seed rate as establishment varied considerably between successive seed rates. There was however a significant effect of slug control treatment on establishment, and a significant interaction between seed rate and slug treatment. The untreated plots achieved on average 65% of the established population of the prophylactic treatment with no consistent pattern with seed rate. This indicates that the numbers of seeds lost to slugs increased with seed rate, resulting in a significant seed rate and slug treatment interaction.

Table 3.6 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on established spring plant population Edinburgh, 2001.

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	15.9	30.5	27.9	24.8
80 seeds/m^2	28.3	47.8	48.9	41.7
160 seeds/m^2	53.7	79.7	99.6	77.7
320 seeds/m^2	151.1	192.0	216.7	186.6
640 seeds/m^2	287.7	367.7	422.1	359.2
Mean	107.3	143.5	163.0	138.0

	p	LSD
Slug Treat	<0.001	14.12
Seed rate	<0.001	20.73
Slug Treat * seed rate	0.002	35.92

Ear numbers were relatively low with only the 640 seeds/m^2 treatment achieving 600 ears/m^2 (Table 3.7). There was a significant effect of seed rate, with ear numbers dropping to 350 ears/m^2 at the lowest seed rate. However, there was no significant effect of slug treatment or any interaction between seed rate and slug control treatment.

Table 3.7 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on final ear number per m^2 Edinburgh, 2001,

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	311	372	391	358
80 seeds/m^2	285	350	381	339
160 seeds/m^2	453	405	386	415
320 seeds/m^2	465	556	582	535
640 seeds/m^2	541	609	648	599
Mean	411	458	478	449

	p	LSD
Slug Treat	NS	NS
Seed rate	<0.001	64.2
Slug Treat * seed rate	NS	NS

Grain yield increased significantly with increasing seed rate from 7.1 to 11.3 t/ha at 40 and 640 seeds/m^2 respectively (Table 3.8). There was a yield reduction with reduced levels of slug control, with the untreated yielding 1 t/ha less than the prophylactic, although this effect was not quite significant at the 5% level. The was also a significant interaction between seed rate and slug treatment, yield of the 640 seeds/m^2 rate being unaffected by slug treatment but the untreated yielding progressively less than the prophylactic culminating in a loss of 1.9 t/ha at 40 seeds/m^2.

Curve fitting to estimate the optimum population, showed that only in the prophylactic slug treatment did yield plateau sufficiently within the range of seed rates used, predicting an optimum of 188 seeds/m^2 or 122 plants/m^2. In the other slug treatments the lower establishment resulted in increasing yield between 320 and 640 seeds/m^2 which outweighed the increased seed cost.

Table 3.8 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on grain yield (t/ha @85%) Edinburgh, 2001,

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	6.0	7.4	7.9	7.1
80 seeds/m^2	7.8	9.1	9.7	8.8
160 seeds/m^2	9.7	10.2	10.6	10.2
320 seeds/m^2	10.7	10.9	11.2	10.9
640 seeds/m^2	11.2	11.4	11.3	11.3
Mean	9.1	9.8	10.1	9.7

	p	LSD
Slug Treat	0.058	0.849
Seed rate	<0.001	0.412
Slug Treat * seed rate	0.010	0.953

Autumn establishment at Edinburgh in the 2003 harvest year was relatively good averaging 80%. At the earliest assessment in November 2002 there was an almost significant effect of slug control treatment on established plant number (Table 3.9), with marginally higher establishment from the prophylactic than the standard farm practice or untreated. Whilst there was still a trend in this direction at later assessments in February (Table 3.10) and March (Table 3.11) it was not significant. Plant numbers did decline significantly over winter and through to March, with establishment declining to 59% by February and then 42% by March, indicating significant over winter kill.

Table 3.9 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on Autumn plant population Edinburgh, 19th November 2002.

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	34.4	31.9	38.0	34.8
80 seeds/m^2	70.3	67.4	79.0	72.2
160 seeds/m^2	116.7	127.5	137.7	127.3
320 seeds/m^2	269.6	262.7	283.7	271.9
640 seeds/m^2	468.5	483.7	505.8	486.0
Mean	191.9	194.6	208.8	198.5

	p	LSD
Slug Treat	0.051	13.62
Seed rate	<0.001	13.08
Slug Treat * seed rate	NS	-

Table 3.10 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on Spring plant population Edinburgh, 21st February 2003.

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	28.7	30.4	28.7	29.3
80 seeds/m^2	37.0	52.2	52.6	47.3
160 seeds/m^2	102.6	104.4	121.7	109.6
320 seeds/m^2	212.6	199.6	219.6	210.6
640 seeds/m^2	331.7	333.0	348.7	337.8
Mean	142.5	143.9	154.3	146.9

	p	LSD
Slug Treat	NS	-
Seed rate	<0.001	12.05
Slug Treat * seed rate	NS	-

Table 3.11 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on established Spring plant population Edinburgh, 25th March 2003.

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	20.0	21.7	27.4	23.0
80 seeds/m^2	34.8	37.0	44.4	38.7
160 seeds/m^2	81.3	84.8	93.9	86.7
320 seeds/m^2	157.4	149.6	160.4	155.8
640 seeds/m^2	213.5	217.8	218.3	216.5
Mean	101.4	102.2	108.9	104.1

	P	LSD
Slug Treat	NS	-
Seed rate	<0.001	9.49
Slug Treat * seed rate	NS	-

Yields at Edinburgh in 2003 were low, averaging only 5.59 t/ha. There was a significant effect of slug control on yield with the prophylactic treatment yielding significantly less than either the untreated or the SFP. There was also a significant effect of seed rate with yield increasing to a maximum at 160 seeds/m^2 and then declining slowly at higher seed rates despite the absence of lodging (Table 3.12). There was also an interaction between seed rate and slug control treatment, but it is difficult to identify any consistent logical reason for the effect.

Curve fitting to estimate the optimum population indicated relatively low optima for this site, contrary to expectation the optimum was lower where no slug control was applied compared to the other treatments. Optima of 97, 127, 150, seeds/m^2 were calculated for the untreated, SFP and prophylactic respectively. Using the establishment figures for 160 seeds/m^2 these equate to 88, 67 and 49 plants/m^2. These very low optima are likely to have been brought about in part by the low yields reducing the value of the return for increasing seed rate.

Table 3.12 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on grain yield (t/ha @85%) Edinburgh, 2003,

	Slug treatment			
seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	4.49	5.09	4.49	4.69
80 seeds/m^2	5.56	5.75	5.37	5.56
160 seeds/m^2	6.63	6.49	5.37	6.16
320 seeds/m^2	6.12	6.48	4.86	5.82
640 seeds/m^2	6.10	5.95	5.02	5.69
Mean	5.78	5.95	5.02	5.59

	p	LSD
Slug Treat	0.038	0.703
Seed rate	<0.001	0.327
Slug Treat * seed rate	0.01	0.803

As at Rosemaund in 2001 there were significant effects of seed rate on grain size. Thousand grain weight decreased significantly ($p<0.001$) from 38.6 g at 40 seeds/m^2 to 33.3g at 640 seeds (Table 3.13).

Table 3.13 Interaction between seed rate, and slug control (untreated, Standard Farm Practice (SFP), and Secur seed treatment followed by SFP) on thousand grain weight, Edinburgh, 2003,

	Slug treatment			
Seed rate	Untreated	SFP	Prophylactic	Mean
40 seeds/m^2	38.8	39.2	38.0	38.6
80 seeds/m^2	37.6	37.7	37.3	37.5
160 seeds/m^2	37.1	37.6	35.8	36.8
320 seeds/m^2	34.8	35.4	33.9	34.7
640 seeds/m^2	33.2	33.8	32.9	33.3
Mean	36.3	36.7	35.6	36.2

	P	LSD
Slug Treat	NS	-
Seed rate	<0.001	0.813
Slug Treat * seed rate	NS	-

3.1.2 Gout Fly

Although not a target of the experimental programme Gout fly infestations occurred at Rosemaund in 2002 and Mamhead in 2002 and 2003. Observations were made of the effect of seed rate on the severity of attack as well as the impact of gout fly infestation on crop shoot production.

At Rosemaund the percentage of plants infested decreased significantly with increasing seed rate, from 54.9% infestation where 40 seeds/m^2 were planted, down to 32.2% at 320 seeds/m^2 (Table 3.14). Using the established spring plant population, the number of infested plants per m^2 could be calculated. This showed that the number of infested plants/m^2 increased with increasing seed rate from 19 to 60.6 plants/m^2 between 40 and 320 seeds/m^2 respectively.

Table 3.14. Established plant population/m^2 from the spring assessment, percentage plants infested with gout fly and calculated number of infested plants/m^2.

Seed rate	Established spring plant population	% plants infested with gout fly	Number of infested plants/ m^2
40 seeds/m^2	34.73	54.88	19.06
80 seeds/m^2	69.96	39.10	27.35
320 seeds/m^2	188.15	32.22	60.62
P	<0.001	0.007	<0.001
LSD	16.14	13.53	12.70

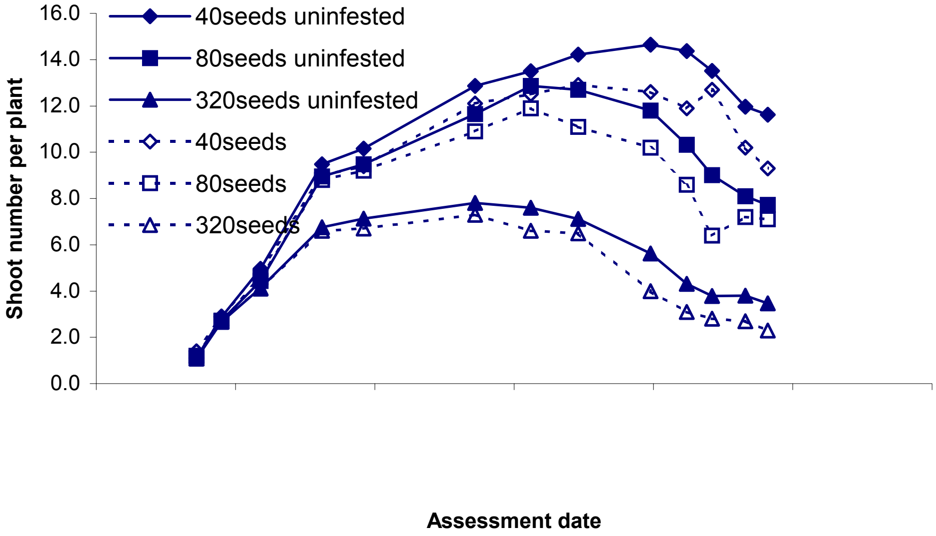

Figure 3.2 Impact of gout fly infestation on shoot production , Rosemaund 2002.

Gout fly infestation at Rosemaund in 2002 was largely limited to the main stem only. A reduction in shoot number per plant was first observed in the assessment made on 21st December 2001. At the time there were predictions that infestation may result in complete plant loss, however observations indicate that at the higher seed rate the loss was restricted to the infested shoot only and at the lowest seed rate the infested shoot was lost plus one additional uninfested shoot (Figure 3.2).

The severity of gout fly infestation at Mamhead in 2002 was much lower than at Rosemaund with an average of 5% plants infected (Table 3.15). As at Rosemaund there were a significantly higher proportion of plants infested at lower seed rates than at higher seed rates. Total established plant population increased with seed rate as expected, but in contrast to the Rosemaund results there was no significant difference in the number of infested plants/m^2 between seed rates.

Table 3.15 Percentage plants infested with Gout fly, total number of plants/m^2 and number of infested plants/m^2 at Mamhead, assessed on 13th February 2002, at GS18/29.

PGR Treatment	Seed rate	% plants infected	Plant number/m^2	Number of infested plants/m^2
Untreated	40	17.6	38.5	6.8
	80	8.4	63.3	5.6
	160	3.7	118.5	4.3
	320	2.1	208.9	4.3
	640	1.2	366.3	4.3
Tillering PGR	40	3.2	38.9	1.2
	80	12.4	68.5	8.6
	160	2.3	101.9	2.5
	320	1.4	215.9	3.1
	640	1.3	348.9	4.3
Stem Extn. PGR	40	11.8	36.7	4.3
	80	3.6	94.8	3.7
	160	3.9	108.5	3.7
	320	2.8	201.1	5.6
	640	1.8	359.6	6.2
Mean		5.2	158.0	4.6
PGR Treat	p	NS	NS	NS
	LSD	-	-	-
Seed rate	p	<0.001	<0.001	NS
	LSD	3.22	22.46	-
PGR * seed rate	p	0.001	NS	NS
	LSD	5.52	-	-

The level of gout fly infestation in the 2003 season was much higher at Mamhead than in the previous season with an average of 47% infestation compared to 5% the previous year. There were significant effects of seed rate on the percentage of plant infested, total plant number and the number of plants infested but no effect of rotational position (first vs. second wheat), or interaction between seed rate and rotational position (Table 3.16). Increasing seed rate reduced the severity of infection from a mean of 67% at 40 seeds/m^2 to 23.5% at 640 seeds/m^2, but as at Rosemaund in 2002 increased the number of plants/m^2 infested.

Table 3.16 Percentage plants infested with Gout fly, total number of plants per m^2 and number of infested plants per m^2 at Mamhead, assessed on 21st February 2003, at GS18/29.

Rotational position	Seed rate	% plants infected	Total plant number/m^2	Number of infested plants/m^2
First wheat	40	59.5	30.4	18.1
	80	52.0	62.6	32.2
	160	43.6	105.9	46.3
	320	37.3	204.4	76.7
	640	19.8	355.9	70.4
Second wheat	40	61.6	32.2	20.0
	80	59.7	56.7	33.7
	160	50.8	101.5	51.5
	320	37.8	183.3	69.6
	640	24.7	321.8	79.6
Second wheat	40	79.8	36.7	28.9
plus	80	62.2	53.0	33.0
Latitude seed	160	54.2	100.4	54.1
treatment	320	37.4	155.9	57.4
	640	26.0	353.3	90.0
Mean		47.1	143.6	50.8
Rotational Trt.	p	NS	NS	NS
	LSD	-	-	-
Seed rate	p	<0.001	<0.001	<0.001
	LSD	3.22	18.75	9.84
Rotation * seed rate	p	NS	NS	NS
	LSD	-	-	-

3.2 Discussion

Slug control experiments are notoriously difficult to conduct due to the difficulty of accurately predicting where conditions will be conducive to high levels of crop damage. Significantly more slug experiments were established than are reported here and not taken beyond the winter due to a lack of slug damage, despite locating experiments on heavy soils after oilseed rape in areas with a history of slug damage. Some interesting results were, however found, particularly in the first year.

It appears that the percentage of seeds lost to slugs remains fairly conservative across a range of seed rates. This was particularly noticeable at Edinburgh where the untreated had 65% of the establishment of the prophylactic treatment irrespective of seed rate. This implies that the proportion of seed accessible to slugs remained relatively constant across seed rates. As slugs can only access seed in soil cavities large enough for them to enter this should perhaps not be an unexpected result if seedbed formation remains constant. It also contradicts the widely held belief that a given slug population will eat a predetermined amount of seed and that as seed rate is reduced this will remain constant, resulting in an increased proportion of cropped area with no plants.

Whilst yield loss at very low seed rates was greater when no slug control was used the optimum number of plants or the number of plants needed to get on the shoulder of the response curve remained relatively stable. This implies that in these experiments any slug grazing of leaf material was not affecting the compensatory ability of the crop, although if there was a much higher slug population or more severe grazing loss of green area may be expected to have an effect.

The importance of slugs in terms of determining the seed rate to drill appears therefore to be largely a consideration of the likely percentage establishment of the site. Whilst there is no need to increase the target plant number, given a high risk of slug damage there is a need to increase the seed number drilled to achieve that population. It also seems prudent that given a risk of poor establishment it is wiser from both an economic and environmental point of view to increase seed rate rather than increase slug pellet use, although greater attention to detail in seed bed formation and consolidation may have a greater effect than either.

The interactions between gout fly and seed rate observed here arose through chance rather than experiments specifically designed to test for the impact of seed rate on the severity of pest attack. The results at Rosemaund clearly indicated that infestation of a shoot will result in the death of that shoot and at a maximum one additional shoot rather than complete plant death.

The percentage of plants infested clearly increased as plant population decreased at all three sites. With the exception of the Mamhead site in the 2002 harvest year, which had the lowest level of infestation of the three sites (5.2% infestation), the number of infested plants per unit area was significantly higher in high than low plant population crops. This implies that low plant populations are not increasing pest incidence per unit area, arguably the reverse is true with 3-4 times the number of infected plants/m^2 in high compared to low plant population plots. It is not however possible to say whether this effect would be seen in field scale grown crops. Low plant population crops have a much reduced excess tiller number than high plant population crops and therefore are likely to be more sensitive to shoot loss. The impact of plant population on yield loss due to gout fly infestation could not unfortunately be assessed in this experiment as no differential treatments affecting gout fly severity were included. The impact of crop structure on yield loss due to pest attack is however an area requiring further formal analysis to improve pest yield loss relationships and therefore threshold values.

4. **The effect of diseases on the optimum plant population**

4.1 Introduction

Several hypotheses exist about how diseases may affect the optimum plant population. Take-all reduces root function and has been shown to reduce nitrogen uptake (Spink *et al.*, 1998). If the reduction in nitrogen uptake occurs early in the plant's lifecycle then tillering may be reduced. Tillering is the most important mechanism by which crops compensate for low plant populations, so it is possible that take-all may increase the optimum plant population. On the other hand, perceived wisdom within the farming industry frequently recommends that plant populations should be reduced for crops with a high risk to take-all infection (Anon. 1996). The effect of foliar disease on optimum plant population is also poorly understood. It may be hypothesised that greater disease will result in a higher optimum plant population, as low plant population crops have a smaller canopy than high plant population crops and are therefore more sensitive to losses of green area due to disease. This hypothesis has led to a common perception that the lower leaves of low plant populations have a greater requirement for disease control than the lower leaves of high plant population crops. However, another common perception is that low plant population crops are less prone to disease infection. If this is true then the requirement to apply fungicides to low plant population crops may be less than in high plant population crops. Experiments were designed to test the above hypotheses and perceptions. The effect of rotational position and take-all is considered first followed by foliar disease.

4.2 Methods

Two experiments were performed to investigate the effect of different diseases on the economically optimum plant population. The main experiment investigated a 1st wheat, non-first wheat and a non-first wheat treated with Latitude ('silthiofam'), each grown at five seed rates (40, 80, 160, 320, 640 seeds/m^2). This experiment was repeated at three site seasons; ADAS High Mowthorpe in 2002 (HM2002), ADAS Mamhead in 2003 (MH2003) and ADAS Rosemaund in 2003 (RM2003). The experiment was designed to investigate the effects of take-all and other diseases common on non-first wheats such as stem base diseases. First and third wheats were compared at HM2002 and RM2003. First and second wheats were compared at MH2003. The second experiment investigated the effect of different fungicide programmes at each of the five seed rates this was done at High Mowthorpe in 2003. The fungicide treatments included; a single spray - Opus (0.75 l/ha) and Corbel (0.5 l/ha) at GS39 (T2), a two spray programme - the T2 treatment + Opus (0.5 l/ha) and Fortress (0.2 l/ha) at GS32 (T1+T2) and a three spray programme - the T1+T2 treatments + Bravo 500 (1.5 l/ha) at GS30 (T0+T1+T2).

4.3 Results

4.3.1 Rotational position and Latitude seed treatment effects

The mean autumn plant populations of each seed rate treatment are described in Table 4.1. There was no effect of rotational position on plant populations in any site. The plant populations were also measured in spring at HM2002 and RM2003 and were not significantly different from the autumn populations. Across the seed rate treatments, plant establishment ranged from 95% at HM02, 89% at RM2003 and 81% at MH2003 (Table 4.2). Establishment decreased with higher seed rates at RM2003 and MH2003 in agreement with the previous HGCA funded seed rate project (Spink *et al*., 2000).

Table 4.1. Plant numbers/m^2 in autumn

seeds/m^2	HM 2002	MH 2003	RM 2003
40	40	38	50
80	75	71	89
160	147	127	141
320	303	238	210
640	610	444	356
Mean	235	183	169
P Value	<0.001	<0.001	<0.001
s.e.d. (36 df)	10.8	11.3	10.33

Table 4.2. Percentage of seeds that established plants in autumn.

seeds/m^2	HM 2002	MH 2003	RM 2003
40	100	95	125
80	94	89	111
160	92	79	88
320	95	74	66
640	95	69	56
Mean	95	81	89

Assessments carried out at MH2003 showed that the 1st wheats had a mean take-all index of 12 compared with 36 for the 2nd wheats with and without Latitude ($P<0.001$). Rotational position did not significantly affect the level of take-all at RM 2003. At both sites, the 320 seeds/m^2 treatment had a greater take-all index than the 40 and 80 seeds/m^2 treatments. At MH2003, the 320 seeds/m^2 treatment had a take-all index of 38 compared with 24 for the other seed rates ($P<0.01$). At RM2003, the 320 seeds/m^2 treatment had a take-all index of 29 compared with 24 for the other seed rates ($P<0.05$).

Monitoring of tagged plants between autumn and June showed that rotational position did not significantly affect the number of shoots at any of the sites, however, in late May at HM2002, the 1st wheat treatment averaged 9.1 shoots per plant (across the 40, 80 and 320 seeds/m^2) compared with 7.6 shoots per plant for the 3rd wheat ($P=0.083$). Seed rate affected shoot number per plant at all sites, effects became detectable during December at MH2003, February at RM2002 and April at HM2002 ($P<0.05$).

Final ear number was significantly affected by seed rate ($P<0.001$; Table 4.3). Final ear number was not affected by rotational position at HM2002 or RM2003, however, at MH2003, the 1st wheat treatment averaged 476 ears/m^2 compared with 393 and 403 ears/m^2 for the second wheat and 2nd wheat with Latitude respectively ($P<0.001$).

There was no interaction between the seed rate and rotational position treatments at any site.

Table 4.3. Effect of seed rate on ears/m^2 at harvest (averaged across rotational position)

seeds/m^2	HM2002	MM2003	RM2003
40	359	298	286
80	379	356	284
160	451	400	342
320	537	471	416
640	554	586	493
Mean	478	424	364
Seed rate P-value	<0.001	<0.001	<0.001
Seed rate s.e.d.	23.1	12.0	26.6
Seed rate d.f.	36	36	24

Across all seed rates, the 1st wheats yielded 2.5 t/ha more than the 3rd wheats at HM2002 and 2.3 t/ha more than the 2nd wheats at MH2003 ($P<0.001$; Tables 4.4 and 4.5; Figures 4.1 and 4.2). However the yield difference between the 1st and 2nd or 3rd wheats was greater at the high seed rates ($P<0.001$). At the 320 and 640 seeds/m^2 treatments the mean yield difference between the 1st and 2nd or 3rd wheats was 2.9 t/ha at both HM2002 and MH2003. At the 40, 80 and 160 seeds/m^2 treatments the mean yield difference between the 1st and 2nd or 3rd wheats was 1.4 and 1.9 t/ha at HM2002 and MH2003 respectively. This increase in yield loss for the 2nd or 3rd wheats grown at high seed rates was proportionately greater than the increase in absolute yield caused by increasing seed rate. The Latitude seed treatment increased the yield of the 2nd or 3rd wheats grown at the highest seed rates (320 and 640 seeds/m^2) by 1 t/ha at both sites. Latitude also increased the 3rd wheat yields grown at low seed rates (40, 80 and 160 seeds/m^2) by 0.5 t/ha at HM2002 but had a negligible effect at MH2003.

These patterns of yield responses meant that 2nd or 3rd wheats without Latitude had a lower economically optimum seed rate than the 1st wheats. At HM2002, the optimum seed rates were 196 seeds/m^2 for 1st wheats and 151 for 3rd wheats without Latitude. At MH2003, the optimum seed rates were 142 seeds/m^2 for 1st wheats and 106 seeds/m^2 for 2nd wheats without Latitude. Latitude treated non-first wheats had intermediate optima of 168 seeds/m^2 at HM2002 and 119 seeds/m^2 at MH2003, having taken account of the extra costs for treating the seed. At RM2003, there were no significant yield differences between the 1st and 3rd wheats or the 3rd wheat treated with Latitude (Figure 4.3). The economically optimum seed rate for the combined data was 138 seeds/m^2.

The 1st wheats had a significantly greater specific weight than the 3rd wheats without Latitude at HM2002 ($P<0.001$) and the 2nd wheats with or without Latitude at MH2003 ($P<0.05$). Specific weight was increased by higher seed rates at HM2002 ($P<0.001$), but was unaffected by seed rate at MH2003 and RM2003.

Table 4.4. Grain yield at 15% moisture content (t/ha) at HM 2002.

seeds/m^2	1st wheat	3rd wheat	3rd wheat + Latitude
40	7.16	5.69	6.33
80	9.36	6.96	7.43
160	10.41	7.66	8.17
320	10.70	8.24	8.59
640	10.93	7.58	9.20
Mean	9.71	7.23	7.94
Rotation P Value	<0.001		
Rotation s.e.d. (6 df)	0.151		
Seed rate P Value	<0.001		
Seed rate s.e.d. (36 df)	0.160		
Interaction P Value	<0.001		
Interaction s.e.d. (36 df)	0.290		

Table 4.5. Grain yield at 15% moisture content (t/ha) at MH 2003.

seeds/m^2	1st wheat	2nd wheat	2nd wheat + Latitude
40	5.35	4.09	3.87
80	6.38	4.24	4.05
160	7.14	4.70	4.97
320	7.11	4.52	5.21
640	7.35	4.20	5.51
Mean	6.67	4.35	4.85
Rotation P Value	<0.001		
Rotation s.e.d. (6 df)	0.269		
Seed rate P Value	<0.001		
Seed rate s.e.d. (36 df)	0.114		
Interaction P Value	<0.001		
Interaction s.e.d. (36 df)	0.321		

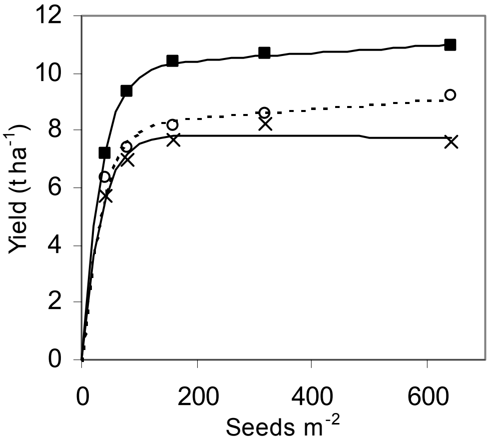

Figure 4.1. Grain yield for 1st wheat (—■—), 3rd wheat (—×—) and 3rd wheat + Latitude (---O---) at HM2002. S.e.d. for comparing individual means = 0.290 (36 df).

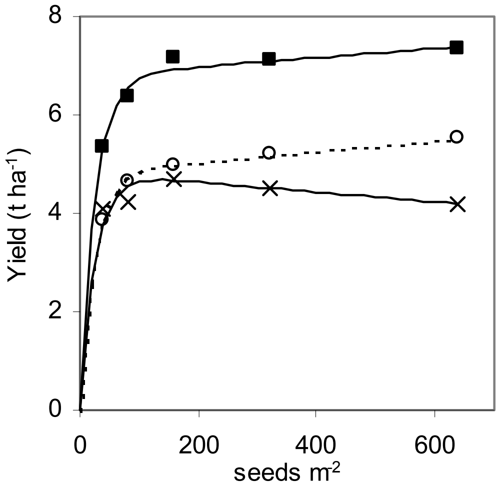

Figure 4.2. Grain yield for 1st wheat (—■—), 2nd wheat (—×—) and 2nd wheat + Latitude (---O---) at MH2003. S.e.d. for comparing individual means = 0.321 (36 df).

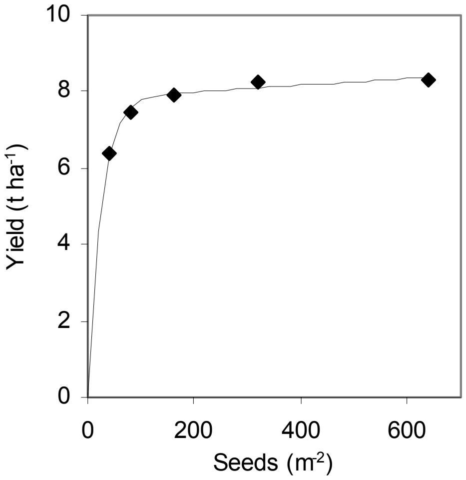

Figure 4.3. Grain yield for average of all treatments at RM2003. S.e.d. for comparing individual means = 0.121 (36 df).

4.3.2 Foliar disease control

Plant establishment in autumn varied from 100% for the 40 and 80 seeds/m^2 treatments to 90% for the 160, 320 and 640 seeds/m^2 treatments. The first fungicide treatment was applied at GS30 and was not therefore expected to affect establishment.

The proportion of leaf that was green, infected with disease or dead was determined at GS77 for leaf 1 (flag leaf), leaf 2 and leaf 3. Small to moderate amounts of *Septoria tritici* were observed on all leaves. Levels of other diseases were negligible. These low levels of disease were consistent with the dry spring. There was no evidence that seed rate affected the level of septoria. This is in agreement with Jones *et al*. (2001) who observed no difference in the level of septoria infection between crops grown at 100 and 350 seeds/m^2. The low seed rate treatments resulted in leaves with a greater proportion of green tissue ($P<0.001$). Whaley *et al.* (2000) showed that low seed rates delayed the dates of anthesis and full senescence, but did not affect the duration of green area between anthesis and senescence. Therefore, the extra greenness observed on the low seed rates in this experiment may be due to delayed development and therefore not indicative of extended green canopy duration during grain filling.

The fungicide treatments did not affect the proportion of leaves 1 and 2 that were diseased, dead or green. The T0+T1+T2 fungicide treatment resulted in about 50% more green tissue on leaf 3 compared with the T2 fungicide treatment ($P<0.05$; Table 4.6). This effect was consistent across all of the seed rates.

Table 4.6. Square root transformation for the percentage of leaf 3 that was green at GS77. Back transformed data in parenthesis.

seeds/m^2	Fungicide at T0+T1+T2	Fungicide at T1+T2	Fungicide at T2	Mean
40	6.01 (36.8)	5.34 (29.0)	5.42 (29.5)	5.59 (31.8)
80	4.61 (21.8)	5.30 (28.2)	3.48 (12.2)	4.46 (20.7)
160	3.29 (11.8)	1.92 (5.0)	2.18 (5.3)	2.46 (7.4)
320	2.47 (6.5)	3.08 (9.9)	2.09 (5.0)	2.55 (7.1)
640	1.46 (3.3)	0.47 (0.7)	0.24 (0.2)	0.72 (1.4)
Mean	3.57 (16.1)	3.22 (14.6)	2.68 (10.4)	3.16 (13.7)
Seed rate	<0.001			
Seed rate s.e.d. (28 df)	0.427			
Fungicide P Value	0.039			
Fungicide s.e.d. (28 df)	0.331			
Interaction P Value	NS			
Interaction s.e.d. (28 df)	0.740			

Yield was significantly reduced by reducing seed rates according to the typical exponential-plus-linear response ($P<0.001$; Table 4.7). The T0+T1+T2 fungicide treatment increased yields compared with the T2 fungicide treatment at the 640, 320 and 160 seeds/m^2 ($P<0.01$; Table 4.7). There was no significant difference between the T0+T1+T2 and T2 fungicide treatments at the 40 and 80 seeds/m^2. A similar pattern of results was observed for the comparison between the T1+T2 and T2 fungicide treatments. The economically optimum seed rates for the T1+T2 and T0+T1+T2 fungicide treatments were similar at 166 and 157 seeds/m^2 respectively (Figure 4.4). The optimum seed rate for the T2 fungicide was considerably smaller at 119 seeds/m^2 (Figure 4.4). After accounting for establishment, the optimum plant populations are 141, 149 and 107 plants/m^2 for the T0+T1+T2, T1+T2 and T2 fungicide treatments respectively.

Increasing the seed rate from 40 to 640 seeds/m^2 caused a steady increase in specific weight from 74.6 kg/hl to 76.6 kg/hl ($P<0.001$). Omitting the T1 and T0 fungicides reduced specific weight from 75.8 to 75.2 kg/hl ($P<0.01$). The fungicide treatments did not affect the thousand grain weight.

Table 4.7. Effect of seed rate and fungicide treatment on grain yield at 15% moisture content (t/ha)

seeds/m^2	Fungicide at T0+T1+T2	Fungicide at T1+T2	Fungicide at T2
40	8.67	8.62	8.98
80	9.72	9.79	9.59
160	10.27	10.21	9.89
320	10.74	10.69	10.32
640	10.98	10.95	10.47
Mean	10.08	10.05	9.85
Seed rate P Value	<0.001		
Seed rate s.e.d. (42 df)	0.082		
Fungicide P Value	0.002		
Fungicide s.e.d. (42 df)	0.064		
Interaction P Value	0.003		
Interaction s.e.d. (42 df)	0.142		

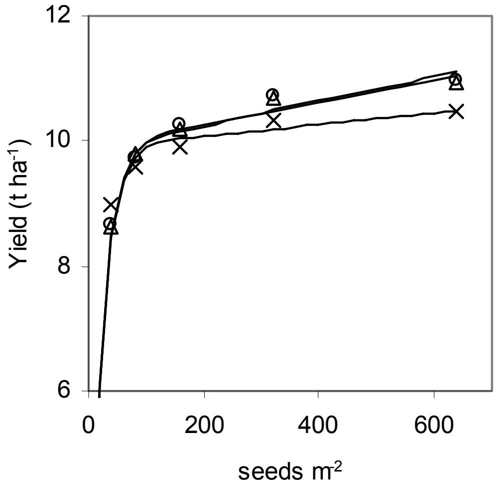

Figure 4.4. Grain yield for wheat grown with fungicide treatments at T0+T1+T2 (—O—), fungicides at T1+T2 (—Δ—) and fungicide at T2 (—×—) and 2nd wheat + Latitude (------) at HM2002. S.e.d. for comparing individual means = 0.142 (24 df).

4.4 Discussion

4.4.1 Rotational position and Latitude seed treatment effects

This study showed the optimum seed rate of 3rd wheats was *lower* than for 1st wheats. After accounting for establishment the optimum plant populations at HM2002, were 180 plants/m^2 for 1st wheats and 139 for 3rd wheats. At MH2003, the optima were 112 plants/m^2 for 1st wheats and 84 plants/m^2 for 2nd wheats. Latitude treated non-first wheats had intermediate optima of 155 and 94 plants/m^2 for HM2002 and MH2003 respectively. At Rosemaund, where no difference in rotational position was detected, the optimum plant population was 121 plants/m^2. Surprisingly at Rosemaund there were no take-all differences between rotational positions, it is though that the oat strain of take-all (*Gaeumanomyces graminis* var. Avenae) may have predominated.

At HM2002 and MH2003, the different optimum seed rates were calculated because the yield depression caused by the 3rd wheat was greater at high seed rates than at low seed rates. This effect appeared to have been caused by greater take-all infection of the high seed rate crops. These observations are supported by another study (Knight, 2002) in which the percentage take-all incidence at GS31 was 34% at 400 seeds/m^2 compared with 28% at 200 seeds/m^2 ($P<0.01$). It seems likely that the greater density of seminal roots in high seed rate crops will increase the degree of primary infection. In addition, high seed rate plants may be less tolerant to root loss because they possess fewer roots per plant. It was hypothesised that low seed rate crops may actually suffer greater take-all losses due to restricted tillering by the take-all. However, very little evidence was found for reduced tillering in the non-first wheats. This observation was supported by Pillinger (2002) and Spink *et al*. (1998).

The profitability of 3rd wheats may be maximised by either reducing the seed rate compared to those used for 1st wheats by 36-45 seeds/m^2 if the seed is not treated with Latitude or reducing the seed rates by 23-28 seeds/m^2 when the seed is treated with Latitude. The best strategy depends whether the extra yield with the seed treatment outweighs the costs of the treatment and extra seed rate. In this study using Latitude at the optimum seed rate would result in 0.23-0.59 t/ha more than using the optimum seed rate for non-treated seed. Given that the cost per hectare of Latitude use has been significantly reduced at these seed rates its use would prove to be the best strategy in these experiments.

Previous studies have not detected an interaction between rotational position or seed treatment and seed rate for grain yield. For example, Knight (2000) found that the yield response of September sown 2nd wheats to the seed treatments 'Beret Gold' (fludioxonil), 'Beret Gold' plus 'Latitude' and 'Baytan flowable' (fuberidazole + triadimmenol) was consistent for crops grown at 200, 300 and 400 seeds/m^2. On average, Beret Gold plus Latitude treated crops yielded 0.3 to 0.8 t/ha more than the Beret Gold treated crops, and Baytan flowable yielded 0.2 to 0.6 t/ha more than the Beret Gold treated crops. The absence of any interaction between seed rate and seed treatment may have been caused by the narrow range of seed rates that were investigated in this study. Another study observed a similar yield reduction of 0.3 t/ha for crops grown as 2nd wheats compared with 1st wheats which was unaffected whether being grown at 80 or 325 seeds/m^2 (Spink *et al.*, 2000b). However, it should be noted that take-all levels in this experiment were low, with only a 5% difference in the take-all index between the 1st and 2nd wheats during June in both years.

Part of the yield losses caused by the non-first wheat treatments appear to be through reduced assimilate production during grain filling. At HM2002 and MH2003, the thousand grain weight of the non-first wheats was about 15% smaller than the 1st wheats ($P<0.01$). However, the reduction in grain size is insufficient to account for the reductions in grain yield of 25-35%. Growth analysis at MH2003 showed that the 2nd wheats had almost 10% fewer grains per ear ($P<0.05$), 15% fewer ears ($P<0.001$) and 20% lower straw weight ($P<0.01$). This indicates that take-all was restricting growth before flowering at this site, which caused a reduction in the number of ears and grains.

4.4.2 Foliar disease control

These findings indicate that low seed rate crops do not require additional fungicides to protect their lower leaves compared to higher seed rate crops. This finding is supported by Jones *et al.* (2001) who observed similar yield responses to fungicides on crops grown at 100 and 350 seeds/m^2. Additionally, this result does not support the hypothesis that low seed rate crops rely more on their lower leaves for photosynthesis and therefore require extra protection against pathogens. This may be due to the greater radiation use efficiency of low seed rate crops, which can be 10-20% greater in crops grown at 160 seeds/m^2 compared with crops grown at 640 seeds/m^2 (Whaley *et al*., 2000). A greater RUE may compensate for less light interception by the smaller canopy. At seed rates below the economic optimum (40 and 80 seeds/m^2), the size of the sink that must be filled is likely to be less than in high seed rate crops. The significantly greater thousand grain weight of low seed rate crops in this experiment ($P<0.05$) is evidence that the supply of assimilates during grain filling was less limiting in low seed rate crops than high seed rate crops. Therefore, crops at very low seed rates may be able to tolerate some loss of green area because they have a smaller requirement for photo-assimilate to fill their smaller number of grains. The results may support the hypothesis that low seed rates require less protection from fungicides because they are less susceptible to disease (*Septoria tritici*). However, this hypothesis would require much wider testing before it could be applied with confidence.

In conclusion, the results from this experiment indicate that crops sown at seed rates of between 160 and 640 seeds/m^2 should be managed with similar fungicide regimes. There is evidence that crops sown at less than 160 seeds/m^2 actually have a *smaller* requirement for their lower leaves to be protected and that in low disease risk situations the GS32 fungicide may not be economical. the use of a pre-stem extension (T0) fungicide did not result in a yield increase at any seed rate.

5. **Plant growth regulator and lodging interactions with plant population**

5.1 Introduction

Plant growth regulators (PGRs) are synthetic compounds, which are primarily used to reduce the shoot length of plants. This is mainly achieved by reducing cell elongation, but also by decreasing the rate of cell division. Plant growth regulators can be classified into two main groups: inhibitors of gibberellic acid biosynthesis (e.g. chlormequat chloride and trinexapac-ethyl (Moddus)) and ethylene releasing compounds (e.g. Cerone and Terpal). PGRs are applied to 89% of winter wheat in the UK and chlormequat containing PGRs account for almost 80% of these applications (Garthwaite *et al.*, 2002). There are two issues concerning the use of chlormequat in relation to different seed rates. Firstly, its requirement for lodging control and secondly its effect on tillering and yield in the absence of lodging.

5.1.1 Effects on lodging risk

Chlormequat has been shown to reduce lodging in almost all of the vast number of published experiments that have studied its effect and in which lodging occurred (reviewed by Berry *et al.*, 2004). The reduction in the percentage area lodged can be anything up to 70% (Herbert, 1982). However, it must also be noted that PGRs do not eliminate lodging in highly susceptible crops. Chlormequat has been shown to reduce plant height by anything up to 24% (Berry *et al.*, 2004). This variation is probably caused by interactions between the cultivar together with the stage of plant development and the environmental conditions when the chemical is applied. For example, it has been shown that semi-dwarf cultivars undergo proportionately less shortening in response to chormequat (Evans *et al.*, 1995). In addition to shortening crops, PGRs are frequently claimed to reduce lodging risk by altering other parts of the plant. These claims usually centre around traits that are, or could be, associated with strengthening the stem base and the anchorage system. However, only two published studies have measured these parameters directly with and without PGRs (Crook and Ennos, 1995; Berry *et al.*, 2000). These showed that a mixture of chlormequat and choline chloride applied to winter wheat at the beginning of its stem extension did not affect the strength of the either the stem base or the anchorage system.

A large number of field experiments have demonstrated that lower seed rates reduce lodging (e.g. Spink *et al.*, 2000). Establishing 200 plants/m^2 compared with 400 plants/m^2 reduced lodging risk by increasing the strength of the anchorage system by more than 50% and the strength of the stem base by 15% (Berry *et al.*, 2000). The increase in anchorage strength more than compensated for the increased shoot number (and hence leverage force) on these plants. The greater anchorage strength has been attributed to several morphological changes including more roots per plant (Easson *et al.*, 1993), stronger and thicker roots (Easson *et al.*, 1995) and a wider and deeper root plate (Berry *et al.*, 2000). Sparsely populated plants have many tillers (Whaley *et al.*, 2000) each of which develop up to four crown roots from each of their subterranean nodes. Therefore, it should be no surprise that establishing fewer plants results in plants with more crown roots. Thicker and stronger roots may be caused by the absence of a strong shade avoidance response by the plant, which stimulates a greater proportion of assimilate to be partitioned to the roots. Similarly the explanation for stronger stems is thought to be due to greater partitioning of resources to strength properties rather than towards greater shoot extension. Contrary to common perception, reducing the plant population density from 400 plants/m^2 to 200/m^2 did not affect the leverage of the shoot (Berry *et al.*, 2000). Reductions in plant height were shown to be small and were countered by a larger ear area.

The relative effects of chlormequat and seed rate on lodging risk have been compared by Berry *et al.* (2003). This showed that a split application of chlomequat applied to the non-dwarf cv. Mercia at GS30/31 reduced stem lodging risk by the same amount as reducing establishment by about 150 plants/m^2 (between 400 and 200 plants/m^2), and reduced root lodging risk by the same amount as reducing establishment by about 75 plants/m^2. It should be noted that chormequat may reduce the lodging risk of semi-dwarf varieties by a smaller amount and that reducing establishment below 200 plants/m^2 is likely to reduce lodging risk by proportionately greater amounts.

5.1.2 Effects on tillering and yield in the absence of lodging

There is a commonly held perception in the farming industry that plant growth regulators (PGRs) improve tillering and shoot number. This effect is believed to be quite strong in barley and also present in wheat. If true, then we may hypothesise that

PGRs will be a useful tool for encouraging tillering in crops with a plant population that would otherwise be below the economic optimum. Expressed another way, PGR treated crops may have a lower optimum seed rate.

The effects of chlormequat on yield and final ear number in the absence of lodging that are reported in the scientific literature are inconsistent. A review of lodging (Berry *et al.*, 2004) identified eight studies of the effects of chlormequat on winter wheat yield in the absence of lodging. Seven of these found that chlormequat had no effect on yield and one observed an increase in yield. Kettlewell *et al.* (1983) observed an increase in ear number after applications at GS13 in one out of three experiments. Increases in ear number have also been observed after applications during tillering (Humphries *et al.*, 1965; Ibrahim and El-Hattab, 1973), the onset of stem elongation (Harris, 1978) or when the first node was detectable (Dilz, 1971). Several other studies have observed no effect on ear number after applications between GS21 and GS31 (Bragg *et al.*, 1984; Matthews and Caldicott, 1981; Berry *et al.*, 1998; Lowe and Carter, 1972). Low and high plant populations are not reported as responding differently to chlormequat (Lowe and Carter, 1972; Kettlewell *et al.*, 1983), but varieties have been reported to influence the effect of chlormequat on ear number (Kettlewell *et al.*, 1983).

Increases in ear number have been shown to be due to chlormequat increasing the survival of shoots rather than by increasing tiller production (Kettlewell *et al.*, 1983; Humphries *et al.*, 1965). Other studies that recorded an increase in ear number have not investigated whether tiller production or survival was affected. A review by Green (1986) concluded that chlormequat may increase tiller survival by two mechanisms; either through the reduction of apical dominance or through delayed ear emergence (Lowe and Carter, 1972). It was hypothesised that reduced apical dominance would make shoots more uniform and this would increase the likelihood of survival. This has been observed in barley (Matthews *et al.*, 1982). Delayed ear emergence is likely to increase the duration of the tiller survival phase since chlormequat has not been shown to affect the duration of tillering (Bragg *et al.*, 1984). This may increase the supply of assimilate to the tillers, and therefore increase their survival, by delaying the onset of competition for resources from the ear.

5.2 Methods

Three split plot experiments and one two-way factorial experiment was set up for seed rate and plant growth regulator (PGR) treatments. The PGR treatment formed the main plot in the split plot experiment. Seed rate treatments included 40, 80, 160, 320, 640 seeds/m^2. The PGR treatments included nil, New 5C Cycocel (2.5 l/ha) during tillering and New 5C Cycocel (2.5 l/ha) at the beginning of stem extension. Each experiment was carried out at four site seasons; Aberdeen in 2000-01 (AB2001), ADAS High Mowthorpe 2000-01 (HM2001), ADAS Mamhead 2001-02 (MH2002) and ADAS Rosemaund 2001-02 (RM2002).

5.3 Results

The number of plants were recorded in October at MH2001 and RM2002, in February at HM2001 and in March at AB2001. Seed rate had a statistically significant effect on the number of plants established at all sites (P<0.001; Table 5.1). The PGR treatments had similar rates of establishment at all sites. Establishment varied from 53% at AB2001 to 89% at MH2002 (Tables 6.2). Greater establishment was observed at the lower seed rates at all sites.

Table 5.1. Plant numbers/m^2 in autumn and spring

seeds/m^2	AB 2001	HM 2001	MH 2002	RM 2002
40	35	32	42	36
80	63	69	76	60
160	97	129	146	131
320	179	230	294	246
640	279	442	543	451
Mean	131	180	220	187
Seed rate P-value	<0.001	<0.001	<0.001	<0.001
Seed rate s.e.d.	9.4	8.9	11.8	15.0
d.f.	36	42	36	36

Table 5.2. Percentage of seeds that established plants in autumn and spring

seeds/m^2	AB 2001	HM 2001	MH 2002	RM 2002
40	88	80	105	90
80	79	86	95	75
160	61	81	91	82
320	56	72	92	77
640	44	69	85	70
Mean	53	73	89	75

Regular monitoring of the growth stage and the number of leaves on the main stem revealed that high seed rates had fewer leaves on the main stem ($P<0.05$), in agreement with Whaley *et al.* (2000). The PGR treatments did not affect either growth stage or the number of leaves on the main stem.

Predictably, lower seed rates increased the number of shoots per plant (as measured on the tagged plants). This effect became statistically significant in November at MH2002 and RM2002, and after February at AB2002 and HM2002. The quadrat assessments of ear number at harvest supported these observations (Table 5.3). In general, the PGR treatments did not affect the number of shoots per plant between the time of application and harvest. The only exception to this was at HM2001, where the PGR treatment applied after the onset of stem extension increased the number of shoots per plant (averaged across the 40, 80 and 320 seeds/m^2 treatments) from 8.2 to 9.7 ($P<0.05$). This effect was first observed on tagged plants in early June and persisted until pre-harvest. However, this effect was not detected using a quadrat assessment of the number of ears at harvest. The PGR treatments did not cause a significant main effect on the ear number as determined by quadrat analysis at harvest in any of the experiments. A significant interaction was observed between the seed rate and PGR treatments at AB2001 ($P<0.05$) and HM2001 ($P<0.01$). However, no consistent differences could be detected, with the PGR treatments causing significant increases and decreases in ear number at both high and low seed rates.

Table 5.3. Effect of seed rate on ears/m^2 at harvest

seeds/m^2	AB 2001	HM 2001	MH 2002	RM 2002
40	243	329	283	410
80	257	395	372	422
160	345	445	423	506
320	366	552	470	533
640	446	659	544	578
Mean	331	476	419	490
Seed rate P-value	<0.001	<0.001	<0.001	<0.001
Seed rate s.e.d.	20.7	28.8	19.3	31.7
Seed rate d.f.	36	42	36	36

No significant lodging or disease was observed within any of the experiments. Grain yield was significantly affected by seed rate at all sites ($P<0.001$; Table 5.4). The PGR treatments did not significantly affect yield in any of the experiments, although an effect at the 10% level was detected at AB2001 (Table 5.5). In this experiment, the PGR treatment applied at GS30/31 increased yield by 0.8 t/ha compared with the nil treatment and by 0.5 t/ha compared with the PGR treatment applied during tillering. There were no clear effects on the yield components to explain how this yield effect had been caused. No interactions were observed between the seed rate and PGR treatment for grain yield. Consequently the PGR treatment had a trivial effect on the economically optimum seed rates. Across all PGR treatments the optimum seed rates were 153 seeds/m^2 at AB2001, 203 seeds/m^2 at HM2001, 91 seeds/m^2 at MH2002 and 110 seeds/m^2 at RM2002 (Figure 5.1). After establishment is taken into account (Table 5.2), these optimum seed rates approximate to 93 plants/m^2 at AB2001, 164 plants/m^2 at HM2001, 86 plants/m^2 at MH2002 and 83 plants/m^2 at RM2002.

Specific weight was increased by high seed rate at HM2001, reduced by 640 seeds/m^2 compared with other treatments at MH2002 ($P<0.001$) and not affected by seed rate at

AB2001 or RM2002. The PGR treatments had no effect on specific weight. Thousand grain weight was increased by low seed rate treatments at MH2002 and RM2002, with no effect at HM2001. At AB2001, the 40 seeds/m^2 treatment had a lower thousand grain weight than the other treatments (P<0.001). The PGR treatments did not affect grain weight in any of the experiments.

Table 5.4. Effect of seed rate on grain yield (t/ha) at 85% dry matter

seeds/m^2	AB 2001	HM 2001	MH 2002	RM 2002
40	5.43	8.86	8.11	8.94
80	6.98	10.72	8.70	9.70
160	7.60	11.91	8.95	10.19
320	7.76	12.44	8.85	10.53
640	7.28	12.64	8.07	10.02
Mean	7.01	11.31	8.54	9.88
Seed rate P-value	<0.001	<0.001	<0.001	<0.001
Seed rate s.e.d.	0.239	0.133	0.179	0.175
Seed rate d.f.	36	42	36	36

Table 5.5. Effect of PGR treatment on grain yield (t/ha) at 85% dry matter

	AB 2001	HM 2001	MH 2002	RM 2002
Nil PGR	6.67	11.27	8.38	9.88
5C at tillering	6.91	11.35	8.81	10.02
5C at GS30/31	7.45	11.32	8.42	9.75
Mean	7.01	11.31	8.54	9.88
PGR P-value	0.088	NS	NS	NS
PGR s.e.d.	0.293	0.103	0.234	0.214
PGR d.f.	6	42	6	6

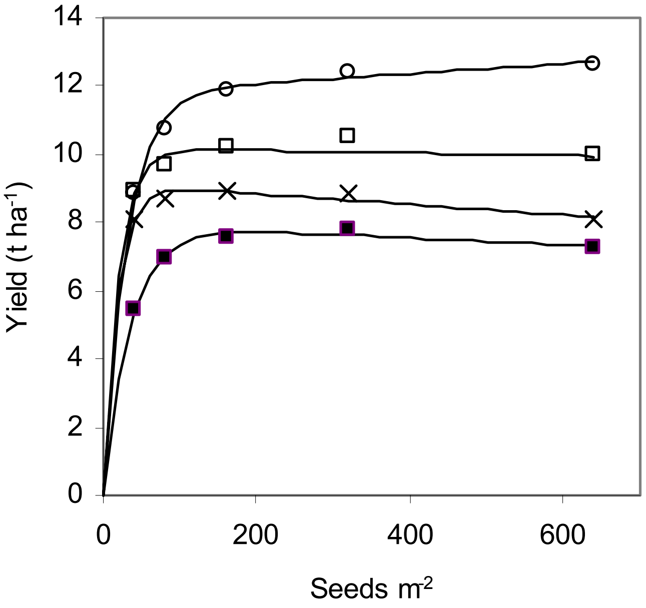

Figure 5.1. Effect of seed rate on yield for HM2001 (○), RM2002 (□), MH2002 (✕) and AB2001 (■).

5.4 Discussion

Chlormequat applied before and after the onset of stem extension did not alter the grain yield of crops grown at seed rates ranging from 40 to 640 seeds/m^2 in the absence of lodging. This result was consistent at each of the four experimental sites in Devon, Herefordshire, North Yorkshire and Scotland. These findings are in agreement with the majority of previous studies on winter wheat that have been reviewed by Berry *et al*. (2004). These results meant that similar optimum seed rates were calculated for crops grown with and without chlormequat at all sites.

The central hypothesis was that chlormequat may increase yield in crops with sub-optimal plant populations by increasing shoot number. This hypothesis has been disproven since none of the experiments were able to detect an effect of chlormequat on the number of ears measured just prior to harvest. These observations were also supported at three sites by monitoring tagged plants throughout the season. At one site, chlormequat applied after stem extension resulted in more shoots between June and harvest. However, this effect could not be detected at harvest. These results are supported by previous studies which include crops grown at different plant densities (Lowe and Carter, 1972; Kettlewell *et al*., 1983).

Several reasons can be postulated to explain why the industry's perception that chormequat increases shoot number in 'thin' crops has not been supported by this study. It is possible that the industry perceptions are based on observations in barley, for which chormequat has previously been observed to increase ear number (Matthews *et al*., 1982; Matthews and Thompson, 1983). The previous studies that have reported more shoots in winter wheat in response to chlormequat are over 20 years old. It is possible that new semi-dwarf varieties are less responsive to chlormequat. This is certainly the case for height reduction (Berry *et al*., 2004).

The main conclusion to draw from this work is that chlormequat should be targeted at crops that establish a large number of plants to help reduce their high lodging risk. Chlormequat should not be targeted at crops that have established a sub-optimal number of plants with the objective of increasing tiller number.

6. Bayesian estimation of optimum seed rates

6.1 Introduction

This project (number 2860) considers the evidence on optimum seed rates from HGCA-funded trial series for winter wheat, using data from Phase I (Project 1814, 1997-1999) and Phase II (Project 2249, 2001-2003).

We first identify and investigate several issues relating to the analysis of the data and the resulting recommendations on seed rate, as follows.

1. Should the advice given to growers emphasise seed rate or plant population?

2. Should the data be analysed separately for each combination of environment and variety, as is traditional, or by using models which include effects for environments and varieties?

3. Should a Bayesian analysis be used, potentially allowing prior knowledge of the crop to be incorporated?

4. Several covariates, such as latitude and sowing date, may be incorporated into the analysis, and we may use a new covariate, designed for this purpose by Spink *et al* (2000), the *thermal time to full vernalisation*. It may also be useful to include emergence as a covariate, so that the grower can apply knowledge of previous emergence and of the condition of his fields at the time of sowing. Which, if any, of these covariates is it worthwhile to include?

5. Do the results of the analyses depend substantially on the form of the function relating yield to seed rate (or to plant population)? If so, is a particular function to be preferred?

6. Some managerial decisions, such as slug treatment, are made before or at the same time as the choice of seed rate: how should recommended rates depend on these decisions? Other treatments are chosen later in the growing season:

how might they affect the expected profit margin if seed rate is near the optimum for a standard set of treatments?

7. Are the costs of seed and of the treatments applied appropriate? Should savings in labour and fuel from reducing seed rates be included?

We then present Bayesian analyses of the combined data which relate crop yields to seed rate, covariates and treatments for five varieties and 38 environments using the exponential-plus-linear and inverse-quadratic dose-response functions. We also model the dependence of crop yield on autumn plant population for the environments for which these populations are available.

6.2 The Data Available

The data relate to two phases of work, as follows.

Phase I based at Rosemaund and Sutton Bonington in harvest years 1997-99 used seed rates 20, 40, 80, 160, 320 and 640 seeds per m^2 and sowing dates from September to November: see Spink *et al*. (2000) for further details.

Phase II based at seven sites between the south coast of England and Aberdeen in 2001-03 used rates 40, 80, 160, 320 and 640. In addition to a wide range of latitudes, it included treatments related to rotational position, slug control, nitrogen timing and the use of PGR and fungicide, but herbicide use was not varied.

As a result of the different emphases in the two phases, the combined data are rather unbalanced: for example there are data for 24 of the potential 42 year by site combinations. There were three sowing dates within a season for each of three of these, and these dates are treated as defining separate environments. Similarly, another two of these year by site combinations had two levels of residual nitrogen (denoted by RN^-,RN^+) which we also treat as separate, giving 38 environments in all. We regard these as unrelated environments, rather than including year and site effects and their interactions. For these environments, we also consider the following five covariates (in addition to seed rate),

- latitude, in degrees
- sowing date, in days from 1 January
- plant populations in autumn (recorded for 32 environments) and spring (15 environments)
- thermal time to full vernalisation (abbreviated as TTver).

Values of TTver at Rosemaund for four sowing dates (15 and 30 Sep, 15 and 30 Oct) from 1983 were also made available to provide information on the long-term variation in this covariate.

Data on the following varieties of winter wheat were analysed in Phase I: Cadenza, Claire, Haven, Soissons, Spark. Only Claire was sown in Phase II. A further 21 varieties were omitted from analyses because at most eight yields were available for each.

We have analysed means over blocks for each variety rather than individual plot yields. Where plot yields were missing, variety means were calculated using the ANOVA Procedure in GenStat for Windows (6th edition). There were 627 means in all, 427 of them relating to the standard combination of treatments. We refer to these means as 'yields' in what follows. There were 307 yields for Claire and 80 each for the other four varieties. Table 6.1 gives information on the seven sites (ordered from north to south).

The treatments included in our analysis are listed in Table 6.2 with the numbers of environments in which each was varied. The investigation of rotational position contrasted first and third wheat at High Mowthorpe and Rosemaund, but first and second at Mamhead: our analysis ignores the distinction between second and third wheats. Fungicide treatments were ignored because they were varied in only one environment. Table 6.2 also shows the costs assumed for the treatments relative to the standard level.

Table 6.1. Trial sites with latitudes, harvest years, sowing dates, treatments varied and total numbers of yields at each site

Site	Latitude (degrees)	Harvest years	Sowing dates (from 1 Jan)	Treatments varied	Numbers of yields
Aberdeen	57.34	01-03	266-280	N timing, PGR	45
Edinburgh	55.87	01-03	280-290	Slug treatments, N timing	45
High Mowthorpe	54.11	01-03	270-319	Rotation, PGR	35
Sutton Bonington	52.83	97-99, 01-03	263-293	N timing, Residual N	162
Rosemaund	52.13	97-99, 01-03	266-350	Sowing date, Rotation, Slug treatments, PGR	295
Bridgets	51.10	01	279	N timing	15
Mamhead	50.62	02-03	276-282	Rotation, PGR	30

Table 6.2. Treatment factors included in the analyses: the standard level is underlined, and any differences in cost for others are given in brackets (per ha or per tonne of seed).

Treatment	Environments with differing treatments	Level 1	Level 2	Level 3
Rotation	3	First	Second/third	Second/third + Latitude (£150/t)
Slug treatment	3	None (–£13/ha)	Post drilling	Post drilling + Sibutol Secur (£80/t)
Nitrogen timing	9	Early	Normal	Late
PGR treatment	4	None (–£9.5/ha)	At tillering	At stem extension

We have assumed the value of grain to be £80 per tonne, the cost of seed to be £300 per tonne and the average mass of a seed to be 45 mg. It would be straightforward to change any of these figures or to allow them to depend on the variety.

6.3 Issues Arising in the Analysis of the Data

6.3.1 Recommended seed rates or plant populations?

Guidance to farmers often emphasises optimum plant populations rather than optimum seed rates. For example, HGCA's Topic Sheet 36 gives optimum populations for different sowing dates, and recommends that corresponding seed rates 'should normally be 25% to 50% higher than optimum plant populations'. This allows the grower to make some adjustment for local soil conditions.

Our investigation of the plant population data has shown that autumn emergence rates (i.e. measured plant populations divided by corresponding seed rates averaged over plots and varieties) were sometimes well over 100%, and as high as 151% (but also as low as 2%). Figure 6.1 shows these emergence rates for autumn and spring. If seed rates can be assumed correct, only sampling variation should lead to emergence rates exceeding 100%. Thus these graphs provide evidence of substantial upward bias in recording plant populations, especially at low seed rates. This bias can be expected to result from a failure to adjust the sampling scheme to low plant densities, for example by using larger quadrats. It would be difficult to accept that this bias is consistent over sites and years, and that farmers given advice in the form of recommended plant populations would be able to correct for the bias.

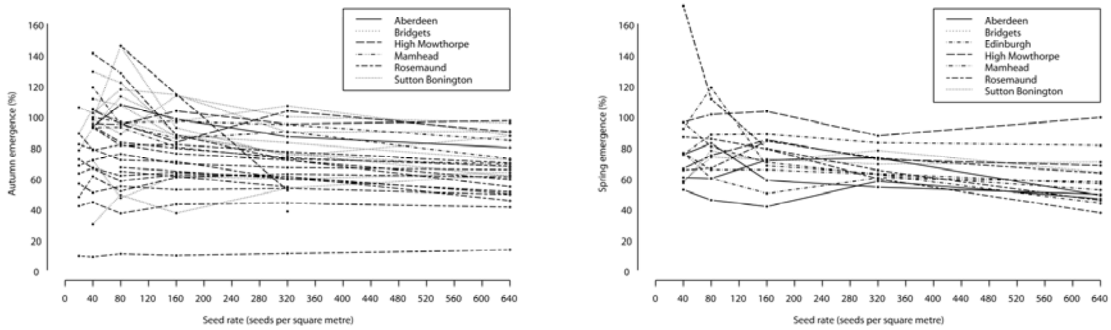

Figure 6.1. Mean emergence over varieties for autumn (left) and spring (right): each line links the sequence of seed rates for one environment

Apart from inaccuracies in the plant population data and their absence for several environments, we see the following difficulties with modelling the dependence of yield on plant population, and hence in making recommendations about target populations rather than seed rates.

1. Although the agronomist may consider plant population an essential concept in modelling plant growth, the grower has to decide on what seed rate to use (combined with other choices about managing the crop). Some growers may feel entitled to advice on the appropriate rate for their sites, even if this advice is interpreted by reference to plant population.

2. For any seed rate, it ought to be straightforward to calculate the cost of seed and of drilling. The same is not true of a specified plant population without some formula relating population to seed rate. If the formula is assumed to be exact then plant population is regarded as equivalent to seed rate: if not, there is no 'optimum plant population'.

3. Emergence seems to vary substantially with seed rate even in the same environment, as illustrated by Figure 6.1.

Although we have identified difficulties with recommending plant populations rather than seed rates, it may be possible to assist the levy payer who wishes to modify a recommended seed rate by using his knowledge of previous emergence on his fields and of their condition at the time of planting. This might be achieved by defining an index measuring the grower's assessment of likely emergence, and including it as a further covariate in the model.

6.3.2 Separate or combined analyses?

The conventional method for combining information from seed-rate (or fertilizer) experiments over several environments is to fit a parametric dose-yield function such as the exponential-plus-linear function for each environment, compare the estimates for the various environments and combine them in an informal way, rather than using a statistical model which includes effects for environments. If several varieties are being compared then 'environments' in the last sentence may be replaced by 'variety by environment combinations'. Fisher (1935) and Yates and Cochran (1938) recognized the need to combine information on variety yields over several environments: methods and models for this purpose are reviewed by Patterson (1997). We argue below that there are also advantages in a combined analysis of seed-rate data over varieties and environments. Combining a large number of non-linear regression analyses with common parameters has been too complex to attempt until recently, but software now exists which makes it feasible, at least for a Bayesian model.

We see the following benefits in modelling seed-rate data from several environments (and possibly from several varieties) within a single model which includes random effects for the environments.

1. Individual analyses are usually based on rather small data sets, and are thus likely to lead to unsatisfactory estimates. With an exponential-plus-linear model, for example, it is easy to obtain estimates which imply that the expected yield increases indefinitely with seed rate, possibly leading to an infinite 'optimum' rate.

2. One might wish to relate the estimates of these optima to sowing date and to the characteristics of the site, but this is hampered by their sensitivity to changes in the model fitted and the seed price assumed.

3. Individual analyses address the question 'What would the best seed rate have been in this environment?', whereas the grower has to choose the rate for a site elsewhere on a future occasion. For this task one needs to make some assumption about how the target site is related to the trial sites. At the simplest, this relationship would be that trial and target environments are taken at random from the same population, so that we are led to model environment differences using a random-effects model. This model may be generalized to incorporate covariate information.

4. If the analysis for each environment includes factors such as the treatments listed in Table 6.2 and non-significant factors are omitted from the fitted

models, there is the extra difficulty of combining information over different models.

Because we believe an inclusive analysis to be more relevant to choosing future seed rates, we have not attempted individual analyses. However, the combined analysis can provide optimum rates for individual trial sites, and some are shown for one variety, Claire, in Section 6.5.1.

6.3.3 Conventional or Bayesian analysis?

The Bayesian approach to statistical inference and decision making is being applied increasingly in science and technology, aided by advances in computing techniques. An accessible introduction to Bayesian statistics for biologists (in the context of conservation biology) is given by Marin *et al*. (2003), and a standard work on the Bayesian approach is Gelman *et al*. (2003).

An essential part of the Bayesian framework is that the unknown parameters in a statistical model are assumed to be random variables which have to be assigned a probability distribution, the *prior* distribution, reflecting our knowledge before the data are considered. This may be a difficult task, particularly for models with many parameters, but in the present context it gives us the opportunity to incorporate knowledge of the crop. Such knowledge includes assessments of likely yields in relation to seed rate and of variation between environments and between varieties. It may be based on experience of many more seasons, locations and varieties than are represented in the data. In particular, it can automatically exclude parameter values corresponding to unreasonable models, such as exponential-plus-linear models without finite maxima. Information on costs and the value of the crop are combined into a utility function.

The prior distribution is combined with the data to form a *posterior* distribution for the parameters: the optimum choice of seed rate (and possibly of variety and treatment) in the Bayesian framework is that which maximizes the expected utility over this distribution, known as the *posterior expected utility*.

Calculation of the posterior distribution and the posterior expected utility for complex models may require specialized programs and many hours of computation. We have been able to implement these calculations using the WinBUGS program (Spiegelhalter *et al.*, 2003), which is freely available from http://www.mrc-bsu.cam.ac.uk/bugs.

It is possible to imagine a conventional statistical analysis of a model for the combined data in which variance components, treatment effects and regression coefficients are estimated by maximum likelihood, but it would require the use of dubious large-sample approximations for inference.

6.3.4 Inclusion of environment-specific covariates

Latitude and sowing date are expected to have substantial effects on the the optimum seed rate, and other characteristics of the environment such as soil type may be influential. Including such covariates in the analysis offers the possibility of seed-rate recommendations which are specific to each target site and vary with date, at the cost of providing the covariate data and calculating the optimum rate for each site. The number of such covariates might be restricted to one or two in order to make communicating the results feasible.

We distinguish two types of covariate according to whether their values are or are not available at the time of sowing: the first type includes latitude, sowing date and soil type, while the second includes measures of accumulated temperature over the growing season or of average emergence for the environment. It is arguable that sowing date is itself uncertain, since a grower may purchase seed with the intention of sowing it on particular dates but be unable to do so: we ignore this complication here. If a covariate of the second type is included in a model then

- Its value would need to be estimated for any target environment, possibly by interpolation from data provided by nearby weather stations.

- Any predictions from the model would have to make allowance for the uncertainty in its value for the target site in the coming season.

It is difficult to make proper allowance for the effect of uncertainty in the value of the covariate on predictions of future yield. In principle, it could be made by repeating the predictions at covariate values sampled from its distribution for the site. If the covariate is known to be roughly normally distributed over seasons for each site (and effects such as climate change are negligible) then its future distribution can be estimated using a mean and standard deviation. It may be more satisfactory to replace the covariate in the model by one of the first type, such as its long-term mean value for the site (or the site and combinations of other covariates); this mean can be expected to have less explanatory power than the value for the current season.

Thermal time to full vernalisation (Spink *et al*. 2002) is a covariate of the second type, and combines information on sowing date, latitude, altitude and weather during the growing season. It is highest at early sowing dates and also tends to be higher at lower latitudes. Plotting mean yields over varieties at each seed rate against TTver shows that the yields tend to increase with TTver at low seed rates, reflecting the ability of crops grown at low rates to achieve similar yields to those grown at high ones if sowing is sufficiently early. At rates of 160 and 320 seeds per m^2, there is little dependence on TTver, and at 640 yields tend to decrease with TTver.

In Section 6.5.2 we compare models which include TTver with models incorporating two covariates of the first type, latitude and sowing date. We also use an average measure of emergence for each environment as a covariate, in order to investigate whether it might be useful to include an index measuring the grower's assessment of likely emergence.

6.3.5 Inclusion of non-standard treatments

Some managerial factors, such as rotational position and treatments for seed against take-all and slugs, are decided before or at the same time as the choice of seed rate: we consider whether and how recommended rates should depend on these factors. Other treatments, including nitrogen timing and plant growth regulator (PGR) use, are chosen later in the growing season after examining the crop. To assess the value of the latter treatments we should consider not only their cost and the resulting change in yield but also whether the criteria for applying them were satisfied in each environment. In the absence of this knowledge, we are unable to assess the benefit of varying these treatments only in appropriate conditions. Instead we examine how they affect the expected profit margin if they are used regardless of the criteria, assuming that seed rate is near the optimum for a standard set of treatments.

6.3.6 Dose-response functions

Several dose-response functions might be considered for relating crop yield to seed rate. We consider the following functions, assuming their intercepts at zero seed rate to be zero.

1. The exponential-plus-linear function, which may be expressed as $\beta(\rho^x - 1) - \kappa x \; (x > 0)$, where x denotes the seed rate and β, ρ and κ are unknown parameters. This seems to be the function employed most in studies of seed rate and of nitrogen fertilizer, and is used in Spink *et al.* (2000). However, at extremely high rates it either goes negative or carries on increasing, both of which are unrealistic.

2. The inverse-quadratic function (Nelder, 1966). This is the ratio of a linear function and a quadratic, and might be expressed as $x/(\beta_0 + \beta_1 x + \beta_2 x^2) \; (x > 0)$. It can be easily constrained to remain positive at all rates, have a maximum at a finite rate and tend towards zero at very high rates.

In order to facilitate the choice of prior distributions for model parameters, we follow Theobald and Talbot (2002) in expressing these two dose-response functions in terms of parameters intended to have clear interpretations. Two of these parameters are the maximum expected yield and the corresponding seed rate. Because of the importance of different varieties' susceptibility to lodging, we choose as a third parameter a measure of how rapidly expected yield declines beyond the maximum. Thus we consider the following parameters.

γ is the maximum expected yield

δ is the seed rate giving maximum expected yield

λ is the ratio of the expected yield at 2δ to that at δ

By definition, λ is restricted to the interval (0,1), so it is convenient to define an equivalent parameter η equal to the logit of λ, that is $\ln\{\lambda / (1 - \lambda)\}$: then the range of η is unrestricted and λ is expressed as $\exp(\eta) / \{1 + \exp(\eta)\}$. Also, we might expect a prior distribution for δ to be positively skewed, and this is modelled by taking $\ln \delta$ (which is unrestricted) to be Normally distributed. The two dose-response functions chosen may be redefined in terms of γ, δ and η. For example, the inverse-quadratic function may be expressed as

$$\mathrm{E}(y \mid x, \gamma, \delta, \eta) = \frac{\gamma\delta x}{\delta x + 2e^{-\eta}(x-\delta)^2} \quad (x > 0), \qquad (6.1)$$

where E denotes expected value and y denotes the yield. It is more difficult to express the exponential-plus-linear function in terms of γ, δ and η, and this requires a slight approximation. We also replace negative values of this function by zero in modelling and prediction.

6.4 The Modelling Procedure

The Bayesian method used here is adapted and extended from Theobald and Talbot (2002): it encompasses the trial data (including covariates and treatments), prior information, future yields and costs. It may be summarised as follows.

1. Choose a dose-response function.

2. Express this function in terms of parameters which can be easily interpreted and can be treated as statistically independent *a priori*.

3. Using these parameters, model the variation in yield between environments, possibly also incorporating treatment effects, one or more covariates and the differences between varieties.

4. Choose a prior distribution for all the model parameters to reflect knowledge of the crop varieties, the degree of variation between environments and the likely effects of treatments and covariates.

5. Define the utility of sowing seed at any given rate in the target environment. The choice of utility made here is the value of the crop (per ha) minus the costs of the seed and of non-standard treatments, although a non-linear function of yield might be used to reflect the grower's aversion to risk. Other costs, such as those of sowing seed and recording covariates, may also be included.

6. Combine the prior distribution with the information in the data to find the posterior distribution of the model parameters and the posterior expected utility for any variety at different values of x. The posterior expected utility is found for different values of the covariates (where relevant) and for any non-standard treatments. Make allowance for any uncertainty in the values of the covariates by sampling from their estimated distribution.

7. Identify an optimum rate for those combinations of variety, treatment and covariate values which are of interest: this may exclude treatments applied after sowing, as explained in Section 6.3.5. Possibly assess the economic benefits to be expected from using non-standard treatments.

8. Repeat the calculations to assess the robustness of the optimum rates to changes in the prior distribution, in costs and in the dose-response function.

Note that point estimation of parameters does not form part of this procedure.

6.4.1 Including environment, variety, covariate and treatment effects

Theobald and Talbot (2002) model variation between environments and varieties by allowing the parameters γ, δ and λ to vary according to the combinations of these factors, leading to a random-effects model: the random environment effects for the trial and target environments are treated as arising from a common distribution.

This model may be extended to include dependence on environment-specific covariates such as latitude or TTver and on treatments. Thus for the maximum-yield parameter γ_{ijk} corresponding to the combination of variety i, environment j and level k of a treatment, we might assume an additive model

$$\gamma_{ijk} = \gamma_{vi} + \gamma_{ej} + \beta_{\gamma x}(x_j - \bar{x}) + \tau_{\gamma k}, \qquad (6.2)$$

where γ_{vi} and γ_{ej} denote variety and environment effects respectively, x_j is the value of a covariate for that environment, $\bar{x}$ is the mean of the x_j, $\beta_{\gamma x}$ is the corresponding regression coefficient and $\tau_{\gamma k}$ is the effect of the treatment level relative to the standard level. The effects of any further covariates and treatments are also taken to be additive on this scale. We take γ_{vi} and γ_{ej} to be Normal and statistically independent, and define the prior distribution of the γ_{ijk} in terms of the variance components $\sigma^2_{\gamma v}$ and $\sigma^2_{\gamma e}$ for the γ_{vi} and γ_{ej} and distributions for the regression coefficients and treatment effects. We also take the γ_{ej} to have expectation zero, and assume a common expectation μ_γ for the variety effect γ_{vi}. Thus we use the same prior distribution for all varieties, although the expectations of the γ_{vi} could be made to depend on the variety, for example if some are known to be prone to lodging.

Note that the model in (6.2) is hierarchical in the sense that the distribution for the γ_{ijk} is defined in terms of higher-level parameters such as the γ_{vi}, whose distributions are themselves defined by parameters μ_γ and $\sigma^2_{\gamma v}$.

Applying a decomposition similar to equation (6.2) to the parameters δ_{ijk} and λ_{ijk} would be problematic, because they are restricted to positive values and the interval (0,1) respectively: instead we assume an additive model like (6.2) for $\ln \delta_{ijk}$ and η_{ijk}. In addition, the parameter σ_y^2 represents the residual variance of the yield, assumed to be the same for all environments, varieties and treatments.

Because of the non-linearity of the dose-response functions, the additive assumptions in (6.2) and the corresponding equations for $\ln \delta_{ijk}$ and η_{ijk} do not imply that variety, environment, covariate and treatment effects are additive on the scale of yield, but they restrict the type of interaction which can be represented: for example, a treatment having substantial and opposite effects on different varieties would not be modelled well. It would be possible to include interaction between factors in these equations or allow the regression coefficients to depend on variety.

The prior distribution for each variance component may be specified using a prior estimate and corresponding degrees of freedom: higher degrees of freedom imply greater confidence in the estimate. The remaining parameters are given Normal distributions specified using their prior means and standard deviations. The model parameters are assumed statistically independent *a priori*. To try to ensure that this assumption is reasonable, the parameters γ, δ and λ (or η) used in Section 6.3.6 are intended to measure distinct aspects of the dose-response functions.

To see how the covariates and non-standard treatments influence the dependence of yield on seed rate, we may consider Bayesian confidence intervals for the corresponding coefficients or treatment effects in the fitted models. Note, though, that this does not make allowance for the uncertainty about future values of covariates of the second type described in Section 6.3.4.

6.4.2 The prior distributions

The distributions used for the variety effects, treatment effects and regression coefficients are set out in Table 6.3, and have been chosen after discussion with Mike

Talbot of BioSS. For example, in the 'Variety effects' row of Table 6.3, the value of 10.0 is the prior expected value of the maximum yield for all varieties; the value of 5.3 is approximately ln(200), implying that maximum yield is expected to occur at a rate of about 200 seeds per m^2; also 1.4 is approximately ln(0.8/0.2), suggesting that if the seed rate which gives maximum expected yield is doubled we can expect a yield around 80% of the maximum. The corresponding standard deviations express our uncertainty about the prior expected values.

Effects for the non-standard treatment levels are expressed as differences from the standard levels, and we have taken the sceptical view that the expected results of varying the treatments are around zero. For each non-standard level we have assumed that the effect on the maximum expected yield γ has prior standard deviation 0.5 t/ha, and the effect on $\ln\delta$ has prior standard deviation 0.05 (so that the change in maximizing seed rate is of the order of 5%).

The values given in Table 6.3 for the regression coefficients of γ, $\ln\delta$ and η on latitude and sowing date assume that the dependence is linear but that the effects are again around zero. We suppose that differences of 5 degrees in latitude and 50 days in sowing date might produce effects of about 1 t/ha on maximum expected yield, a doubling or halving of the seed rate giving maximum expected yield and a 1 unit change in the logit of the ratio of the expected yields. For average emergence, we assume that the effects of a change of 10% might be of a similar order to those above. Similarly, we might not expect variation due to TTver of much more than 5 t/ha, $\ln 4$ and 2 respectively from their means over the observed 500-unit range for this variable.

Table 6.3. Values defining the prior distributions of Normal parameters

	Maximum expected yield (γ)		Log of rate for maximum (ln δ)		Logit of ratio of expected yields (η)	
	Expectation	SD	Expectation	SD	Expectation	SD
Variety effects	10.0	1.5	5.3	0.5	1.4	0.5
Non-standard treatments	0.0	0.5	0.0	0.05	0.0	0.05
Coefficient for latitude	0.0	0.2	0.0	0.14	0.0	0.2
Coefficient for sowing date	0.0	0.02	0.0	0.014	0.0	0.02
Coefficient for TTver	0.0	0.01	0.0	0.003	0.0	0.004
Coefficient for emergence	0.0	10	0.0	7	0.0	10

The prior distributions of the variance parameters in the model are given in Table 6.4. Note that the introduction of a covariate changes the interpretation of the variance components $\sigma^2_{\gamma e}$, $\sigma^2_{\ln\delta,e}$ and $\sigma^2_{\eta e}$: they now measure that part of the variation between environments in the γs, $\ln\delta$ s and ηs which is *not* accounted for by the covariate, so we might use lower estimates than before. We retain these values for the sake of simplicity.

Table 6.4. Values defining the prior distributions of variance parameters

Parameter	$\sigma^2_{\gamma e}$	$\sigma^2_{\gamma v}$	$\sigma^2_{\ln\delta,e}$	$\sigma^2_{\ln\delta,v}$	$\sigma^2_{\eta e}$	$\sigma^2_{\eta v}$	σ^2_{y}
Estimate	0.30	0.10	0.10	0.08	0.25	0.15	0.10
Degrees of freedom	10	10	5	5	2	2	50

One way to examine whether the prior distribution is reasonable is to look at the expected utility under the prior distribution: this is shown in Figure 6.2 for the two dose-response functions. The corresponding 'optimum' seed rates are 165 and 188.

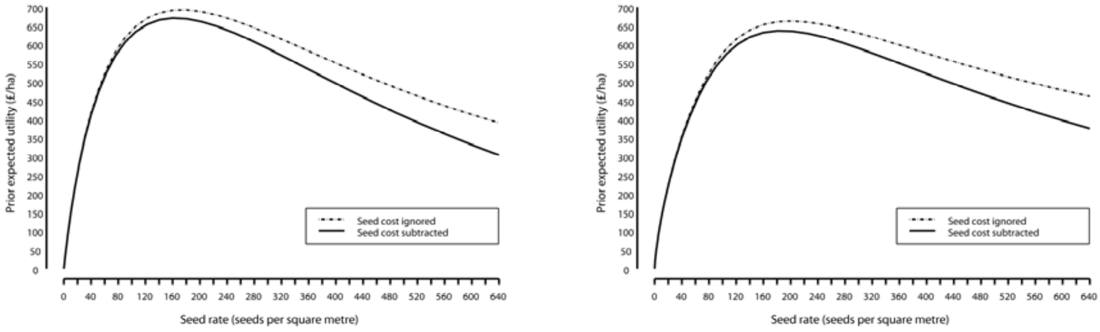

Figure 6.2. Prior expected crop values with and without seed cost: (a) exponential-plus-linear dose-response function, (b) inverse-quadratic function.

6.4.3 What do we mean by an optimum seed rate?

Point 3 of Section 6.3.2 explains that rather than estimate an optimum seed rate for each trial environment, or for each combination of trial environment and variety, we consider the seed rate which might be applied in an environment chosen at random from a population of environments in a future year. We suppose that the environments used in the trials are similarly sampled from this population. The latter assumption is unrealistic to the extent that the seven trial sites were not intended to be representative of levy payers' fields, and were in fact chosen to minimise variation in establishment. If covariates are included in the model then the optimum depends on their values, and we consider the target environment as sampled from a population with the same values. The utility function is meant to represent the value of the crop minus the variable costs associated with different seed rates and non-standard treatments, and the posterior expected utility is its mean over the posterior distribution. This distribution is intended to represent the variation to be expected from season to season. Thus the optimum rate is the rate expected to give the highest return in the coming season, given the treatments already chosen, the covariate values for the site and our knowledge of variation over environments.

6.5 Results of the Analyses

Here we examine the dependence of yield on varieties, covariates and treatments using the modelling procedure of Section 6.4. Because of the complexity of the models, we begin by presenting comparisons between varieties only for the standard combination of treatments, and ignoring covariates. When examining the effects of covariates and non-standard treatments, we have included data on all five varieties in the analysis, but we present results only for Claire, since it was the most widely grown in the trials.

6.5.1 Analyses with standard treatments and no covariates

Table 6.5 shows the optimum seed rates for the five varieties listed in Section 6.2. A seed cost of £200/t is included in addition to £300/t in order to illustrate the sensitivity of the optima to seed costs. The differences in the optimum rates shown for the five varieties are a consequence of including separate variety effects in our models. They prompt the question of whether these differences matter. We seek the answer in the expected utilities for different varieties rather than in statistical significance. If we consider applying to each variety rates close to the median value in each column of optima, say 200, 230, 280 and 320, then the reduction in expected utility for Claire, Haven and Soisson is no more than £2/ha. For Spark it is negligible under the exponential-plus-linear model, but up to £7/ha under the inverse-quadratic. For Cadenza, which is more subject to lodging, the reduction is between £9/ha and £18/ha.

Table 6.6 gives the optimum rates for one variety, Claire, for the 21 environments in which it was grown in 2001-03. The yields for non-standard treatments were omitted in calculating both tables. Note that optimum rates estimated from separate analyses of the data for these environments would be more variable: the assumption of random effects for environments tends to reduce variability in the estimates.

Table 6.5. Optimum seed rates (No/m^2) and posterior expected utilities *(£/ha)* for five varieties assuming two seed costs and exponential-plus-linear and inverse-quadratic dose-response functions

Variety	Exponential-plus-linear		Inverse-quadratic	
	Seed cost £300/t	Seed cost £200/t	Seed cost £300/t	Seed cost £200/t
Cadenza	146, *738*	150, *745*	204, *755*	215, *765*
Claire	204, *736*	228, *746*	284, *731*	324, *744*
Haven	197, *788*	241, *798*	323, *776*	364, 792
Soissons	205, *675*	230, *684*	256, *675*	276, *687*
Spark	231, *693*	247, *704*	390, *689*	462, *708*

Table 6.6. Optimum seed rates (No/m^2) for Claire in the 21 environments in which it was grown in 2001-03 assuming exponential-plus-linear and inverse-quadratic dose-response functions

Site	Year		
	2001	2002	2003
Aberdeen	153, 226	303, 409	250, 351
Edinburgh	198, 308	144, 227	143, 199
High Mowthorpe	185, 300	195, 295	140, 226
Sutton Bonington (RN$^-$)	96, 136	143, 225	248, 346
Sutton Bonington (RN$^+$)	120, 186	149, 236	387, 465
Rosemaund	115, 184	123, 197	157, 238
Bridgets	164, 254		
Mamhead		107, 155	163, 240

Figure 6.3 shows the posterior expected utilities against seed rate for the two dose-response functions and the same five varieties. The optimum seed rates are consistently lower (by about 30%) for the exponential-plus-linear function than for the inverse-quadratic. This can be attributed to the difference in shape of the

corresponding posterior expected utility functions: it is clear from Figure 6.3 that the exponential-plus-linear function has a sharper elbow than the inverse-quadratic when they are fitted to the same data. There is little evidence that one function fits better than the other: the estimates of the residual standard deviation parameter are 0.564 and 0.572 t/ha for the exponential-plus-linear and inverse-quadratic functions respectively.

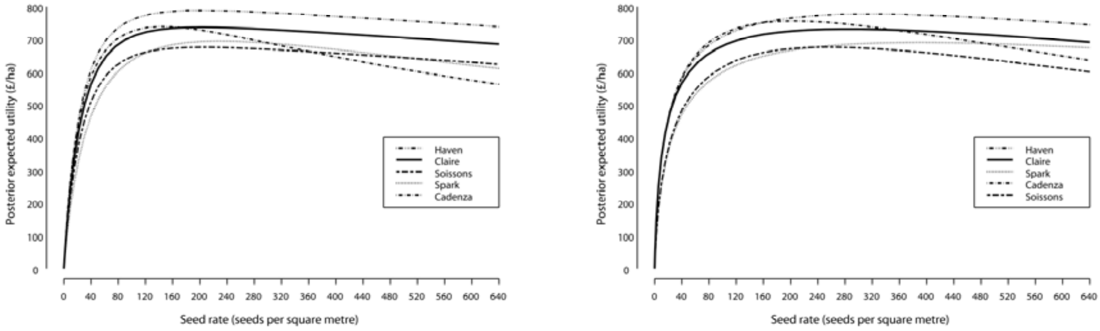

Figure 6.3. Posterior expected utilities for five varieties assuming exponential-plus-linear (left) and inverse-quadratic (right) dose-response functions: the ordering of the varieties in the legends is according to their posterior expected utilities at 640 seeds per m^2.

6.5.2 Analyses including covariates

We first consider a model with latitude and sowing date as covariates. Denoting their values in environment j by l_j and s_j respectively and their means by $\bar{l}$ and $\bar{s}$, the maximum-yield parameter γ_{ij} for the combination of variety i and environment j is expressed as

$$\gamma_{ij} = \gamma_{vi} + \gamma_{ej} + \beta_{\gamma l}(l_j - \bar{l}) + \beta_{\gamma s}(s_j - \bar{s}), \qquad (6.3)$$

where γ_{vi} and γ_{ej} are as defined in (6.2): similar equations are assumed for $\ln \delta_{ijk}$ and η_{ijk}. Under both dose-response models, the only coefficient with a Bayesian 95% confidence interval excluding zero is that for the dependence of the seed rate giving maximum expected yield on sowing date, which is significantly positive. Higher latitudes also tend to give higher rates for maximum expected yield, but this effect is not quite 'significant'. The estimated sizes of these effects are such that one extra day and one degree of latitude give respective increases in the maximizing rate of about 1.4% and 10% under the exponential-plus-linear model and 1.7% and 12% under the inverse-quadratic.

We illustrate predictions from the model by calculating the optimum seed rates and corresponding posterior expected utilities for Claire at two latitudes, those of Rosemaund (52.13) and Edinburgh (55.87), on four sowing dates, 15 and 30 September, 15 and 30 October: these are given in Table 6.7. Note that these predictions involve some extrapolation relative to the sowing dates shown in Table 6.1. As expected, the optima depend substantially on sowing date. The reduction in expected utility from later sowing is quite small, especially at the lower latitude.

Table 6.7. Optimum seed rates (No/m^2) and posterior expected utilities *(£/ha)* for Claire at two latitudes on four sowing dates assuming exponential-plus-linear and inverse-quadratic dose-response functions with latitude and sowing date as covariates

Latitude (degrees)	Sowing date (from 1 Jan)	Exponential - plus-linear	Inverse-quadratic
52.13 (Rosemaund)	258 (15 Sep)	138, *749*	186, *745*
	273 (30 Sep)	162, *749*	230, *746*
	288 (15 Oct)	190, *747*	280, *745*
	303 (30 Oct)	226, *744*	339, *741*
55.87 (Edinburgh)	258 (15 Sep)	177, *723*	251, *717*
	273 (30 Sep)	208, *721*	307, *715*
	288 (15 Oct)	243, *718*	368, *710*
	303 (30 Oct)	288, *713*	443, *702*

We next use TTver on its own as a covariate in place of latitude and sowing date, making allowance for the uncertainty in its value for the target site in the coming season by using means and standard deviations calculated for Rosemaund on the same sowing dates as above in the years 1983-99 (see Section 6.3.4). These are given in Table 6.8 along with the optimum seed rates and corresponding posterior expected utilities for Claire. Comparing the first four rows of Table 6.7 with Table 6.8 suggests that the use of TTver rather than latitude and sowing date leads to reduced posterior expected utilities (and higher optimum seed rates), so that latitude and sowing date together appear more useful for choosing a seed rate. This comparison may be unfair to TTver, though, because of the difficulties of comparing covariates of the two types identified in Section 6.3.4.

Table 6.8. Means and standard deviations of TTver for Rosemaund on four dates with optimum seed rates (No/m^2) and posterior expected utilities *(£/ha)* for Claire at these dates assuming exponential-plus-linear and inverse-quadratic dose-response functions with TTver as covariate

Sowing date (from 1 Jan)	Mean TTver	SD of TTver	Exponential - plus-linear	Inverse-quadratic
258 (15 Sep)	645	72	162, *733*	224, *745*
273 (30 Sep)	501	70	195, *737*	284, *731*
288 (15 Oct)	408	57	221, *738*	330, *729*
303 (30 Oct)	332	47	245, *739*	368, *727*

We have also used as a covariate the mean emergence for each environment over varieties and over the seed rates 160 and 320: spring emergence is used for Aberdeen and Edinburgh and autumn emergence elsewhere. The coefficients for the dependence on emergence of the maximum expected yield and of the logit of the expected yield at 2δ relative to that at δ are significantly positive for both dose-response functions: the dependence on the maximizing seed rate is significantly negative for the exponential-plus-linear function. Table 6.9 gives the optimum seed rates and corresponding posterior expected utilities for Claire at four values of mean emergence: allowance for uncertainty in future values is made by using the variance component for years from fitting a linear model for emergence with random effects for years and sites.

In contrast to TTver, we have no independent estimate of variability for emergence, and any dependence of the standard deviation on the mean is ignored. Also, using recorded emergence as a covariate provides only weak evidence that growers' estimates of emergence could be used in the same way.

Note that if the emergences were equal to the the mean values listed in Table 6.9 then the plant populations under each dose-response function would be very similar, within ranges 132 to 138 for the exponential-plus-linear and 188 to 199 for the inverse-quadratic.

Table 6.9. Optimum seed rates (No/m2) and posterior expected utilities *(£/ha)* for Claire at four values for the mean emergence over rates 160 and 320 assuming exponential-plus-linear and inverse-quadratic dose-response functions with mean emergence as covariate

Mean emergence	Exponential - plus-linear	Inverse-quadratic
0.6	230, *709*	314, *704*
0.7	197, *735*	281, *730*
0.8	169, *759*	249, *755*
0.9	147, *782*	216, *780*

It would be possible to include emergence or TTver in addition to latitude and sowing date as covariates: we have not done so because of the difficulty in allowing for uncertainty in future emergence and TTver.

6.5.3 Analyses including non-standard treatments

We then included in our analyses the data relating to the non-standard treatments defined in Table 6.2, but ignoring covariates. The only set of treatments whose effect is 'significant' in the sense that the Bayesian 95% confidence intervals for the non-standard effects exclude zero is rotational position. The intervals for the reduction in maximum expected yield (t/ha) from second/third wheat (without the Latitude seed treatment) rather than first wheat are (0.70,1.47) and (0.71,1.50) for the exponential-plus-linear and inverse-quadratic dose-response functions. With second/third wheat plus Latitude the corresponding intervals are similar, (0.79,1.56) and (0.80,1.59).

Figure 6.4 shows, for the exponential-plus-linear dose-response function, the posterior expected utilities calculated for Claire under the standard combination of treatments and under each of the non-standard ones, assuming that only one treatment is varied at a time. [The corresponding plot for the inverse-quadratic function shows the same general difference in shape as in Figure 6.3, but leads to similar conclusions.] The reductions in expected utility with seed rate beyond the optima are steeper for 'Sibutol Secur slug treatment' and 'Second/third wheat + Latitude' than for other treatments because their cost increases in proportion to seed rate. The use of Latitude appears not to correct the large loss in expected utility from second/third rather than first wheat, and both variations from the standard slug treatment appear to reduce expected utility slightly.

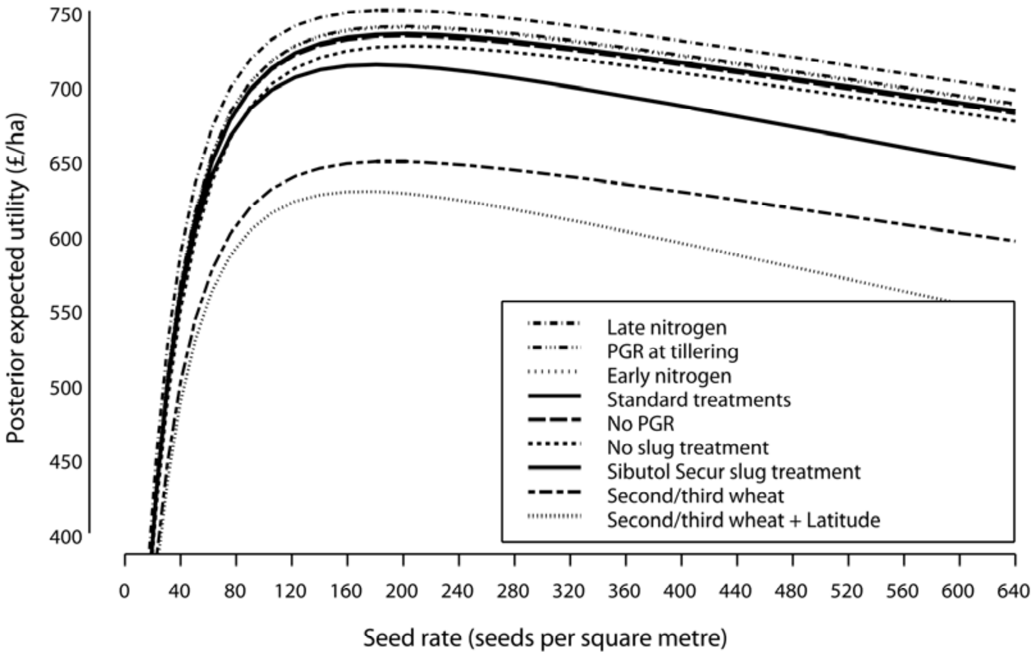

Figure 6.4. Posterior expected utilities under various treatments assuming exponential-plus-linear dose-response functions: the ordering of the treatments in the legend is according to their posterior expected utilities at 640 seeds per m^2.

Table 6.10 shows the optimum seed rates and corresponding expected utilities for Claire under those treatments which are fixed at the time of sowing. Of the remaining treatments, late nitrogen appears to raise expected utility by about £15/ha, and PGR at tillering rather than at stem extension seems to increase it by about £5/ha. Comparison of the results for the standard treatment in Table 6.10 with those for Claire in Table 6.5 shows that the inclusion of the data for non-standard treatment levels has little effect on the optimum rates. The effects of the variations in treatment and the maximum expected utilities are similar for the two dose-response functions, but the optimum rates are again consistently lower for the exponential-plus-linear function. The estimates of the residual standard deviation parameter are 0.560 and 0.552 t/ha for the exponential-plus-linear and inverse-quadratic functions respectively: thus the fit of the latter function appears slightly better when the data for the non-standard levels are included.

Table 6.10. Optimum seed rates (No/m^2) and posterior expected utilities *(£/ha)* for Claire with standard and non-standard treatments assuming exponential-plus-linear and inverse-quadratic dose-response functions

Treatment	Exponential-plus-linear	Inverse-quadratic
Standard	201, *735*	271, *732*
Rotational position: second/third	192, *649*	258, *646*
Rotational position: second/third + Latitude	173, *629*	224, *622*
Slug treatment: none	208, *726*	280, *723*
Slug treatment: + Sibutol Secur	182, *714*	240, *709*

It is also possible to fit a model including latitude and sowing date in addition to the treatments. Combinations of latitude, sowing date and treatment are rather cumbersome to illustrate on paper, but could in principle be included in an interactive system.

6.5.4 Dependence of yield on plant population

An argument for modelling the dependence of grain yield on plant population rather than on seed rate is that it should lead to more precise predictions of yield. We therefore fitted the inverse-quadratic model (but not the exponential-plus-linear) to seed rate and to autumn plant populations for all the environments for which these populations were available and the standard treatments were applied. The prior distribution defined in Table 6.3 was altered so that the maximum yield was expected to occur at an autumn population of about 150 rather than at a seed rate of 200 per m^2. With plant population and seed rate as the explanatory variables, the estimates of the residual standard deviation parameter are 0.518 and 0.582 t/ha respectively. Thus using plant population gives a slightly better fit to the data. This comparison takes no account, though, of the additional uncertainty in finding the seed rate corresponding to a recommended plant population.

6.6 Discussion

Given the task of combining the information from seed-rate experiments with a large number of combinations of environment and variety, we have developed a method that allows for differences between environments, between varieties and between treatment levels, and allows some expert knowledge of the crop to be incorporated. The results of our analyses appear reasonable in the sense that they depend on covariates, treatments and changes in seed cost in sensible ways. They show more sensitivity to a change in the assumed dose-response function than might be expected, with the exponential-plus-linear dose-response function giving consistently lower optima than the inverse-quadratic.

Historically advice has often been given on the basis of target plant populations rather than optimum seed rates. While plant populations may be essential to understanding the process of crop growth, we have chosen to emphasise seed rates because the agronomist's task is different from that of the grower: the latter's direct concern is how much seed to sow (Gooding et al., 2002). He may, though, wish to interpret guidance on seed rates in the light of his knowledge of previous emergence on his fields and of soil conditions for the current season.

Other difficulties arise with the concept of plant populations here: for example, no particular seed cost can be associated with a given population, and the population varies over the season, particularly if winter kill is a possibility. For this project, we have found that the data available on emergence rates show upward bias and are highly variable within and between environments. Consideration needs to be given to improving the measurement of plant populations, especially at low seed rates.

The information from a set of seed-rate trials is usually combined by fitting a separate dose-response model for each environment, combining them in an informal way and making some upward adjustment as insurance against adverse growing conditions. Our Bayesian formulation attempts to model the variation between environments in the response of yield to changes in seed rate. The posterior expected utility for any seed rate then represents an average over the possible future environments, and therefore automatically includes some insurance. The success of the method in achieving this depends on how representative conditions in the trials are of those which might be experienced in future, and also on the appropriateness of the dose-response model and the prior distribution.

It may seem disappointing that the choice between the exponential-plus-linear and inverse-quadratic dose-response functions has a large effect on the calculation of optimum seed rates, and that neither of these functions appears to fit better than the other. We can use the posterior expected utility to examine the consequences of basing optimum rates on one model when the other is in fact appropriate. Under the standard set of treatments, the optimum rate from the exponential-plus-linear model is (from Table 6.10) 201 seeds per m^2: the expected utility of this choice under the inverse-quadratic is £727/ha, only slightly lower than the maximum under this model of £732/ha. Indeed the posterior expected utility under the inverse-quadratic is within £5/ha of the maximum for rates in the interval (199, 363): the corresponding interval for the exponential-plus-linear is (147, 280). The overlap between these intervals shows that the expected utility curves are fairly flat near their maxima as a consequence of being derived from averages over many dose-response functions with different maxima: hence the difference between the two optima in terms of expected margin is less alarming than it first appears.

It seems to be essential that any guidance on seed rate should make reference to latitude and sowing date. The results presented in Table 6.7 show that the optima from models including these two covariates do depend substantially on their values. Communicating the results of data analyses would become difficult if other covariates, such as applied nitrogen or soil type, were included: the inclusion of variety differences or of other responses, such as quality characteristics, would add to the burden. It would be better to make advice available via an interactive system similar to HGCA's RL *Plus* (http://www.hgca.com/varieties/rl-plus/index.html).

Although plotting mean yields over varieties against TTver indicates that it has some value for explaining variation in yield, comparison of Tables 6.6 and 6.7 suggests that it is less useful than latitude and sowing date for *predicting* yield. Some doubt remains about how to allow for the uncertainty in its value for the coming season: using an estimated normal distribution is only one possible method. Extra uncertainty would be introduced if its value were interpolated from weather stations.

Mean emergence over seed rates of 160 and 320 at each environment was also used as a covariate, and appears to have some value for prediction even when corrected for uncertainty in its future value. This suggests that it may be worth investigating the use of an index measuring the grower's assessment of likely emergence in the coming season, and include it as a further covariate in the model.

By contrast with the results on latitude and sowing date, Table 6.10 suggests that little adjustment to seed rates needs to be made for the non-standard treatment levels, except perhaps where the cost of the treatment increases with seed rate.

Similarly, Table 6.5 provides little evidence that rates should depend on the variety sown, except perhaps for varieties such as Cadenza which are more subject to lodging.

Table 6.5 also gives some idea of the effect of changes in seed cost: other costs which vary with seed rate, such as that of drilling, could be included in the estimation of optimum rates.

Our choice of utility function, the value of the crop (per ha) minus the costs of the seed and of non-standard treatments, may be criticized for failing to reflect the grower's aversion to risk: he may be more concerned with avoiding bankruptcy than with maximizing profit. However, using alternative functions appears to require modelling of all the other costs of production, and of the grower's utility of money.

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Appendix 1 – Site details

Site Details for Winter Wheat Seed Rate x Nitrogen Timing – Harvest 2001

Site:	ADAS Bridgets		
Field Name:	Arizona		
Soil Description:	Silty clay loam		
		mg/l	ADAS Index
Soil Analysis	P	30	3
	K	177	2
	Mg	26	1
	Organic matter %	4.2	
	pH	8.0	
Date of Drilling:	05/10/2000		
Cultivar:	Claire	Ploughed	
Previous Cropping:	2000	1999	1998
	Spring barley	Forage maize	Linseed
Previous Crop Residue:	Baled and removed		
Previous Cultivations:	Ploughed		
	<u>Application date</u>	Product	Rate
Treatment details:	15/02/01	Amm Nit - N1	40 N
N	08/03/01	Amm Nit – N2	40 N
	29/03/01	Amm Nit – N3	40 N
	11/04/01	Amm Nit – all plots	85 N
	14/05/01	Amm Nit – all plots	45 N
Herbicides:	16/02/01	IPU	1.2 l/ha
	16/02/01	Panther	1 l/ha
	11/04/01	Duplosan	0.6 l/ha
	25/05/01	Starane	0.4 l/ha
Fungicides:	10/05/01	Amistar	0.5 l/ha
	10/05/01	Opus	0.6 l/ha
	10/05/01	Unix	0.6 l/ha
	09/06/01	Opus	0.4 l/ha
	09/06/01	Twist	1.0 l/ha
Insecticides:	16/02/01	Cypermethrin	0.2 l/ha
PGRS:	11/04/01	5C Chlormequat	1.5 l/ha
Molluscicides:	10/10/00	Metarex green	
	01/11/00	Metarex green	
Fertiliser inputs:	<u>Application date</u>	Product	Rate kg/ha
N	See treatment details		
P	15/01/01	P_2O_5	65
K	15/01/01	K_2O	98
Harvest date	28/09/01		

Site Details for Winter Wheat Seed Rate x Slug Control – Harvest 2001

Site:	Rosemaund		
Field Name:	Drive Meadow	OS564474	
Soil description:	Silty Clay Loam		
Series:	Bromyard		
		mg/l	ADAS Index
Soil Analysis	P		3
	K		2
	Mg		2
	Organic matter %		
	pH	7.4	
Drainage	Good		
Cultivations:	30/07/00	Subsoiled	
	07/08/00	Light Disced	
	03/10/00	Plough	
	03/10/00	Power Harrowed	
Date of drilling:	04/10/00	Drilled	
	06/10/00	Cambridge Rolled	
Cultivar:	Claire		
Previous cropping:	2000	1999	1998
	W. OSR	Winter Wheat	Maize
	<u>Application date</u>	Product	Rate
Treatment details:	05/10/00 - Trt 2 & 3	Decoy Wettex	7.5 kg/ha
	25/10/00 - Trt 3	Decoy Wettex	7.5 kg/ha
	30/11/00 - Trt 3	Decoy Wettex	7.5 kg/ha
	08/01/01 - Trt 2 & 3	Decoy Wettex	7.5 kg/ha
Herbicides:	17/02/01	Isoguard	2015 l/ha
	17/02/01	Duplosan	0.7 l/ha
	17/02/01	Panther	0.8 l/ha
	01/05/01	Starane 2	0.7 l/ha
Fungicides:	11/05/01	Amistar	0.5 l/ha
	11/05/01	Opus	0.5 l/ha
	11/06/01	Amistar	0.5 l/ha
	11/06/01	Opus	0.5 l/ha
Insecticides:	10/11/00	Cyperkil	0.25 l/ha
	17/02/01	Cyperkill	0.25 l/ha
	02/07/01	Cyperkill	1.67 l/ha
Molluscicides:	See treatment details		
Dessicant:	15/08/01	Glyphosate	3.0 l/ha
Fertiliser inputs:	<u>Application date</u>	Product	Rate kg/ha
N	05/03/01	Nitram	40 N
	05/05/01	Nitram	82 N
	06/06/01	Nitram	43 N
P	None		
K	None		
Harvest:	29/08/01		

Site Details for Winter Wheat Seed Rate x PGR – Harvest 2001

Site:	ADAS High Mowthorpe		
Field Name:	Old Type	SE 893 696	
Soil description:	Shallow silt clay loam overlying chalk.		
Series:	Panholes		
		mg/l	ADAS Index
Soil Analysis	P	18	2
	K	124	2
	Mg	34	1
	Organic matter %	3.8	
	pH	8.0	
Drainage	Good		
Cultivations:	18/10/00	Ploughed / pressed	
	14/11/00	Rotavated	
Date of drilling:	14/11/00	Not rolled	
Cultivar:	Claire		
Previous cropping:	2000	1999	1998
	Potatoes	W Wheat	WOSR
	<u>Application date</u>	Product	Rate
Treatment details:	12/04/01	New 5c Cycocel	2.5 l/ha
	10/05/01	New 5c Cycocel	2.5 l/ha
Herbicides:	15/02/01	Encore	4.0 l/ha
	30/04/01	Eagle	30 g/ha
Fungicides:	20/05/01	Opus	0.6 l/ha
	20/05/01	Twist	0.8 l/ha
	06/06/01	Landmark	0.5 l/ha
	04/07/01	Folicur	0.3 l/ha
Insecticides:	27/02/01	Dimethoate	1.7 l/ha
	27/02/01	Dursban	1.5 l/ha
Dessicant:	None		
Molluscicides:	27/11/00	Draza	5.5 kg/ha
Fertiliser inputs:	<u>Application date</u>	Product	Rate kg/ha
N	13/03/01	Nitram	43.8 N
	04/05/01	Nitram	188.7 N
P	None		
K	None		
Harvest:	28/08/01		

Site Details for Winter Wheat Seed Rate x Nitrogen Timing – Harvest 2001

Site:	Sutton Bonington			
Field Name:	Field No. S26	450326		
Soil description:	Sandy Loam			
		mg/l	ADAS Index	
Soil Analysis	P		5	
	K		4-	
	Mg		4	
	Organic matter %			
	pH	7.7		
Drainage	Good			
Cultivations:	14/09/00	Power harrow		
	06/10/00	Power Harrow		
	16/10/00	Spring tine		
	17/10/00	Rolled after drilling		
Date of drilling:	17/10/00			
Previous cropping:	2000	1999		1998
	Winter Oats	W Wheat		Sugar Beet
	<u>Application date</u>	Product		Rate
Treatment details:	29/11/00	Residue N		80 kg/ha
	20/02/01	N applied to N1		80 kg/ha
	06/03/01	N applied to N2		80 kg/ha
	02/04/01	N applied to N3		80 kg/ha
	27/04/01	N applied to Res N1		55 kg/ha
	27/04/01	N applied to Red N0		145 kg/ha
Herbicides:	26/01/01	Cougar		0.8 l/ha
	26/01/01	IPU500		3.6 l/ha
	13/05/01	Ally		25 g/ha
	13/05/01	Starane		0.75 l/ha
	25/05/01	Cheetah S		1 l/ha
	25/05/01	Oil		1 l/ha
Fungicides:	21/04/01	Unix		0.5
	21/04/01	Folicur		300 ml/ha
	13/05/01	Unix		0.8 kg/ha
	13/05/01	Landmark		0.75 l/ha
	13/05/01	Tern		0.5 l/ha
	04/06/01	Landmark		0.75 l/ha
	04/06/01	Tern		0.5 l/ha
	22/06/01	Folicur		0.4 l/ha
Insecticides:	26/01/01	Cypermethrin		0.25 l/ha
	22/06/01	Clinch		1.5 l/ha
Fertiliser inputs:	<u>Application date</u>	Product rate		Rate kg/ha
N	See treatment details			
P	None			
K	None			
Mn	26/01/01	Headland	Jett	2 l/ha
	13/05/01	Manganese		2 l/ha
Harvest:	Block 1 & 2	15/08/01		
	Block 3 & 4	17/08/01		

Site Details for Winter Wheat Seed Rate x Slug Control – Harvest 2001

Site:	Edinburgh			
Field Name:	Boghall Farm, Bush Estate	NT 246651		
Soil description:	Clay Loam (Macmerry series)			
		mg/l	ADAS Index	
Soil Analysis	P	20.6		
	K	299		
	Mg	277		
	Organic matter %			
	pH	6.5		
Drainage	Good			
Cultivations:	16/10/00	Plough		
	16/10/00	Power Harrow		
Date of drilling:	16/10/00			
Previous cropping:	2000	1999	1998	1997
	WOSR	W Barley	Spring Barley	W Wheat
	<u>Application date</u>	Product		Rate
Treatment details:	16/10/01	Draza – Trts 2 & 3		5.5 kg/ha
Herbicides:	20/04/01	Oxytril		1 l/ha
	20/04/01	Duplosan		1 l/ha
Fungicides:	07/05/01	Sportak Delta		1.25 l/ha
	25/06/01	Amistar		0.5 l/ha
	25/06/01	Folicur		0.4 l/ha
Fertiliser inputs:	<u>Application date</u>	Product		Rate kg/ha
N	21/03/01	Nitram		20.7 N
	27/04/01			41.4 N
P	16/01/01	P_2O_5		60
K	16/01/01	K_2O		60
S	21/03/01	Sulphur		15.2 kg/ha
Mn	01/05/01	Mantrac 500		1 l/ha
Harvest:	17/09/01			

Site Details for Winter Wheat Seed Rate x PGR – Harvest 2001

Site:	Oldmeldrum, Aberdeenshire		
Field Name:	Muirton of Barra	NJ 782266	
Soil description:	Sandy clay loam		
		mg/l	ADAS Index
Soil Analysis	P	5.7	
	K	158	
	Mg	80	
	Organic matter %	10.8%	
	pH	6	
Cultivations:		Plough	
	06/10/00	Power Harrow	
Date of drilling:	06/10/00		
Cultivar:	Claire		
Previous cropping:	2000	1999	1998
	WOSR	Winter Barley	Winter Wheat
	<u>Application date</u>	Product	Rate
Treatment details:	27/04/01	5C Cycocel Trt 2	2.5 l/ha
PGRS:	21/05/01	5C Cycocel Trt 3	2.5 l/ha
	06/06/01	Terpal all plots	1.5 l/ha
Herbicides:	27/05/01	Swipe P	1.5 l/ha
	27/05/01	Ally	15 g/ha
Molluscicides:	07/10/00	Metaldehyde	8.0 kg/ha
Fungicides:	21/05/01	Unix	0.6 kg/ha
	21/05/01	Opus	0.4 l/ha
	21/05/01	Fortress	0.1 l/ha
	06/06/01	Twist	1.5 l/ha
	06/06/01	Opus	0.5 l/ha
Fertiliser inputs:	<u>Application date</u>	Product	Rate kg/ha
N	07/10/00	Ammonium nitrate	30 N
	10/04/01		50 N
	08/05/01		150 N
P	07/10/00	P_2O_5	90
K	07/10/00	K_2O	90
Harvest:	03/10/01		

Site Details for Winter Wheat Seed Rate x PGR – Harvest 2002

Site:	Mamhead		
Field Name:	Powderham Estates	SX954817	
Soil description:	Sandy Loam		
Series:	Bromyard		
		mg/l	ADAS Index
Soil Analysis	P	27	3
	K	87	1
	Mg	44	1
	Organic matter %		
	pH	6.6	
Cultivations:	04/10/01	Ploughed	
	05/10/01	Power-harrowed, drilled	
Date of drilling:	05/10/01		
Cultivar:	Claire		
	<u>Application date</u>	Product	Rate
Treatment details:	13/02/02	Chlormequat -Trt 2	2.25 l/ha
	08/04/02	Chlormequat -Trt 3	2.25 l/ha
Herbicides:	09/09/01	Gallup	2.0 l/ha
	10/10/01	Triflralin	2.0 l/ha
	14/01/01	Mecoprop	1.75 l/ha
	13/02/02	Ally	30 g/ha
Fungicides:	19/04/02	Opus	0.25 l/ha
	07/05/02	Opus	0.25 l/ha
	10/06/02	Opus	0.75 l/ha
	10/06/02	Amistar	0.75 l/ha
Insecticides:	14/11/01	Cypermethrin	0.25 l/ha
	31/10/01	Hallmark	50 ml/ha
Fertiliser inputs:	<u>Application date</u>	Product	Rate kg/ha
N	28/02/02	Ammonium nitrate	40 N
	27/03/02		50 N
	15/4/02		110 N
P	None		
K	None		
Harvest:	17/08/02		

Site Details for Winter Wheat Seed Rate x PGR – Harvest 2002

Site:	Rosemaund		
Field Name:	Moorfield	OS566477	
Soil description:	Silty Clay Loam		
Series:	Bromyard		
		mg/l	ADAS Index
Soil Analysis	P		3
	K		3
	Mg		32
	Organic matter %	2.47	
	pH	7.2	
Drainage	Good		
Cultivations:	16/08/01	Subsoiled	
	25/09/01	Ploughed	
	25/09/01	Cambridge Roll	
	25/09/01	Power Harrow	
Date of drilling:	25/09/01		
Cultivar:	Claire		
Previous cropping:	2001	2000	1999
	Winter OSR	W. Wheat	Potatoes
	Application date	Product	Rate
Treatment details:	04/03/02	Chlormequat	2.25 l/ha
PGRS:	20/03/02	Chlormequat	2.25 l/ha
Herbicides:	02/11/01	Arelon	l/ha
	02/11/01	Stomp 330	l/ha
	18/02/02	Topik	0.125 l/ha
	05/04/02	Grasp	1.41 l/ha
Fungicides:	15/04/02	Landmark	0.5 l/ha
	31/05/02	Opera	1.2 l/ha
Insecticides:	02/11/01	Cyperkill	0.25 l/ha
Dessicant:	13/08/02	Roundup Biactive	2.5 l/ha
Fertiliser inputs:	Application date	Product	Rate kg/ha
N	05/04/02	Nitram	92 N
	06/05/02		79 N
P	None		
K	None		
Harvest:	28/08/02		

Site Details for Winter Wheat Seed Rate x Nitrogen Timing – Harvest 2002

Site:	Sutton Bonington		
Field Name:	Bunny Field No 458329 B01		
Soil description:	Keuper Marl		
		mg/l	ADAS Index
Soil Analysis	P		2
	K		2+
	Mg		6
	Organic matter %		
	pH	7.5	
Drainage	Fairly good		
Cultivations:	01/08/101	Heavy disc cultivated (Simba mono)	
	09/09/01	Ploughed	
	11/09/01	Power Harrowed	
	04/10/01	Rolled	
	04/10/01	Discard drilled with Nordstein	
Date of drilling:	28/09/01, 04/10/01		
Previous cropping:	2001	2000	1999
	WOSR	Winter Wheat	Winter Wheat
	Application date	Product	Rate
Treatment details:	04/03/02	Amm nitrate - N1	40 kg/ha
	18/03/02	Amm nitrate – N2	40 kg/ha
	09/04/02	Amm nitrate – N3	40 kg/ha
	15/04/02	Ammo nitrate	110 kg/ha
	01/05/02	Amm nitrate –RN0	70 kg/ha
	01/05/02	Amm nitrate –RN1	30 kg/ha
Herbicides:	03/12/01	Lexus	20 g/ha
	03/12/01	Stomp	2.5 l/ha
	24/04/02	Starane	0.7 l/ha
	16/05/02	Ally	16.7 g/ha
PGR	28/03/02	Chlormequat	2.5 l/ha
	16/05/02	Terpal	1.5 l/ha
Fungicides:	28/03/02	Quinoxyfen	0.2 l/ha
	24/04/02	Landmark	0.7 l/ha
	24/04/02	Unix	0.4 kg/ha
	27/05/02	Landmark	0.7 l/ha
Insecticides:	03/12/01	Cypermethrin	0.25 l/ha
Fertiliser inputs:	Application date	Product	Rate kg/ha
N	See treatment details		
P	None		
K	None		
Harvest:	14/08/02		

Site Details for Winter Wheat Seed Rate x Rotation – Harvest 2002

Site:	High Mowthorpe		
Field Name:	Smithfield	SE880692	
Soil description:	Shallow silt clay loam overlying chalk		
Series:	Wold		
		mg/l	ADAS Index
Soil Analysis	P	32	3
	K	164	2
	Mg	41	1
	Organic matter %	4.4	
	pH	7.9	
Drainage	Good		
Cultivations:	14/06/01	Ploughed/pressed	
	02/10/01	Rotavated	
Date of drilling:	02/10/01	Rolled	
Cultivar:	Claire		
Previous cropping:	2001	2000	1999
	W Wheat/Oats	W. Wheat	Linseed
	Application date	Product	Rate
Treatment details:	None Rotation		
Herbicides:	21/11/01	IPU	1.0 l/ha
	21/11/01	Stomp	2.5 l/ha
Fungicides:	02/05/02	Landmark	0.6 l/ha
	02/05/02	Unix	0.4 l/ha
	01/06/02	Twist	0.8 l/ha
	01/06/02	Opus	0.5 l/ha
	21/06/02	Folicur	0.25 l/ha
Insecticides:	21/11/01	Cypermethrin	0.3 l/ha
PGR:	15/04/02	Hive	2.3 l/ha
Fertiliser inputs:	Application date	Product	Rate kg/ha
N	25/03/02	Nitram	37.6 N
	17/04/02		202.5 N
P	None		
K	None		
Harvest:	29/08/02		

Site Details for Winter Wheat Seed Rate x PGR – Harvest 2002

Site:	Edinburgh		
Field Name:	Boghall Farm	NT254650	
Soil description:	Loan		
Series:	Duncrahill		
		mg/l	ADAS Index
Soil Analysis	P	8.9	
	K	209	
	Mg	167	
	Organic matter %		
	pH	5.9	
Cultivations:	09/10/01	Plough	
		Power Harrow	
Date of drilling:	09/10/01		
Previous cropping:	2001	2000	1999
	Set-Aside	Spring Barley	Winter Wheat
	Application date	Product	Rate
Treatment details:	18/02/02	Nitram – N1	60 kg/ha
	12/03/02	Nitram – N2	60 kg/ha
	02/04/02	Nitram – N3	60 kg/ha
Herbicides:	16/11/01	Trump	3.5 l/ha
	02/05/02	Ally	15 g/ha
	02/05/02	Duplosan	1.0 l/ha
PGR:	08/05/02	Moddus	0.4 l/ha
Fungicides:	08/05/02	Radius	1.5 kg/ha
	20/06/02	Twist	1.35 l/ha
	20/06/02	Folicur	0.5 l/ha
Fertiliser inputs:	Application date	Product	Rate kg/ha
N	See treatment details		
	02/05/02	Nitram	130 kg/ha
P	11/10/01	P_2O_5	70 kg/ha
K	11/10/01	K_2O	70 kg/ha
Mn	09/04/02	Mantrac 500	2.0 l/ha
	08/05/02		2.0 l/ha
Harvest:	17/09/02	Sulphur	

Site Details for Winter Wheat Seed Rate x PGR – Harvest 2002

Site:	Aberdeenshire		
Field Name:	Woodlands Field	NJ778277	
Soil description:	Sandy Loam		
		mg/l	ADAS Index
Soil Analysis	P	4.9	
	K	64	
	Mg	139	
	Organic matter %	10.1%	
	pH	6.3	
Cultivations:		Plough	
	03/10/01	Power Harrow	
Date of drilling:	03/10/01		
Cultivar:	Claire		
Previous cropping:	5 Years Grass		
	Application date	Product	Rate
Treatment details:	08/03/02	Nitram – N1	40 kg/ha
	29/03/02	Nitram – N2	40 kg/ha
	18/04/02	Nitram – N3	40 kg/ha
	18/04/02	Nitram – all plots	60 kg/ha
Herbicides:	16/11/01	Stomp	3.5 l/ha
	16/11/01	IPU	1.5 l/ha
Fungicides:	07/05/01	Unix	1.0 kg/ha
	07/05/01	Opus	0.75 l/ha
	07/05/01	Bravo	1.0 l/ha
	07/06/01	Landmark	l/ha
	14/06/01	Amistar	0.5 l/ha
	14/06/01	Folicur	0.75 l/ha
Insecticides:	Pre ploughing	Dursban	1.5 l/ha
PGR:	30/04/02	5C Cycocel	2.5 l/ha
Molluscicides:	04/10/01	Metaldehyde	5.0 kg/ha
Fertiliser inputs:	Application date	Product	Rate kg/ha
N	28/11/01	Compound	19 N
	See treatment details		
P	28/11/01	Compound	90
K	28/11/01	Compound	90
Harvest:	19/09/02		

Site Details for Winter Wheat Seed Rate x Rotation – Harvest 2003

Site:	Mamhead		
Field Name:	Powderham Estates	SX954817	
Soil description:	Sandy Loam		
		mg/l	ADAS Index
Soil Analysis	P	32	3
	K	87	1
	Mg	33	1
	Organic matter %		
	pH	6.1	
Drainage	Good		
Cultivations:	02/10/02	Ploughed and power harrowed	
Date of drilling:	03/10/02		
Cultivar:	Claire		
Previous cropping:	2002	2001	2000
	W. Wheat/W. Oats	W. Wheat	Potatoes
	Application date	Product	Rate
Treatment details:	None rotation		
Herbicides:	21/09/02	Glyphosate	1.5 l/ha
	04/11/02	Tigress Ultra	1.5 l/ha
	30/01/03	IPU	2.5 l/ha
	30/01/03	Cougar	0.5 l/ha
	30/01/03	Oxytril	1.0 l/ha
Fungicides:	16/04/03	Opus	0.5 l/ha
	16/04/03	Amistar	0.6 l/ha
	23/05/03	Opus	0.25 l/ha
	23/05/03	Bravo	1.0 l/ha
Insecticides:	30/01/03	Cypermethrin	0.25 l/ha
Fertiliser inputs:	Application date	Product	Rate kg/ha
N	25/03/03	Nitram	80 N
	15/04/03	Nitram	110 N
P	None		
K	None		
Harvest:	07/08/03		

Site Details for Winter Wheat Seed Rate x Rotation – Harvest 2003

Site:	Rosemaund		
Field Name:	Drive Meadow	OS564474	
Soil description:	Silty Clay Loam		
Series:	Bromyard		
		mg/l	ADAS Index
Soil Analysis	P		2
	K	164	2+
	Mg	41	2
	Organic matter %		
	pH	7.2	
Drainage	Good		
Cultivations:	20/09/02	Subsoiled	
	23/09/02	Ploughed	
	23/09/02	Power Harrowed	
Date of drilling:	24/09/02	Drilled	
	26/06/02	Cambridge Rolled	
Cultivar:	Claire		
Previous cropping:	2002	2001	2000
	Winter Oats	Winter Wheat	Winter OSR
	Application date	Product	Rate
Treatment details:	None rotation		
Herbicides:	16/09/02	Azural	1.5 l/ha
	16/09/02	Frigate	l/ha
	26/02/03	Arelon	l/ha
	26/02/03	Picopro	l/ha
	03/04/03	Cheetah S	0.7 l/ha
	15/04/03	Eagle	30 g/ha
Fungicides:	07/05/03	Opus	0.5 l/ha
	07/05/03	Twist	0.5 l/ha
	15/05/03	Fortress	0.3 l/ha
	28/05/03	Opus	0.5 l/ha
	28/05/03	Twist	1.0 l/ha
Insecticides:	10/10/02	Cyperkill	0.25 l/ha
Dessicant:	05/08/03	Glyphosate	3.0 l/ha
Fertiliser inputs:	Application date	Product	Rate kg/ha
N	13/03/03	Nitram	23 N
	31/03/03	Nitram	29 N
	13/05/03	Nitram	48 N
P	None		
K	None		
Harvest:	16/08/03		

Site Details for Winter Wheat Seed Rate x Nitrogen Timing – Harvest 2003

Site:	Sutton Bonington		
Field Name:	Bunny Field	459328	
Soil description:	Keuper Marl		
		mg/l	ADAS Index
Soil Analysis	P		2
	K		3
	Mg		5
	Organic matter %		
	pH	7.1	
Drainage	Fairly Good		
Cultivations:	13/08/02	Heavy disc	
	11/09/02	Ploughed	
	17/09/02	Power Harrowed	
	18/09/02	Cambridge Rolled	
	20/09/02	Power Harrow	
	20/09/02	Roll (post drilling)	
Date of drilling:	20/09/02		
Previous cropping:	2002	2001	2000
	Winter OSR	Set-aside	W. Wheat
	Application date	Product	Rate
Treatment details:	19/02/03	Amm nitrate – N1	40 kgN/ha
	19/03/03	Amm nitrate – N2	40 kgN/ha
	09/04/03	Amm nitrate – N3	40 kgN/ha
	24/04/03	Amm nitrate – all	90 kgN/ha
	12/05/03	Amm nitrate – all	100 kgN/ha
Herbicides:	28/12/02	Lexus 50 DF	20 g/ha
	28/12/02	Stomp	2.5 l/ha
	28/05/03	Starane 2	0.65 l/ha
	28/05/03	Ally	20 g/ha
Fungicides:	09/05/03	Landmark	0.7 l/ha
	09/05/02	Unix	0.4 l/ha
	28/05/03	Opera	0.5 l/ha
	28/05/03	Tern	0.1 l/ha
Insecticides:	28/12/02	Permasect C (cypermethrim)	28/12/02
PGR:	09/05/03	5C Cycocel	2.5 l/ha
Molluscicides:	14/09/02	Metaldehyde	7.5 kg/ha
	01/11/02	Metaldehyde	8.0 kg/ha
Fertiliser inputs:	Application date	Product	Rate kg/ha
N	See treatment details		
P	04/04/03	P_2O_5	90
K	04/04/03	K_2O	90
Mn	09/05/03	Jett Manganese	2.0 l/ha
Harvest:	05/08/03		

Site Details for Winter Wheat Seed Rate x Disease Control – Harvest 2003

Site:	High Mowthorpe		
Field Name:	Wether Plain	SE889 694	
Soil description:	Shallow silt clay loam overlying chalk		
Series:	Andover		
		mg/l	ADAS Index
Soil Analysis	P	18	2
	K	122	2
	Mg	37	1
	Organic matter %	3.8	
	pH	7.9	
Drainage	Good		
Cultivations:	19/09/02	Ploughed/pressed	
	27/09/02	Rotavated	
Date of drilling:	27/09/02	Rolled	
Cultivar:	Claire		
Previous cropping:	2002	2001	2000
	WOSR	W. Wheat	S Barley
	<u>Application date</u>	Product	Rate
Treatment details:	Trt 1 - 16/04/03	Bravo 500	1.5 l/ha
	Trt 2 - 07/05/03	Opus	0.5 l/ha
		Fortress	0.2 l/ha
	Trt 3 - 27/05/03	Opus	0.75 l/ha
		Corbel	0.5 l/ha
Herbicides:	18/11/02	Fieldguard	2.1 l/ha
	18/11/02	Inter Pendimeth	3.1 l/ha
Fungicides:		l	
Insecticides:	30/09/02	Draza	5.0 kg/ha
	18/11/02	Cypermethrin	0.25 l/ha
Molluscicides:	30/09/02	Draza (Trt 2&3)	5.0 kg/ha
Dessicant:	None		
Fertiliser inputs:	<u>Application date</u>	Product	Rate kg/ha
N	13/13/03	Nitram	39 N
	01/05/03	Nitram	196 N
P	None		
K	None		
Harvest:	20/08/03		

Site Details for Winter Wheat Seed Rate x Slug Control – Harvest 2003

Site:	Edinburgh		
Field Name:	Boghill Farm	NT249659	
Soil description:	Loam		
Series:	Winton/Duncrahill		
		mg/l	ADAS Index
Soil Analysis	P	18.2	
	K	357	
	Mg	249	
	Organic matter %		
	pH	6.1	
Cultivations:	07/10/02	Power Harrow	
Date of drilling:	07/10/02		
Previous cropping:	2002	2001	2000
	Spring Barley	W. Wheat	Spring Barley
	Application date	Product	Rate
Treatment details:	08/10/02	Draza - Trt 2 & 3	5.5 kg/ha
Herbicides:	10/04/03	Swipe	4.5 l/ha
	15/05/03	Harmony M	50 g/ha
Fungicides:	23/04/03	Sportak Delta	0.9 l/ha
	23/04/03	Tern	0.3 l/ha
	03/06/03	Landmark	0.75 l/ha
	03/06/03	Orka	1.0 l/ha
	16/06/03	Twist	0.8 l/ha
	16/06/03	Folicur	0.4 l/ha
Molluscicides:	See treatment details		
PGR:	07/05/03	Moddus	0.4 l/ha
Fertiliser inputs:	Application date	Product	Rate kg/ha
N	14/03/03	Nitram	60 N
	16/04/03	Nitram	140 N
P	08/10/02	P_2O_5	70
K	08/10/02	K_2O	70
S	14/03/03		15.2
Mn	16/04/03	Mantrac 500	1.0 l/ha
Harvest:	20/08/03		

Site Details for Winter Wheat Seed Rate x Nitrogen Timing – Harvest 2003

Site:	Aberdeen		
Field Name:	Sunnybrae	NJ878117	
Soil description:	Sandy Clay Loam		
Series:	Countesswells		
		mg/l	ADAS Index
Soil Analysis	P	8.6	
	K	83.5	
	Mg	85.7	
	Organic matter %	9.8%	
	pH	5.9	
Cultivations:		Plough	
	27/09/02	Power Harrow	
Date of drilling:	27/09/02		
Cultivar:	Claire		
Previous cropping:	3 Years Grass		
	Application date	Product	Rate
Treatment details:	07/03/03	Amm nitrate – N1	40 kgN/ha
	27/03/03	Amm nitrate – N2	40 kgN/ha
	17/04/03	Amm nitrate – N3	40 kgN/ha
	17/04/03	Amm nitrate – all	50 kgN/ha
Herbicides:	17/12/02	Stomp	3.3 l/ha
	17/12/02	IPU	1.5 l/ha
	17/12/02	Quantum	7 g/ha
	06/05/03	Harmony	40 g/ha
Fungicides:	15/05/03	Unix	1.0 kg/ha
	15/05/03	Opus	0.75 l/ha
	15/05/03	Bravo	1.0 l/ha
	04/06/03	Opera	150 l/ha
	21/06/03	Amistar	0.6 l/ha
	21/06/03	Folicur	0.5 l/ha
Insecticides:	Pre-ploughing	Dursban	1.5 l/ha
Molluscicides:	29/09/02	Metaldehyde (trts 2&3)	5.0 kg/ha
PGR:	06/05/03	5C Cycocel	2.5 l/ha
Dessicant:	Pre-ploughing	Touchdown	4.0 l/ha
Fertiliser inputs:	Application date	Product	Rate kg/ha
N	See treatment details		
P	14/09/02	P_2O_5	98
K	14/09/02	K_2O	98
Harvest:	02/09/03		

Appendix 2 – Yield data

Year	site	seed rate	Fungicide	Nitrogen timing	Residual Nitrogen	Rotation	PGR	Slug Control	Grain yield, t/ha (15%mc)
2001	Bridgets	40	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	7.82
2001	Bridgets	80	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	8.50
2001	Bridgets	160	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	9.04
2001	Bridgets	320	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	9.02
2001	Bridgets	640	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	9.37
2001	Bridgets	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.14
2001	Bridgets	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.98
2001	Bridgets	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.25
2001	Bridgets	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.54
2001	Bridgets	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.43
2001	Bridgets	40	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	6.94
2001	Bridgets	80	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	8.06
2001	Bridgets	160	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	8.83
2001	Bridgets	320	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	9.53
2001	Bridgets	640	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	9.68
2001	Rosemaund	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	6.88
2001	Rosemaund	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	7.71
2001	Rosemaund	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	8.50
2001	Rosemaund	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	9.11
2001	Rosemaund	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	8.60
2001	Rosemaund	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.74
2001	Rosemaund	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.92
2001	Rosemaund	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.42
2001	Rosemaund	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.02
2001	Rosemaund	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.57
2001	Rosemaund	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	7.42

2001	Rosemaund	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	7.98
2001	Rosemaund	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	8.75
2001	Rosemaund	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	8.99
2001	Rosemaund	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	9.21
2001	Sutton-B	40	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	8.24
2001	Sutton-B	80	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	8.56
2001	Sutton-B	160	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	8.58
2001	Sutton-B	320	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	7.85
2001	Sutton-B	640	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	7.50
2001	Sutton-B	40	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	8.03
2001	Sutton-B	80	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	8.80
2001	Sutton-B	160	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	8.67
2001	Sutton-B	320	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	8.05
2001	Sutton-B	640	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	7.94
2001	Sutton-B	40	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	8.18
2001	Sutton-B	80	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	8.86
2001	Sutton-B	160	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	8.81
2001	Sutton-B	320	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	8.96
2001	Sutton-B	640	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	8.14
2001	Sutton-B	40	GS32 & GS39	Early	high	1st	PGR at GS30/31	Postdrilling	8.39
2001	Sutton-B	80	GS32 & GS39	Early	high	1st	PGR at GS30/31	Postdrilling	9.13
2001	Sutton-B	160	GS32 & GS39	Early	high	1st	PGR at GS30/31	Postdrilling	9.39
2001	Sutton-B	320	GS32 & GS39	Early	high	1st	PGR at GS30/31	Postdrilling	8.87
2001	Sutton-B	640	GS32 & GS39	Early	high	1st	PGR at GS30/31	Postdrilling	8.97
2001	Sutton-B	40	GS32 & GS39	Normal	high	1st	PGR at GS30/31	Postdrilling	8.22
2001	Sutton-B	80	GS32 & GS39	Normal	high	1st	PGR at GS30/31	Postdrilling	9.01
2001	Sutton-B	160	GS32 & GS39	Normal	high	1st	PGR at GS30/31	Postdrilling	9.41
2001	Sutton-B	320	GS32 & GS39	Normal	high	1st	PGR at GS30/31	Postdrilling	9.39

2001	Sutton-B	640	GS32 & GS39	Normal	high	1st	PGR at GS30/31	Postdrilling	9.41
2001	Sutton-B	40	GS32 & GS39	Late	high	1st	PGR at GS30/31	Postdrilling	7.67
2001	Sutton-B	80	GS32 & GS39	Late	high	1st	PGR at GS30/31	Postdrilling	9.22
2001	Sutton-B	160	GS32 & GS39	Late	high	1st	PGR at GS30/31	Postdrilling	9.33
2001	Sutton-B	320	GS32 & GS39	Late	high	1st	PGR at GS30/31	Postdrilling	8.92
2001	Sutton-B	640	GS32 & GS39	Late	high	1st	PGR at GS30/31	Postdrilling	9.27
2001	H-Mowthorpe	40	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	8.77
2001	H-Mowthorpe	80	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	10.72
2001	H-Mowthorpe	160	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	12.01
2001	H-Mowthorpe	320	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	12.39
2001	H-Mowthorpe	640	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	12.47
2001	H-Mowthorpe	40	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	9.13
2001	H-Mowthorpe	80	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	10.73
2001	H-Mowthorpe	160	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	11.90
2001	H-Mowthorpe	320	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	12.38
2001	H-Mowthorpe	640	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	12.61
2001	H-Mowthorpe	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.67
2001	H-Mowthorpe	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.71
2001	H-Mowthorpe	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	11.81
2001	H-Mowthorpe	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	12.55
2001	H-Mowthorpe	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	12.85
2001	Edinburgh	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	6.03
2001	Edinburgh	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	7.77
2001	Edinburgh	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	9.69
2001	Edinburgh	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	10.70
2001	Edinburgh	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	11.23
2001	Edinburgh	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.36
2001	Edinburgh	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.06
2001	Edinburgh	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.21
2001	Edinburgh	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.92
2001	Edinburgh	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	11.35

2001	Edinburgh	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	7.90
2001	Edinburgh	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	9.70
2001	Edinburgh	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	10.64
2001	Edinburgh	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	11.15
2001	Edinburgh	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	11.28
2001	Aberdeen	40	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	4.90
2001	Aberdeen	80	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	6.86
2001	Aberdeen	160	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	7.41
2001	Aberdeen	320	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	7.59
2001	Aberdeen	640	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	6.58
2001	Aberdeen	40	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	5.38
2001	Aberdeen	80	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	6.61
2001	Aberdeen	160	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	7.53
2001	Aberdeen	320	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	7.66
2001	Aberdeen	640	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	7.39
2001	Aberdeen	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	6.02
2001	Aberdeen	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.46
2001	Aberdeen	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.86
2001	Aberdeen	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.05
2001	Aberdeen	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.86
2002	Mamhead	40	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	8.23
2002	Mamhead	80	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	8.50
2002	Mamhead	160	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	8.75
2002	Mamhead	320	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	8.66
2002	Mamhead	640	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	7.76
2002	Mamhead	40	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	8.22

2002	Mamhead	80	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	9.00
2002	Mamhead	160	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	9.25
2002	Mamhead	320	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	9.16
2002	Mamhead	640	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	8.43
2002	Mamhead	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.89
2002	Mamhead	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.62
2002	Mamhead	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.85
2002	Mamhead	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.73
2002	Mamhead	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.02
2002	Rosemaund	40	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	8.95
2002	Rosemaund	80	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	10.02
2002	Rosemaund	160	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	10.28
2002	Rosemaund	320	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	10.81
2002	Rosemaund	640	GS32 & GS39	Normal	Normal	1st	No PGR	Postdrilling	10.44
2002	Rosemaund	40	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	9.40
2002	Rosemaund	80	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	9.98
2002	Rosemaund	160	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	10.79
2002	Rosemaund	320	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	10.57
2002	Rosemaund	640	GS32 & GS39	Normal	Normal	1st	PGR at tillering	Postdrilling	10.28
2002	Rosemaund	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.94
2002	Rosemaund	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.53
2002	Rosemaund	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.03
2002	Rosemaund	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.85
2002	Rosemaund	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.97
2002	Sutton-B	40	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	8.88
2002	Sutton-B	80	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	10.03
2002	Sutton-B	160	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	11.24
2002	Sutton-B	320	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	10.81
2002	Sutton-B	640	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	10.61
2002	Sutton-B	40	GS32 & GS39	Early	high	1st	PGR at GS30/31	Postdrilling	7.57
2002	Sutton-B	80	GS32 & GS39	Early	high	1st	PGR at GS30/31	Postdrilling	9.10

2002	Sutton-B	160	GS32 & GS39	Early	high	1st	PGR at GS30/31	Postdrilling	10.68
2002	Sutton-B	320	GS32 & GS39	Early	high	1st	PGR at GS30/31	Postdrilling	10.84
2002	Sutton-B	640	GS32 & GS39	Early	high	1st	PGR at GS30/31	Postdrilling	10.99
2002	Sutton-B	40	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	8.13
2002	Sutton-B	80	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	10.14
2002	Sutton-B	160	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	10.25
2002	Sutton-B	320	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	9.85
2002	Sutton-B	640	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	10.91
2002	Sutton-B	40	GS32 & GS39	Normal	high	1st	PGR at GS30/31	Postdrilling	8.24
2002	Sutton-B	80	GS32 & GS39	Normal	high	1st	PGR at GS30/31	Postdrilling	9.56
2002	Sutton-B	160	GS32 & GS39	Normal	high	1st	PGR at GS30/31	Postdrilling	10.48
2002	Sutton-B	320	GS32 & GS39	Normal	high	1st	PGR at GS30/31	Postdrilling	10.69
2002	Sutton-B	640	GS32 & GS39	Normal	high	1st	PGR at GS30/31	Postdrilling	10.43
2002	Sutton-B	40	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	8.01
2002	Sutton-B	80	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	9.63
2002	Sutton-B	160	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	10.58
2002	Sutton-B	320	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	11.21
2002	Sutton-B	640	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	10.97
2002	Sutton-B	40	GS32 & GS39	Late	high	1st	PGR at GS30/31	Postdrilling	7.95
2002	Sutton-B	80	GS32 & GS39	Late	high	1st	PGR at GS30/31	Postdrilling	9.91
2002	Sutton-B	160	GS32 & GS39	Late	high	1st	PGR at GS30/31	Postdrilling	10.99
2002	Sutton-B	320	GS32 & GS39	Late	high	1st	PGR at GS30/31	Postdrilling	11.27
2002	Sutton-B	640	GS32 & GS39	Late	high	1st	PGR at GS30/31	Postdrilling	10.83
2002	H-Mowthorpe	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.16
2002	H-Mowthorpe	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.36
2002	H-Mowthorpe	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.41
2002	H-Mowthorpe	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.70
2002	H-Mowthorpe	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.93
2002	H-Mowthorpe	40	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	6.33
2002	H-Mowthorpe	80	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	7.43
2002	H-Mowthorpe	160	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	8.17

2002	H-Mowthorpe	320	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	8.59
2002	H-Mowthorpe	640	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	9.20
2002	H-Mowthorpe	40	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	5.69
2002	H-Mowthorpe	80	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	6.96
2002	H-Mowthorpe	160	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	7.66
2002	H-Mowthorpe	320	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	8.24
2002	H-Mowthorpe	640	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	7.58
2002	Edinburgh	40	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	7.84
2002	Edinburgh	80	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	8.71
2002	Edinburgh	160	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	9.34
2002	Edinburgh	320	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	9.22
2002	Edinburgh	640	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	9.73
2002	Edinburgh	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.60
2002	Edinburgh	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.59
2002	Edinburgh	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.27
2002	Edinburgh	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.60
2002	Edinburgh	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.56
2002	Edinburgh	40	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	7.53
2002	Edinburgh	80	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	8.29
2002	Edinburgh	160	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	9.02
2002	Edinburgh	320	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	9.30
2002	Edinburgh	640	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	9.53
2002	Aberdeen	40	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	4.57
2002	Aberdeen	80	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	6.64
2002	Aberdeen	160	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	8.71
2002	Aberdeen	320	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	9.51
2002	Aberdeen	640	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	9.92
2002	Aberdeen	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	4.23
2002	Aberdeen	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	6.60
2002	Aberdeen	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.42
2002	Aberdeen	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.40

2002	Aberdeen	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.82
2002	Aberdeen	40	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	4.68
2002	Aberdeen	80	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	6.86
2002	Aberdeen	160	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	8.58
2002	Aberdeen	320	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	9.45
2002	Aberdeen	640	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	9.82

2003	Rosemaund	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	6.03
2003	Rosemaund	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.28
2003	Rosemaund	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.65
2003	Rosemaund	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.14
2003	Rosemaund	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.10
2003	Rosemaund	40	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	6.74
2003	Rosemaund	80	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	7.79
2003	Rosemaund	160	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	7.96
2003	Rosemaund	320	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	8.28
2003	Rosemaund	640	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	8.40
2003	Rosemaund	40	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	6.36
2003	Rosemaund	80	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	7.36
2003	Rosemaund	160	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	8.04
2003	Rosemaund	320	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	8.40
2003	Rosemaund	640	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	8.41
2003	Mamhead	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	5.35
2003	Mamhead	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	6.38
2003	Mamhead	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.14
2003	Mamhead	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.11
2003	Mamhead	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.35
2003	Mamhead	40	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	4.09
2003	Mamhead	80	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	4.24
2003	Mamhead	160	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	4.70

2003	Mamhead	320	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	4.52
2003	Mamhead	640	GS32 & GS39	Normal	Normal	2nd	PGR at GS30/31	Postdrilling	4.20
2003	Mamhead	40	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	3.87
2003	Mamhead	80	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	4.43
2003	Mamhead	160	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	4.97
2003	Mamhead	320	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	5.21
2003	Mamhead	640	GS32 & GS39	Normal	Normal	2nd plus Latitude	PGR at GS30/31	Postdrilling	5.51
2003	Sutton-B	40	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	6.20
2003	Sutton-B	40	GS32 & GS39	Early	hign	1st	PGR at GS30/31	Postdrilling	4.44
2003	Sutton-B	40	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	5.98
2003	Sutton-B	40	GS32 & GS39	Normal	hign	1st	PGR at GS30/31	Postdrilling	2.71
2003	Sutton-B	40	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	7.20
2003	Sutton-B	40	GS32 & GS39	Late	hign	1st	PGR at GS30/31	Postdrilling	6.96
2003	Sutton-B	80	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	7.60
2003	Sutton-B	80	GS32 & GS39	Early	hign	1st	PGR at GS30/31	Postdrilling	7.02
2003	Sutton-B	80	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	7.81
2003	Sutton-B	80	GS32 & GS39	Normal	hign	1st	PGR at GS30/31	Postdrilling	7.04
2003	Sutton-B	80	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	9.24
2003	Sutton-B	80	GS32 & GS39	Late	hign	1st	PGR at GS30/31	Postdrilling	8.26
2003	Sutton-B	160	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	9.56
2003	Sutton-B	160	GS32 & GS39	Early	hign	1st	PGR at GS30/31	Postdrilling	9.39
2003	Sutton-B	160	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	10.08
2003	Sutton-B	160	GS32 & GS39	Normal	hign	1st	PGR at GS30/31	Postdrilling	8.05
2003	Sutton-B	160	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	9.92
2003	Sutton-B	160	GS32 & GS39	Late	hign	1st	PGR at GS30/31	Postdrilling	10.79
2003	Sutton-B	320	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	10.04
2003	Sutton-B	320	GS32 & GS39	Early	hign	1st	PGR at GS30/31	Postdrilling	10.33
2003	Sutton-B	320	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	10.59
2003	Sutton-B	320	GS32 & GS39	Normal	hign	1st	PGR at GS30/31	Postdrilling	10.44
2003	Sutton-B	320	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	10.71
2003	Sutton-B	320	GS32 & GS39	Late	hign	1st	PGR at GS30/31	Postdrilling	10.84

2003	Sutton-B	640	GS32 & GS39	Early	low	1st	PGR at GS30/31	Postdrilling	10.34
2003	Sutton-B	640	GS32 & GS39	Early	hign	1st	PGR at GS30/31	Postdrilling	10.38
2003	Sutton-B	640	GS32 & GS39	Normal	low	1st	PGR at GS30/31	Postdrilling	10.53
2003	Sutton-B	640	GS32 & GS39	Normal	hign	1st	PGR at GS30/31	Postdrilling	10.73
2003	Sutton-B	640	GS32 & GS39	Late	low	1st	PGR at GS30/31	Postdrilling	10.95
2003	Sutton-B	640	GS32 & GS39	Late	hign	1st	PGR at GS30/31	Postdrilling	11.41
2003	H-Mowthorpe	40	GS30 & GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.67
2003	H-Mowthorpe	80	GS30 & GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.72
2003	H-Mowthorpe	160	GS30 & GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.27
2003	H-Mowthorpe	320	GS30 & GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.74
2003	H-Mowthorpe	640	GS30 & GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.98
2003	H-Mowthorpe	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.62
2003	H-Mowthorpe	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.79
2003	H-Mowthorpe	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.21
2003	H-Mowthorpe	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.69
2003	H-Mowthorpe	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.95
2003	H-Mowthorpe	40	GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	8.98
2003	H-Mowthorpe	80	GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.59
2003	H-Mowthorpe	160	GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	9.89
2003	H-Mowthorpe	320	GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.32
2003	H-Mowthorpe	640	GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	10.47
2003	Edinburgh	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	4.49
2003	Edinburgh	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	5.56
2003	Edinburgh	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	6.63
2003	Edinburgh	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	6.12
2003	Edinburgh	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	None	6.10
2003	Edinburgh	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	5.09

2003	Edinburgh	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	5.75
2003	Edinburgh	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	6.49
2003	Edinburgh	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	6.48
2003	Edinburgh	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	5.95
2003	Edinburgh	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	4.49
2003	Edinburgh	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	5.37
2003	Edinburgh	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	5.37
2003	Edinburgh	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	4.86
2003	Edinburgh	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling plus Sebutol Secure	5.02
2003	Aberdeen	40	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	4.41
2003	Aberdeen	80	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	5.57
2003	Aberdeen	160	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	6.76
2003	Aberdeen	320	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	7.58
2003	Aberdeen	640	GS32 & GS39	Early	Normal	1st	PGR at GS30/31	Postdrilling	7.62
2003	Aberdeen	40	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	4.02
2003	Aberdeen	80	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	5.25
2003	Aberdeen	160	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	6.31
2003	Aberdeen	320	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.04
2003	Aberdeen	640	GS32 & GS39	Normal	Normal	1st	PGR at GS30/31	Postdrilling	7.52
2003	Aberdeen	40	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	4.28
2003	Aberdeen	80	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	5.05
2003	Aberdeen	160	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	6.30
2003	Aberdeen	320	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	6.83
2003	Aberdeen	640	GS32 & GS39	Late	Normal	1st	PGR at GS30/31	Postdrilling	7.37