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The effect of location and management on the target drilling rate for winter wheat

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This is the final report covering two projects. Project No. 2249 started in August 2000 for 39 months with an HGCA contract of £250,041 and Project No. 2860 which started in January 2003 for 15 months with an HGCA contract of £27,909.

Contents

Abstract

Previous HGCA-funded project work showed that optimum winter wheat plant populations for yield can be as low as 70 plants/m^2. Many farmers have reduced seed rates as a result of this work. However, these earlier trials were carried out at two sites only and did not consider other agronomic factors. A single statistical method was used to analyse the results.

The current trials were carried out at six sites over three years. Additional agronomic factors (rotational position, slug control, plant growth regulator use, nitrogen nutrition or foliar disease control) were included to test for specific interactions with seed rate at each site.

Results were analysed using two methods:

- as in the previous project, a conventional exponential-plus-linear model was used to relate plant population to yield,
- in collaboration with BioSS, Bayesian methodology using both exponential-plus-linear and inverse-quadratic models were used to relate seed rate to yield.

Both models provided equally good fits to the data in the Bayesian analysis but the inverse-quadratic consistently predicted optima up to 30% higher than did the exponential-plus-linear method. Optimum plant populations were similar, or slightly higher, than in the previous project, ranging from 70 plants/m^2 in September drillings in southern England, to 250 plants/m^2 in Scotland.

Other agronomic effects:

1. Overall, the conventional analysis did not predict a consistent increase in the optimum plant population with latitude, although relatively high optimum plant populations were calculated more frequently at the northern sites. The Bayesian analysis predicts that optimum seed rate must increase by 7 or 8% (or 11 and 28 seeds/m^2) per degree of latitude.
2. Low soil mineral nitrogen reserves or delayed spring nitrogen application reduced tillering at most sites, but this affected optimum plant population in only one of the seven experiments.
3. Slugs ate approximately the same proportion of plants at all seed rates. Optimum seed rates were higher if slugs were not controlled, but optimum plant populations were unaffected because, in this study, slugs only reduced the percentage establishment and did not affect the compensatory ability of plants.
4. Optimum plant populations were 30-40 plants lower in rotational positions where take-all infection occurred than in first wheats. Where Latitude seed treatment was used the optimum was 20-25 plants lower than first wheats. Using Latitude seed treatment yielded 0.23-2.59 t/ha more at the optimum plant population than untreated seed.
5. Yield response to foliar disease control (only tested at one site) was significantly reduced at low seed rates, suggesting disease control savings may be possible in sparser crops.
6. No effects of PGR use were found on tillering or compensation for low plant populations; their use should be targeted at high plant population crops where lodging risk is high.

Summary

Conventional seed rate

It has been widely acknowledged for many years that many farmers sow winter wheat seed at rates that are unnecessarily high. This not only increases seed cost but also exacerbates lodging and disease control problems.

Winter wheat has traditionally been grown in the UK to produce a target spring plant population of 275 plants/m^2. The weight of seed to drill being calculated using the following formula:

$$\text{Seed rate (kg/ha)} = \frac{\text{Target plant number (m}^{-2}\text{)* Thousand grain weight (g)}}{\text{Expected establishment (\%)}}$$

Findings from the last project

A previous HGCA-funded project (Project Report No. 234) set out to determine the extent to which plant population could be reduced without compromising the economic performance of the crop. This project tested effects of seed rates (20- 640 seeds/m^2) at sowing dates from September through to November, at ADAS Rosemaund in Herefordshire and Sutton Bonington in Leicestershire.

Potentially large reductions in target plant population were identified with economic optimum plant populations as low as 70 plants/m^2 for September sowings. No significant interaction between variety and plant population was found, but there was a large effect of sowing date, the economic optimum increasing by 10 plants/ week delay in sowing from late September.

Rationale for the current project

Low plant population crops rely on increased tiller production as the primary mechanism by which they compensate. The previous project left unanswered a number of questions, about possible interactions of agronomic factors with optimum plant population, including effects of:

- latitude

- nitrogen nutrition
- take-all and the effect of Latitude seed treatment
- pest damage
- plant growth regulators (PGR)
- disease control

Because of the large difference between the results of the first phase of plant population work and current practice, the applicability of the analysis method used in the first experiment (linear-plus-exponential curve fitting) was questioned. Thus, the expertise of Bioss was sought to analyse the findings of the current project and also to re-examine the results of the previous project.

A project was set up with six plant population response experiments each year distributed between the south coast of England and Aberdeen, to test the applicability of previous results across a range of sites. Additionally, within each experiment a single agronomic factor was varied either to test its effect on optimum plant population or to test what effect low plant population had on the response to the input. Contrasts of slug control, rotational position, nitrogen timing and PGR use were included.

<u>Data analysis</u>

Data from this project was subjected to two separate analyses. The first was a conventional statistical approach of fitting an exponential-plus-linear model to the seed rate and yield data from each site, with the line constrained to intercept with the origin, such that zero seed equated to zero yield. Using a ratio of seed cost to grain value of 4:1 an optimum seed rate, which is the seed rate above which the rate of yield increase is no longer sufficient to cover the increasing seed cost was calculated. Percentage establishment data were then interpolated from the closest seed rates to calculate the number of plants required. The results of this analysis as reported in HGCA project report No 234 is presented first. Secondly data from this project and the previous one were collated into a large data-set and analysed using Bayesian methodology. In this analysis both exponential-plus-linear and inverse-quadratic models were fitted and the predicted optimum seed rates compared. The results of this analysis are given at the end of the summary.

Site and season

The average percentage crop establishment was 72%. Mean grain yield was slightly above the national average in the 2001 and 2002 harvest years at 9 t/ha but significantly lower in the 2003 season at 6.8 t/ha. There was significant variation within this, with treatment yields ranging from 4.2 t/ha to 12.9 t/ha. The results of the experiments can therefore be assumed to be representative of commercial practice.

The optima were similar or slightly higher than in the previous work (Table S1). There was significant variation in the calculated optimum between years within a site as well as in the ranking order of sites within a year. There was no relationship between site latitude and optimum plant population, additionally taking account of sowing date and site latitude did not improve the relationship. Whilst low plant populations were occasionally applicable even at the most northerly sites there was a greater frequency of occasions when the economic optimum population was high in the north compared with the south This indicates that there is an increased risk from using lower seed rates at more northerly sites.

Table S1. Optimum plant population taken from a linear-plus-exponential fitted curve with a seed to grain price ration of 4:1, for the standard treatments.

	2001	2002	2003
Bridgets, Hampshire (BR)	115	-	-
Mamhead, Devon (MH)	-	85	127
Rosemaund, Herefordshire (RM)	72	84	120
Sutton Bonington, Leicestershire (SB)	74	134	215
High Mowthorpe, Yorkshire (HM)	161	195	127
Edinburgh, Lothian (ED)	118	121	76
Aberdeen, Aberdeenshire (AB)	85	248	127

Effective vernalisation date (EVD) and thermal time from drilling to EVD (TTver) were calculated in the previous project and a strong correlation between TTver and final leaf number on the main stem was shown, across sowing dates and seasons at one site. The final number of main stem leaves then explained a significant proportion of the variation in optimum plant populations across years and sowing dates. An objective of this project was to test if these same relationships would predict optimum plant population across

sites at different latitudes and seasons. A similar relationship between TTver and leaf number was observed with an r^2 of 0.68 (Figure S2). However, a multiple regression between sowing date, latitude and final leaf number provided a tighter relationship:-
*Final leaf number = 52.9 – 0.04437 * sowing date – 0.51584 * latitude (r^2 of 0.81).*
Where sowing date is expressed as days from 1 January and latitude is expressed as degrees.

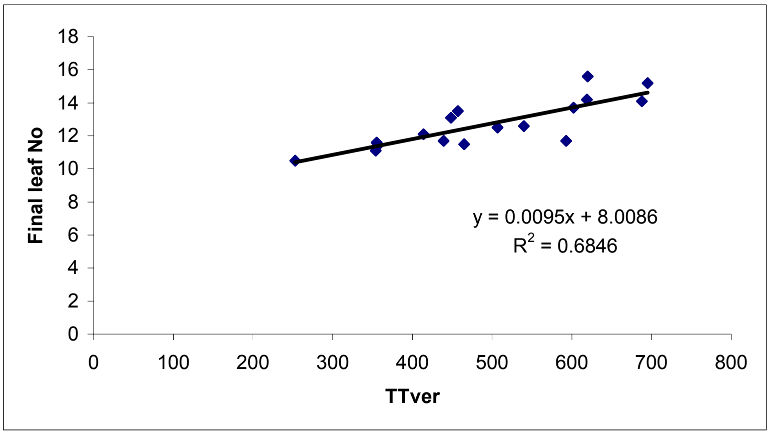

Figure S2. Relationship between final culm leaf number and thermal time accumulated between sowing and 50 effective vernalisation days.

Site and season variation in optimum plant population could not, however, be explained by either TTver or final main stem leaf number. It is likely that a range of factors associated with the treatments being tested or due to site and season variation influenced the crops ability to compensate for reduced plant population and masked the innate physiological response.

Nitrogen nutrition

The effect of differential levels of soil mineral nitrogen on tillering and optimum plant population was tested at Sutton Bonington in all three years. Effects were generally small and inconsistent.

The effect of timing of the early spring dressing of nitrogen was tested across seven site seasons. There was a fairly consistent response of shoot production to the application of early nitrogen. At three of the sites 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 other sites there were similar but smaller effects and only in one case no impact of N timing on tiller production. The timing of early spring nitrogen had no significant effect on the yield of wheat (Table S2).

Table S2. 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. In general, however, there was no interaction between seed rate and timing of early nitrogen on yield resulting in a single optimum plant population being calculated across the three nitrogen timings. The one exception was at ADAS Bridgets in 2001 (Figure S3) (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, the optima for early normal and late nitrogen were 84, 118 and 149 plants/m^2.

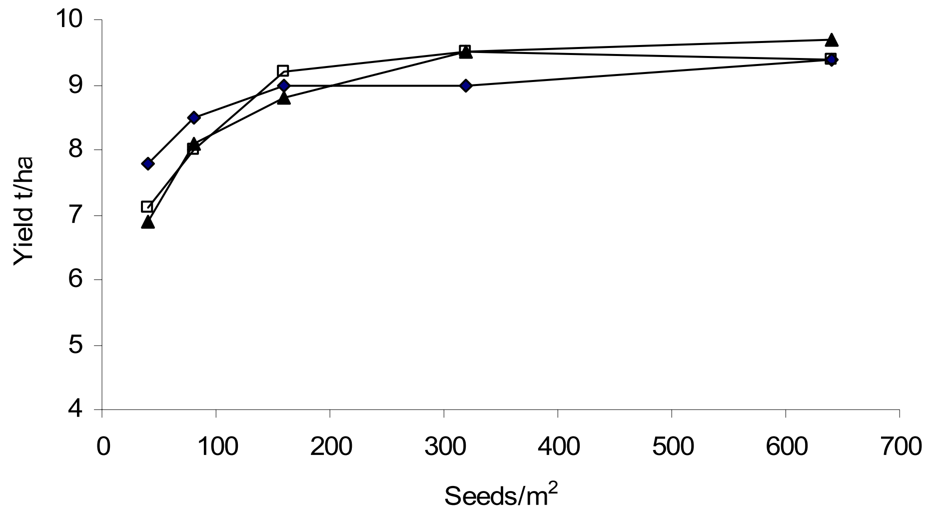

Figure S3. Interaction between seed rate and timing of early nitrogen: ♦ early □ normal ▲late. ADAS Bridgets 2001

These experiments do not generally indicate 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 (except Bridgets, 2001). However, previous work has shown that low seed rate crops are much less susceptible to lodging, and therefore the risk of applying early N, in terms of lodging is much reduced. Early first nitrogen application may therefore be advisable on the basis that there is a potential benefit in some circumstances but little risk of an adverse effect.

<u>Pests</u>

The interaction between slug control and seed rate was tested at three sites; slug control treatments significantly increased establishment at all sites although at Edinburgh in 2003 the absolute effect was small, increasing establishment from 192 in the untreated to 209 plants in the prophylactic treatment which had a Secur seed treatment and slug pellets. The percentage increase in plant population due to slug control remained fairly constant across the range of seed rates; thus a significantly higher number of seeds/m^2 were lost at high compared to low seed rates.

In all sites there was a significant interaction between slug control treatment and seed rate on crop yield. In the experiments at Rosemaund and Edinburgh in the 2001 season significantly higher seed rates were needed where no slug control was applied than where a prophylactic approach was taken. Allowing for the reduced establishment where no slug control was applied, however, showed that the different optimum seed rates related to very similar optimum plant populations for the different slug control treatments. At Edinburgh in the 2003 season were there had been a very small effect of slug control on plant establishment the plots untreated for slug control had a lower optimum plant population than either where a standard or prophylactic approach to slug control had been taken.

Whilst there is no need to increase the target plant number, given a high slug population, there is a need to increase the seed number drilled to achieve that population. Given a risk of poor establishment due to slug damage, it is wiser from both an economic and environmental point of view to increase seed rate rather than increase slug pellet use. Greater attention to detail in seed bed formation and consolidation may have a greater effect on improving establishment than either slug pellets or increased seed rate.

Interactions between gout fly and seed rate were observed through chance rather than experiments specifically designed to test for the impact of seed rate on the severity of pest attack. Infestation of a shoot resulted in the death of that shoot plus one additional shoot at the most 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 monitored (5.2% infestation) and where there was no difference, the number of infested plants per unit area was significantly higher in high than low plant population crops.

This implies that low plant populations did not increase 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 at a field scale.

Low plant population crops have a much reduced excess tiller number compared to 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 unfortunately could not be assessed in these experiments, 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, pest thresholds for treatment.

Diseases

The interaction between take-all and optimum plant population was tested in an experiment at three sites comparing 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).

Rotational position did not significantly affect the level of take-all at the Rosemaund site, and as such it could not be used to investigate take-all seed rate interactions. In common with the other sites however, take-all was more severe at high seed rates than low, the 320 seeds/m^2 treatment having a take-all index of 29 compared with 24 for the other seed rates ($P<0.05$).

Across all seed rates, the 1st wheats yielded 2.5 t/ha more than the 3rd wheats at High Mowthorpe and 2.3 t/ha more than the 2nd wheats at Mamhead ($P<0.001$). However, the yield difference between the 1st and 3rd wheats was greater at the high seed rates ($P<0.001$) (eg Figure S4). At the 320 and 640 seeds/m^2 treatments the mean yield difference between the 1st and 3rd wheats was 2.9 t/ha whilst at the 40, 80 and 160 seeds/m^2 treatments the mean yield difference between the 1st and 3rd wheats was 1.4 and 1.9 t/ha[1] at High Mowthorpe and Mamhead respectively.

Latitude seed treatment increased the yield of the 3rd wheats grown at the highest seed rates (320 and 640 seeds/m^2) by 1 t/ha at both sites and at low seed rates (40, 80 and 160 seeds m^{-2}) by 0.5 t/ha at High Mowthorpe and had a negligible effect at Mamhead. These patterns of yield responses meant that the optimum plant populations at High Mowthorpe, were 180 plants/m^2 for 1st wheats and 139 for 3rd wheats. At Mamhead, 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 the two sites respectively having taken into account of the extra costs for treating the seed. These different optimum plant populations were caused by the yield depression in non-first wheats being greater at high than at low plant populations. This effect appeared to have been caused by greater take-all infection of the high seed rate crops.

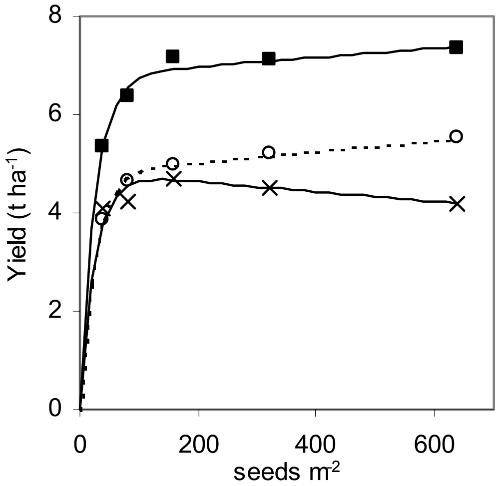

Figure S4. Grain yield for 1st wheat (—■—), 2nd wheat (—×—) and 2nd wheat + Latitude (---O--) at Mamhead. S.e.d. for comparing individual means = 0.321 (36 df).

The profitability of non-first wheats could have been maximised by either reducing the seed rate used for 1st wheats by 35-45 seeds/m^2 if the seed is not treated with Latitude or reducing the seed rates by 25-30 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 untreated seed, more than covering the additional costs.

The impact of foliar disease was only assessed at High Mowthorpe when insufficient slug damage was experienced to continue with the slug control experiment. Three foliar disease control strategies were compared; a three spray programme applied at GS30 (1.5 l/ha Bravo 500), GS32 (0.5 l/ha Opus + 0.2 l/ha Fortress) and GS39 (0.75 l/ha Opus + 0.5 l/ha Corbel), a two spray programme which missed the first spray timing and a single spray applied at GS39 only. Given the site, dry spring weather and the use of the cv. Claire only low to moderate levels of Septoria tritici were observed; levels of other diseases were negligible.

Seed rate did not affect the level of Septoria. However, the low seed rate treatments resulted in leaves with a greater proportion of green tissue (P<0.001). The fungicide treatments did not affect the proportion of leaves 1 and 2 that were diseased, dead or green. However, the 3-spray programme resulted in about 50% more green tissue on leaf 3 compared with the single spray fungicide treatment (P<0.05), a consistent effect across all the seed rates.

The 2 and 3-spray programmes increased yields compared with the single spray at 640, 320 and 160 seeds/m^2 (P<0.01; Table S3), but there was no significant difference at 40 and 80 seeds/m^2. The economically optimum seed rates for the 2- and 3-spray programmes were similar at 166 and 157 seeds/m2 respectively. The optimum seed rate for the single spray was considerably lower at 119 seeds/m^2. After accounting for establishment, the optimum plant populations are 141, 149 and 107 plants/m^2 for the 3-, 2- and 1- spray programmes respectively.

Table S3. Effect of seed rate and fungicide treatment on grain yield at 15% moisture content (t/ha)

	3- spray	2-spray	1- spray
40 seeds m^{-2}	8.67	8.62	8.98
80 seeds m^{-2}	9.72	9.79	9.59
160 seeds m^{-2}	10.27	10.21	9.89
320 seeds m^{-2}	10.74	10.69	10.32
640 seeds m^{-2}	10.98	10.95	10.47
Mean	10.08	10.05	9.85
	p	SED	
Seed rate	0.001	0.82	
Fungicide	0.002	0.064	
Interaction	0.003	0.142	
d.f.	28		

Plant growth regulator

Four experiments tested seed rate and plant growth regulator (PGR) interactions. 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. Lower seed rates increased the number of shoots per plant but, generally the PGR treatments did not affect the number of shoots per plant between the time of application and harvest.

No significant lodging or disease was observed in any trial. Chlormequat should be targeted at crops that establish a large number of plants to help reduce their high lodging risk, not at crops that have established a sub-optimal number of plants with the objective of increasing tiller number.

Statistical review and analysis

The Bayesian analysis included seed rate data from trials at Rosemaund and Sutton Bonington in harvest years 1997-99 and at the seven sites between Aberdeen and the south coast of England in 2001-03 in which this study was carried out.

During this work a novel method for combining information from seed-rate trials was developed. This incorporates information on treatments, varieties and covariates, e.g. sowing date and latitude, with expert knowledge of the crop and of the target site.

In the Bayesian analysis yield was related to seed rate rather than to plant population because the concept of an economically optimum plant population is difficult to define, since no particular cost could be associated with a given population.

Two dose-response functions were fitted to the data; the exponential-plus-linear function (as used in the conventional analysis) and the inverse-quadratic function. Neither provided a substantially better fit than the other, but, because of differences in the shapes of these two functions, the estimated optimum seed rates are lower by about 30% for the exponential-plus-linear function than for the inverse-quadratic. However, the economic consequences of basing seed rate decisions on one of these functions rather than the other were small.

Conclusions

- Two statistical approaches were used:- conventional in which each experiment was analysed and exponential-plus-linear curves fitted separately and Bayesian in which the data from this and the previous seed rate project were combined into one analysis. The Bayesian analysis considered both an exponential-plus-linear and inverse-quadratic curve fits. Neither fitted the data better than the other but the inverse-quadratic predicted optima 30% higher than the exponential-plus-linear.
- Using the output from one curve when in-fact the other was correct was predicted to have a negligible effect on the economic performance of the crop.
- The Bayesian analysis predicted optimum seed rate as it is a statistical and economic optimisation process and the cost of a plant is difficult to assess, the conventional analysis predicts optimum plant population as it is based on agronomic and crop physiological principals which recognise the factors controlling establishment as being different from those which determine the plant number needed for canopy closure and yield optimisation.
- The conclusions from the Bayesian and the conventional analysis were generally in agreement, except that for non-first wheats the Bayesian analysis predicts lower optimum seed rates with Latitude than without it.
- Using the conventional analysis optimum plant populations for first wheats at the southern sites, were similar for late September/early October drillings (70-80 plants) to those found previously.
- Optimum plant population did not increase with increasing latitude in the conventional analysis but high optimum plant populations were found at northerly sites more frequently. The Bayesian analysis indicated seed rates should increase by between 11 and 28 seeds/m^2 per degree latitude increase.
- Delayed nitrogen application reduced tillering at most sites, however, optimum population was only affected at one site. In terms of crop growth at reduced populations, there was no benefit to delaying N applications, normal or early N timing may, however, in some circumstances be beneficial.
- The proportion of seed lost to slugs appeared to be fairly consistent across a wide range of seed rates. Where slug damage risk is high increasing seed rates to avoid

a sub-optimal population rather than using slug control treatments is likely to be beneficial.

- The number of plants infested with gout fly increased as plant population increased. Low plant populations are, however, likely to be less tolerant of shoot loss.
- Yield loss in 2nd or 3rd wheats averaged 2.4 t/ha, but was greater at higher plant populations (2.9 t/ha) than at low populations 1.65 (t/ha), due to reduced take-all severity at low plant populations.
- Under the conventional analysis, optimum populations were 30-40 plants/m^2 lower in 2nd and 3rd wheats than 1st, and intermediate at 20-25 plants/m^2 where seed was treated with Latitude. For the Bayesian analysis, the corresponding reductions in seed rate were about 30 and 45plants/m^2.
- The response to early season foliar disease control was greater at high than low plant populations, reduced early season disease control inputs may be appropriate when low plant populations are established.
- Early season PGR use neither increased tiller number per plant nor improved compensation for low plant populations. PGR use on low population crops is therefore unlikely to be economic.

Introduction

Winter wheat grown in the UK has traditionally been grown with a target spring plant population of 275 plants/m^2. In order to decide on the amount of seed to plant, the grower has made an estimate of establishment, which has usually been estimated to be 85%, or lower in poorer seedbed conditions. These two figures in conjunction with knowledge of the average seed size expressed as the thousand grain weight (tgw), can then be used to calculate the weight of seed to drill thus:

$$\text{Seed rate (kg/ha)} = \frac{\text{Target plant number (m}^{-2}\text{)* thousand grain weight (g)}}{\text{Estimated establishment (\%)}}$$

Work on lodging in winter wheat during the early 1990's (Berry et al. 1998) demonstrated that plant population had a large effect on the susceptibility of the crop to root lodging. It seems logical therefore to reduce plant population in order to reduce lodging risk. An HGCA funded project subsequently set out to see to what extent plant population could be reduced without compromising the economic performance of the crop (Spink *et al*. 2000). This project looked at a wide range of seed rates from 20 to 640 seeds/m^2 at sowing dates from September through to November at ADAS Rosemaund in Herefordshire and Sutton Bonington in Leicestershire. Exponential-plus-linear curves were fitted through the yield data and economic optima were calculated where the rate of yield increase was no longer sufficient to cover increased seed cost. Potentially large reductions in target plant population were identified, with economic optimum plant populations as low as 70 plants/m^2 for September sowings. There were 4 varieties in the sowing date experiments and a much larger number in supplementary experiments, however no significant interaction between variety and plant population could be found. There was a large effect of sowing date on the plant population needed to maximise output, the economic optimum increasing by 10 plants per week delay in sowing from late September. This increase in the number of plants needed was identified as being due to a reduced number of leaves produced per plant in later sowings. Fewer leaves per main stem resulted in a reduction in the final shoot number per plant, and therefore an increase in the number of plants needed to maintain ear number per m^2. Whilst this project resulted in a general reduction in seed rates within the industry, it also resulted in a large number of questions relating to the wider applicability of the results and subsequent management of low plant population crops.

Because of reliance of low plant population crops on increased tiller production as the primary mechanism by which they compensate, there was particular concern as to the applicability of the results on other sites, particularly at more northerly latitudes where wheat crops are traditionally considered to tiller less than at more southerly latitudes. A hypothesis was developed that growing wheat at more northerly latitudes would be similar in effect to later drilling at a more southerly site. There is also a generally accepted effect of crop nutrition, primarily nitrogen nutrition, on the ability of the crop to produce and maintain tillers, low fertility sites where tillering may be restricted due to nutrient stress were also therefore of concern. Previous work on take-all (*Gaeumanomyces graminis*) has shown that through infecting and damaging the vascular system of the root it can reduce root function and nutrient uptake (Spink et al. 1998 and Pillinger, 2002). There were therefore concerns about the effect of rotational position particularly the effects of take-all risk in non-first wheat crops on the applicability of low plant population crops.

There were also a number of questions as to the subsequent management of wheat crops established at much lower than traditional plant populations. The main concerns related to risk of poor establishment due to slug damage, there being a tendency amongst growers to increase slug pellet applications when seed rates are reduced, a potentially self defeating exercise that could increase costs over those that would have been incurred had seed rate been maintained at a high level. Plant growth regulators (PGR), particularly pre-stem extension applications have been claimed to increase tiller number usually through decreasing tiller death. There was therefore a tendancy for increased, or at least maintained, PGR applications to low plant population crops despite the reduced lodging risk. A canopy management approach to nitrogen often results in delayed early season applications of nitrogen to wheat to reduce excessive tillering, given the reliance of low plant populations on tillering to maintain ear number, there is a question as to whether the same approach is likely to be applicable on low plant population crops.

Other questions related to the increased or decreased need for disease control at low plant populations. Some advisers in the industry suggested that because the crop canopy is generally less dense in low plant population crops the crop will be more reliant on its lower leaves for light interception. This in turn would result in the crop losing more yield for each unit disease on lower (leaf 3 and 4) leaves, and therefore requiring greater early season fungicide inputs. The alternative view is that the sparser crop canopies would result in microclimatic conditions that are less conducive to disease development and therefore a general reduction in the need for fungicide input.

It is generally recognised that the competitive ability of the crop has a significant influence on weed survival. Uncompetitive (low plant population) crops may therefore require herbicides to be applied at higher rates or additional applications to achieve adequate weed control. It is not known however whether the crop is adequately competitive down to the low plant populations previously suggested to have no material effect on the rate or number of herbicides needed. If there is a significant reduction in the competitive ability of the crop it may result in higher economic optima than previously calculated where, for example, high populations of herbicide resistant black grass exist and reduced herbicide efficacy results in increased reliance on crop competition.

Because of the large difference between the results of the first phase of plant population work and current practice, there was debate about the applicability of the exponential-plus-linear curve fitted to the data. This resulted in more general discussion about techniques that should be employed for calculating economic optima from biological response data such as that being produced. In particular whether a single curve type should be fitted through all data or whether the curve choice should be allowed to vary between experiments.

To address the questions raised by the first phase of plant population work a project was set up with six plant population response experiments each year distributed between the south coast of England and Aberdeen. Each of the experiments was monitored to provide information on rate and duration of leaf and tiller production as well as the yield response to increasing plant population, to test the hypothesis that latitude effects would be mediated through the same physiological processes as the sowing date effect, well as the applicability of previous results across a range of sites. Additionally within each of these experiments a single agronomic factor was varied either to test for its effect on optimum plant population or to test what effect low plant population had on the response to the input. Contrasts of slug control, rotational position, nitrogen timing and PGR use were included. Interactions between plant population and weed and foliar disease control were considered to be adequately covered in other ongoing HGCA and Defra funded projects, and would be considered by reanalysis of these extant data-sets.

In order to consider the questions relating to the estimation of economic optima from seed rate response experiments, data from this project and the previous one were combined and comprehensive models were fitted which included effects for environments, varieties, treatments and dependence on sowing date and latitude. This allowed optima calculated assuming the exponential-plus-linear dose-response model to be compared with those based on an alternative, the inverse-quadratic model.

Materials and Methods

Field experiments were carried out on winter wheat cv. Claire at six sites (Table M1.) (five sites were common in all years, but Bridgets was used in the first year only and Mamhead in the second and third years) in each of three years (2001 – 2003). Seed rate treatments of 40, 80, 160, 320, 640 seeds/m^2 were consistent at all sites in all years. A second agronomic treatment was varied across site years (Table M2.) with a different treatment tested at each site in each year.

Table M1. Site locations

Sites	Organisation	Address	County	Latitude	Longitude
Bridgets (BR)	ADAS	Martyr Worthy	Hampshire	51.10^{O}N	1.26^{O}W
Mamhead (MH)	ADAS	Mamhead	Devon	50.62^{O}N	3.48^{O}W
Rosemaund (RM)	ADAS	Preston Wynne	Herefordshire	52.13^{O}N	2.64^{O}W
Sutton Bonington (SB)	University of Nottingham	Sutton Bonington	Nottinghamshire	52.83^{O}N	1.25^{O}W
High Mowthorpe (HM)	ADAS	Malton	Yorkshire	54.11^{O}N	0.64^{O}W
Edinburgh (ED)	SAC	Bush Estate	Edinburgh	55.87^{O}N	3.19^{O}W
Aberdeen (AB)	SAC	Craibstone	Aberdeen	57.34^{O}N	2.37^{O}W

Table M2. Agronomic treatments

Sites	2001	2002	2003
Bridgets	Nitrogen timing	-	-
Mamhead	-	Plant growth regulators	Rotational Position
Rosemaund	Slug control	Plant growth regulators	Rotational Position
Sutton Bonington	Nitrogen timing	Nitrogen timing	Nitrogen timing
High Mowthorpe	Plant growth regulators	Rotational Position	Disease control
Edinburgh	Slug control	Nitrogen timing	Slug control
Aberdeen	Plant growth regulators	Nitrogen timing	Nitrogen timing

Three levels of agronomic treatment were used at each site in each year (Table M3.). A split-plot design was used with agronomic input treatment as main plots and seed rate as sub-plots, replicated four times. The exception was SB where a split-split plot design was used with two levels of residual nitrogen as main plots, nitrogen application timing as sub-plots and seed rate as sub-sub plots.

Table M3. Agronomic input treatment details

	Main plot treatment number		
Treatment	1	2	3
Plant growth regulators	No PGR	PGR at Tillering	PGR at start of stem extension (GS 30/31)
Slug control	Sibutol treated seed - no slug control	Sibutol treated seed - slug pellet application immediately post drilling	Sibutol secur treated seed - slug pellet application immediately post drilling + follow up application(s) as necessary
Rotational Position	First wheat	Second/third wheat - no take-all seed treatment	Second/third wheat + take-all seed treatment (Latitude)
Nitrogen timing	Early Nitrogen application timing	Normal Nitrogen application timing	Late Nitrogen application timing
Disease control	T1+T2 treatments + Bravo 500 (1.5 l/ha) at GS30 (T0+T1+T2)	T2 treatment + Opus (0.5 l/ha) and Fortress (0.2 l/ha) at GS32 (T1+T2)	Opus (0.75 l/ha) and Corbel (0.5 l/ha) at GS39 (T2) only

Plot dimensions were 2 m wide by 24 m long, drilled with an ‘Oyjord type’ tractor mounted seed drill. Seed was supplied from a single batch each year with a common thousand grain weight. A standard single purpose seed dressing (Sibutol) was used except in the slug control and rotational position experiments where seed dressing was part of the agronomic input under investigation. Sowing dates were aimed to be typical of winter wheat sowings for the site (Table M4.).

Table M4. Sowing dates

	Sowing dates		
	2000/1	2001/2	2002/3
Bridgets (BR)	5 October	-	-
Mamhead (MH)	-	3 October	3 October
Rosemaund (RM)	4 October	23 September	23 September
Sutton Bonington (SB)	17 October	20 October	20 September
High Mowthorpe (HM)	14 November	23 September	27 September
Edinburgh (ED)	16 October	7 October	7 October
Aberdeen (AB)	6 October	23 September	27 September

Crop establishment was assessed pre-tillering with the number of plants counted in 5 x 1m row lengths per plot, chosen randomly. Plant population was calculated using the following equation:

Plants/m^2 = (Total number of plants in 5 m length of row)/ (5 x mean row width in m)

Leaf number and tiller production was assessed by counts on ten tagged plants per plot on three seed rates (40, 80, and 320). The number of main stem leaves were counted from the onset of tillering (GS21) until flag leaf emergence (GS39), at approximately 100^{o}C day intervals; and the number of potentially fertile shoots per plant until harvest.

Crop development was monitored by the date at which 50% of the shoots reached Zadoks growth stages 31, 39 and 61 recorded.

An assessment of the components of yield was made on hand-harvested samples taken immediately pre-harvest from an area of 1m^2. From these samples plant height, total biomass, shoot number/m^2, harvest index, number of spikelets per ear and thousand grain weight was established.

At the RM and SB sites additional measurements of canopy green area index, total biomass and light interception were taken. At RM light interception was assessed fortnightly using two ceptometers (Sunfleck meters). A hand harvested sample taken at GS 61 from 0.81 m^2 representative area from three seed rates (80, 160 and 320) were used to establish total biomass and canopy green area index. Green area index was measured using a digital image analysis system (Delta-T devices).

At Sutton Bonington, light interception was measured fortnightly using a Sunscan (Delta-T Devices). The Sunscan has a probe, similar to a ceptometer, that is used to measure light penetrating through the canopy. A simultaneous measurement of incident radiation is made from an above canopy reference. Growth analysis was carried out every four weeks on N3 plots (40, 80 & 320 at both residual N levels). A 0.72m^2 area was harvested from each plot and used to establish shoot number, total biomass and green area index (using a Licor leaf area meter). Both light measurements and growth analyses started in February and the final measurement was taken at GS61.

A plot combine harvester was used to measure the grain yield on each plot. A representative grain sample of 1 kg was sampled from each plot. After cleaning, part of this sample was used for determination of the moisture content and specific weight using either a Dickey John grain analysis meter or by oven drying and chondronometer. Grains were counted using a numigral grain counter and the thousand grain weight established.

The data for each site was analysed using analysis of variance for a split-plot analysis in Genstat to identify main factor effects of husbandry and seed rate, and if there was a significant interaction. An exponential-plus-linear fit was applied to the seed rate and yield data from each site either overall, or individually to each husbandry input if a significant interaction had been identified. The line was constrained to intercept with the origin, such that zero seed equated to zero yield. Using a ratio of seed cost to grain value of 4:1 the seed rate above which the rate of yield increase was no longer sufficient to cover increasing seed cost was calculated. This could be considered to be the minimum seed rate needed to get onto the flat part of the seed rate to yield response curve. Percentage establishment data was then interpolated from the closest seed rates to calculate the optimum plant population or minimum number of plants required to optimise margin over seed cost. This physiological approach considers the factors which affect the establishment rate element of the seed rate calculation to be different from those that effect the target plant population. To combine the two elements of the calculation into a single analysis would therefore compromise the accurate prediction of either.

A further Bayesian analysis was carried out which combined all the data from this project with the data from the previous HGCA-funded seed rate project reported by Spink *et al*. (2000) into a single analysis. This approach uses a formal statistical and economic method to combine the data from individual sites, and uses this analysis to predict the optimum seed rate for some future crop based on the variates included in the dataset. Because of the difficulty of assigning a cost to a plant and because the approach seeks to predict for some future crop the preferred approach was to predict optimum seed rate. The details of the approach taken are given in the chapter 'Bayesian estimation of optimum seed rates'.

1. The effect of site on the optimum plant population

1.1 Introduction

In previous plant population work a large effect of sowing date on the economic optimum plant population was observed. The accumulated thermal time above a base of $0^{o}C$ between sowing and the crop accumulating 50 effective vernalisation days (TTver) was shown to explain a significant proportion of the variation in minimum plant population required (Spink *et al.* 2000). It was hypothesised that altering the altitude or latitude at which a crop is grown will have a physiological effect similar to sowing date and the TTver function may be able to explain variation in the plant population required across sites and sowing dates. In order to test this hypothesis, in this project, six sites were chosen from Mamhead on the south Devon coast (50.6 ^{o}N) to Aberdeen in Scotland (57.3 ^{o}N). The experiments were of a split plot design with management factors as main plots and seed rate as sub-plots. Within each experiment there was one management treatment defined as standard practice for comparison between sites. The standard treatments were: standard farm practice slug control (pellets applied according to risk), stem extension plant growth regulator timing, first wheat rotational position, and normally timed first nitrogen fertiliser application.

1.2 Results

Crop establishment averaged 72%, although there was significant variation between sites, years and seed rates. Average establishment in the 2001 and 2003 seasons was similar at 68% and 67% respectively, but in the 2002 season establishment was significantly higher at 81% (Table 1.1). There was also a large variation in establishment between sites within each year, High Mowthorpe had consistently the best establishment, and the poorest establishment was in the Scottish sites, Edinburgh in the first year and Aberdeen in the last 2 years. The apparent poor establishment at the Aberdeen site in the last 2 seasons was not due to poor establishment *per se*, but to subsequent plant loss due to over-winter plant heave.

Establishment was generally higher at low seed rates than at high seed rates, across all sites and years 40 seeds per m^2 giving 17% greater establishment than 640 seeds. A proportion of this effect may be accounted for by the difficulty of estimating plant population at very low seed rates due to the patchy nature of the resulting crop, as indicated by the apparent establishments of over 100% of 40 seeds/m^2 at Rosemaund and High Mowthorpe in 2003. However, it still seems likely that a slightly higher establishment percentage can be expected at low compared to high seed rates due to a reduced auto-toxicity effect.

Table 1.1. Percentage establishment across all sites and years meaned across all set-up treatments.

Seed rate (No/m^2)	2001						
	Br	Rm	Sb	Hm	Ed	Ab	Mean
40	91	67	69	81	62	88	75
80	72	74	75	87	52	79	73
160	72	78	69	81	49	61	68
320	60	72	71	72	58	56	66
640	41	66	67	69	56	44	59
Mean	67	71	70	78	55	65	68
	2002						
	Mh	Rm	Sb	Hm	Ed	Ab	Mean
40	95	87	91	89	78	65	85
80	94	87	79	96	88	67	84
160	69	73	97	100	88	75	85
320	65	59	90	96	83	74	79
640	56	38	86	100	80	50	71
Mean	76	69	89	96	83	66	81
	2003						
	Mh	Rm	Sb	Hm	Ed	Ab	Mean
40	94	126	55	104	73	59	79
80	94	92	50	95	59	51	68
160	79	75	61	83	68	45	66
320	74	61	63	103	66	59	66
640	69	44	65	90	53	44	59
Mean	82	80	59	95	64	52	67

Mean grain yield in the first year was above average at 9 t/ha. There was significant variation between sites with Aberdeen averaging 7.4 t/ha and High Mowthorpe 11.3 t/ha (Table 1.2). At 9.7 t/ha the 320 seed rate gave the highest average yield across the sites and there was an average 2.2 t/ha yield loss between this and the lowest yielding seed rate (40 seeds). Increasing seed rate from 320 to 640 seeds resulted in no yield difference on average across the sites, but this was made up of slight yield losses at four sites and yield increases at two. Reducing the seed rate to 160 seeds/m^2

from 320 resulted in a significant yield loss at half of the sites (Edinburgh, High Mowthorpe and Rosemaund), no significant yield difference at Aberdeen and Bridgets and a significant yield increase at Sutton Bonington. Significant yield decreases were measured at all sites except Sutton Bonington when seed rates were reduced from 320 seeds to 80 and 40 seeds/m^2, at Sutton Bonington there was a significant yield increase, with 80 seeds/m^2 being the highest yielding seed rate.

Table 1.2 Grain yields (t/ha @ 85% dm) of standard treatments 2001

seed rate	Aberdeen	Edinburgh	Mowthorpe	Rosemaund	Sut. Bon	Bridgets	Mean
40 seeds/m^2	6.02	7.36	8.67	7.74	8.03	7.1	7.49
80 seeds/m^2	7.46	9.06	10.71	7.92	8.80	8.0	8.66
160 seeds/m^2	7.88	10.21	11.81	8.42	8.67	9.2	9.37
320 seeds/m^2	8.04	10.92	12.55	9.02	8.05	9.5	9.68
640 seeds/m^2	7.86	11.35	12.85	8.57	7.94	9.4	9.66
Mean	7.44	9.78	11.32	8.33	8.30	8.70	8.98
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
LSD	0.488	0.412	0.277	0.533	0.263	0.349	

Mean yield, and yield loss between 320 seeds and 40 seeds were similar in 2002 to 2001 (Table 1.3). There was much less variation in the average site yield than in the previous year, Aberdeen was still the lowest yielding site at 7.7 t/ha but the highest mean yield of 9.9 t/ha was produced at Sutton Bonington. The 320 seed rate only produced a significantly higher yield than the 160 at Aberdeen, Edinburgh and Rosemaund. At Sutton Bonington and Mamhead there were no differences between the yields achieved at 80, 160 or 320 seed rates. Increasing seed rate significantly above the norm to 640 seeds only resulted in a yield increase compared to 320 seeds at Aberdeen and Sutton Bonington. Comparisons of yield at 320 seeds per m^2 at Sutton Bonington compared to other seed rates should be treated with caution however as the 320 seed rate yield appears low compared with either the 160 or 640 seed rate yields. A 1 t/ha yield loss, from the maximum average yield of 9.84 t/ha achieved with 640 seeds was only achieved by reducing seed rate by 87.5% to 80 seeds/m^2.

Table 1.3 Grain yields (t/ha @ 85% dm) of standard treatments 2002

seed rate	Aberdeen	Edinburgh	Mowthorpe	Rosemaund	Sut. Bon	Mamhead	Mean
40 seeds/m^2	4.23	7.60	7.16	8.95	8.13	7.89	7.33
80 seeds/m^2	6.60	8.59	9.36	9.52	10.14	8.62	8.81
160 seeds/m^2	8.42	9.27	10.41	9.94	10.25	8.85	9.52
320 seeds/m^2	9.40	9.60	10.70	10.56	9.85	8.73	9.81
640 seeds/m^2	9.82	9.56	10.93	9.79	10.91	8.02	9.84
Mean	7.69	8.92	9.71	9.75	9.85	8.42	9.06
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
LSD	0.265	0.198	0.327	0.357	0.445	0.366	

Yields overall were 2 t/ha down in the third year compared to either of the previous two years. The highest yielding site was High Mowthorpe, as in the first year, with an average yield of 10 t/ha. In contrast to the two previous years Edinburgh was the lowest yielding site at just under 6 t/ha (Table 1.4). Despite the seasonal variation in absolute grain yield the effect of seed rate remained relatively constant. The yield difference between highest and lowest yielding seed rates was 2.7 t/ha and therefore comparable to the previous two years with differences of 2.3 and 2.5 t/ha respectively, although in this year the 640 seed rate produced the highest average yield.

Table 1.4 Grain yields (t/ha @ 85% dm) of standard treatments 2003

seed rate	Aberdeen	Edinburgh	Mowthorpe	Rosemaund	Sut.Bon	Mamhead	Mean
40 seeds/m^2	4.31	5.09	8.62	4.89	5.98	5.35	5.16
80 seeds/m^2	5.62	5.75	9.79	5.96	7.81	6.38	6.32
160 seeds/m^2	6.75	6.49	10.21	6.41	10.08	7.14	7.34
320 seeds/m^2	7.53	6.48	10.69	6.99	10.59	7.11	7.64
640 seeds/m^2	8.05	5.95	10.95	7.67	10.53	7.35	7.82
Mean	6.45	5.95	10.05	6.39	8.40	6.67	6.76
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
LSD	0.449	0.327	0.223	0.944	0.600	0.232	

For each site and year exponential-plus-linear response curves were fitted to the seed rate and yield data both individually for each main treatment and a single curve across all the data. Optimum plant populations were then calculated for the standard treatments (Table 1.5) as defined in the materials and methods section using spring establishment data. Calculated optima ranged from as low as 72 plants per m^2 at Rosemaund in the first year to 248 plants per m^2 at Aberdeen in the second year.

Table 1.5 Optimum plant population taken from a linear-plus-exponential fitted curve with a seed to grain price ration of 4:1

Site	**2001**	**2002**	**2003**
BR	115	-	-
MH	-	85	127
RM	72	84	120
SB	74	134	215
HM	161	195	127
ED	118	121	76
AB	85	248	127

Effective vernalisation date (EVD) and thermal time from drilling to EVD (TTver) were calculated as described in Spink *et al*(2000), and are shown in Table 1.6. The earliest date at which 50 effective vernalisation days were accumulated was 20th November at Sutton Bonington following a drilling on the 20th September in the third year. At the other extreme the crop at High Mowthorpe sown on the 14th November 2000 did not reach its EVD until 10th January of the following year. The number of calendar days between sowing and EVD averaged 59, with a range of 53 (achieved at SB and AB in the first year and ED in the third year) and 72 (at HM in the second year). The thermal time accumulated prior to vernalisation averaged 489 ^{o}C days, with a wide range from 253 ^{o}C days at HM in the first year to 730 ^{o}C days at RM in the second year.

Table 1.6. Sowing date, Effective vernalisation date (EVD), days from sowing to EVD and Thermal time accumulated between sowing and EVD above a base of 0^{o}C (TTver).

Site	Sowing date	EVD	Days sowing - EVD	TTver
BR	5/10/00	28/11/00	54	460
RM	4/10/00	27/11/00	54	457
SB	17/10/00	9/12/00	53	448
HM	14/11/00	10/1/01	57	253
ED	16/10/00	9/12/00	54	357
AB	6/10/00	28/11/00	53	355
MH	3/10/01	14/12/01	72	620
RM	23/9/01	29/11/01	67	730
SB	20/10/01	15/12/01	56	414
HM	23/9/01	1/12/01	69	540
ED	7/10/01	3/12/01	57	507
AB	23/9/01	23/11/01	61	593
MH	3/10/02	6/12/02	64	695
RM	23/9/02	23/11/02	61	619
SB	20/9/02	20/11/02	61	602
HM	27/9/02	22/11/02	56	465
ED	7/10/02	29/11/02	53	354
AB	27/9/02	21/11/02	55	439

The work reported in Spink *et al* (2000) showed a strong correlation between TTver and final leaf number on the main stem, when applied across sowing dates and seasons at one site. An objective of this project was to test this same relationship across sites at different latitudes and seasons. In this project a similar relationship was observed with an r^2 of 0.68 (Figure 1.1). However, a multiple regression between sowing date, latitude and final leaf number provided a tighter relationship:-

*Final leaf number = 52.9 – 0.04437 * sowing date – 0.51584 * latitude (r^2 of 0.81).*

Where sowing date is expressed as days from 1 January and latitude is expressed as degrees.

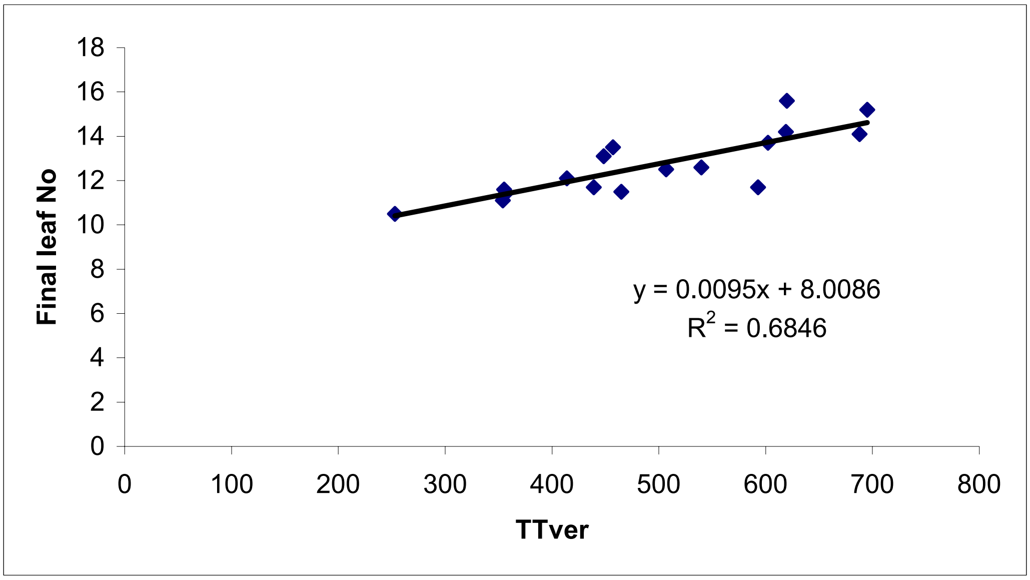

Figure 1.1. Relationship between final culm leaf number and Thermal time accumulated between sowing and 50 effective vernalisation days.

In the previous HGCA funded seed rate work (Spink *et al*. 2000) further correlations between culm leaf number and shoot number, and shoot number and optimum plant population were found. In this study no such relationships could be detected, neither was there a significant relationship directly between TTver and optimum plant population. Because of the strong effect of latitiude and sowing date on final leaf number, effects of latitude, sowing date and altitude and optimum population were tested for, but no combination explained a significant proportion of the variation in optimum population between the sites.

1.3 Discussion

Average establishment in the first and third years of these experiments was very similar to the average of 67% reported previously by Blake *et al* (2003), but was significantly better in the 2002 season, perhaps due to the relatively dry September for cultivations with plenty of moisture subsequently available in October. The improved establishment rate observed at lower seed rates seems to be a consistent effect observed previously in wheat (eg Spink *et al*. 2000), and in other species such as spring barley (eg Wade and Froment, 2003). It seems that if working from a target population back to a seed rate to drill using an expected establishment figure of 67% would be a reasonable starting point. Additionally, if using lower seed rates than normal improved rates of establishment may be expected.

Calculated optimum plant populations were similar or slightly higher than found in the previous work, late September or early October drillings at Rosemaund requiring 70-80 plants per m^2 in the first two seasons compared to 60 in 1997 and 1998 harvest years. The optimum from a late September drilling at Rosemaund was higher again in the 2003 season at 120 plants/m^2 although this was a take-all infected site.

The hypothesis at the start of the project was that the optimum plant population would be higher at more northerly latitudes. And that the accumulated thermal time above a base temperature of 0^oC between sowing and 50 effective vernalisation days may be used to explain effects of both sowing date and latitude on optimum plant populations. It was hypothesised that the mechanism by which this would operate would be that reduced thermal time would reducing culm leaf number, which in turn, would reduce the crops ability to tiller and compensate for reduced population. This project has demonstrated that there is a strong relationship between this variate and leaf number (r^2 = 0.68) indicating that the variate is physiologically meaningful, however there was no relationship through to optimum population. It is possible that the treatments imposed in these experiments, which were intended to impact on the crops ability to compensate for reduced population, or other site and season variables, have had such a large effect as to mask the crops innate physiological response due to latitude. Given that there was a strong relationship between leaf number and latitude and sowing date the absence of an overall effect of latitude on the optimum plant population is not surprising. There appeared to be consistent differences between sites that in terms of their location were hard to explain, for example the Edinburgh site produced relatively low optima (80-120 plants) but is located both at a high latitude 55.87^{o}N and altitude 190m above sea level. There were also large variations within sites, between years, for example at Sutton Bonington and Aberdeen the optima varied from 74-215 and 85-248 respectively between years. There also appeared to be large site and season interactions: In the second year there was a particularly dry spring which restricted water and nutrient uptake and crop growth, this was particularly severe down the east of the country and all four sites in the east had higher than expected optima. In the third year there appeared to a north south divide with the southerly sites producing higher than normal optima and the northerly sites relatively lower optima, possibly due to the very protracted emergence experienced at southern sites the previous autumn.

Whilst there was no consistent trend for optimum plant population with latitude, in more northerly or extreme environments there was a significant likelihood that a higher plant population would be needed. At more southerly sites such as Rosemaund Bridgets or Mamhead lower plant populations could be used with greater confidence as optima never exceeded 130 plants even where take-all or severe gout fly infestations occurred.

Whilst TTver did not explain variation in optimum plant population it did relate reasonably well to crop development in the form of final leaf number, which may be of use for example in predicting leaf emergence in relation to crop growth stage for accurate timing of fungicide inputs. As this variate is affected by factors other than latitude and sowing date, contour maps showing variation in TTver from three theoretical sowing dates for arable areas of England and Wales can be produced as in Figure 1.4.

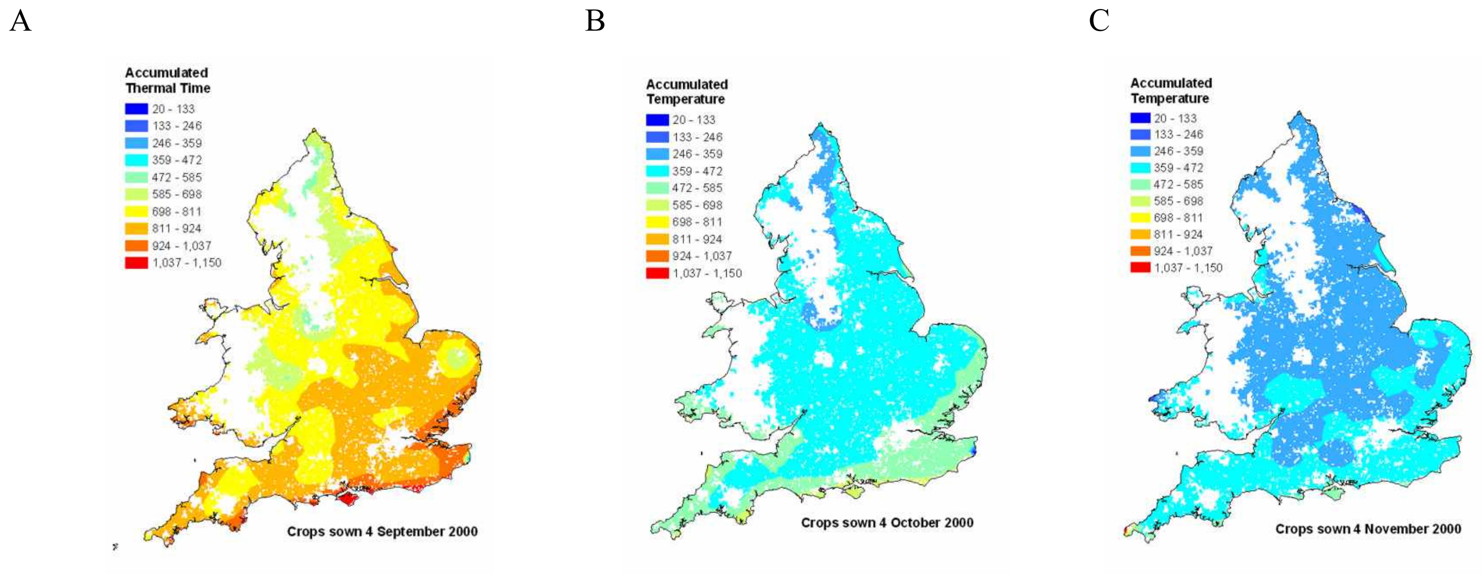

Figure 1.4. Accumulated thermal time from sowing on A – 4 September, B – 4 October, C – 4 November until 50 effective vernalisation days for the arable areas of England and Wales. Data provided by Dr. Moray Taylor, CSL from the Intermet project using the geostatistical analyst extension of the ArcGIS program v8.3, produced by ESRI (Redlands, California, USA).