

Developing Strategies for Spatially Variable Nitrogen Application in Cereals I: Winter Barley

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Abstract.

For precision agriculture to provide both economic and environmental benefits over conventional farm practice, management strategies must be developed to accommodate the spatial variability in crop performance that occurs within fields. Experiments were established in crops of winter barley (*Hordeum vulgare* L.) over three seasons. The aim of which was to evaluate a set of variable rate nitrogen strategies and examining the spatial variation in crop response to applied N. The optimum N application rate varied from 90 to in excess of 160 kg N ha⁻¹ in different parts of the field, which supports the case for applying spatially variable rates of N. This, however, is highly dependent on seasonal variations, e.g. the quantity and distribution of rainfall and the effect that this has on soil moisture deficits and crop growth. Estimates of yield potential, produced from either historic yield data or shoot density maps derived from airborne digital photographic images, were used to divide experimental strips into management zones. These zones were then managed according to two N application strategies. The results from the historic yield approach, based on three years of yield data, were inconsistent, and it was concluded that that this approach, which is currently the most practical commercial system, does not provide a suitable basis for varying N rates. The shoot density approach, however, offered considerably greater potential as it takes account of variation in the current crop. Using this approach, it was found that applying additional N to areas with a low shoot population and reducing N to areas with a high shoot population resulted in an average strategy benefit of up to 0.36 t ha⁻¹ compared with standard farm practice.

1 Introduction

Over the last few years, since the advent of precision farming technologies, the farming and research communities have undoubtedly provided overwhelming evidence of non-uniformity in yields at the within-field level (Stafford, 1997). It has been the purpose of research programmes to better understand the causes of inherent within-field variability and to offer appropriate remedial strategies. In so doing, precision farming aims to provide both economic and environmental benefits.

One of the most significant factors that can be varied by a farmer to influence the economics of arable cropping is nitrogen fertiliser application (Dampney *et al.*, 1998). However, the determination of specific rates is complex. In contrast; other factors, such as P and K, can be measured relatively easily, and areas with a low index can be topped up as needed using grain and straw off-take values as shown in Godwin and Miller (2001).

A number of studies (e.g. Carr *et al.*, 1991; Mulla *et al.*, 1992) have examined the potential for applying variable rates of fertiliser within fields to improve economic performance and minimise environmental impact. In addition, a range of approaches for determining management strategies for applying variable fertiliser have been examined including topography (Nolan *et al.*, 1995); soil sampling with grids (Vetsch *et al.*, 1995) and historic yield strategies (Kitchen *et al.*, 1995).

It has been proposed that yield maps can provide a useful basis for applying variable rates of fertiliser as they integrate soil, landscape, crop and climate factors together into an expression of relative productivity (Kitchen *et al.*, 1995). However, climatic factors can be

variable between seasons, particularly in the UK, which suggests that yield data may be specific to the conditions encountered in that particular season. One solution to this problem would be to devise strategies based on “real-time” information, that take account of variations in the current crop rather than previous crops.

The aim of this work was to evaluate a range of strategies for managing variable inputs of nitrogen based either on historic yield data or crop parameters assessed in “real-time”. Such information should provide an answer to the question often posed: once within-field variability in yield potential is identified, should more or less nitrogen be applied to the good areas of the field and the opposite to the poor? Moreover, it should assist in determining specific N application rates. In addition, the work provides an opportunity to quantify any spatial variation in crop response to applied nitrogen. These studies were conducted on both barley (the subject of this paper) and wheat (the subject of a sister paper by the same authors, Welsh et al (2001)).

2 Materials and Methods

2.1 Site details

Experiments were conducted over three seasons, from September 1997 to July 2000 in crops of winter barley (*Hordeum vulgare* L. cv. Fanfare) in Trent Field (8.76 ha), Andover (Ordnance Survey National Grid Reference SU 3705 4045), UK. In 1997/98 and 1998/99 the barley was grown for malting quality, whilst in 1999/00 the crop was managed as a feed crop. The crops were sown on 19 September 1997, 27 September 1998 and 07 October 1999 and harvested on 24 July 1998, 26 July 1999 and 27 July 2000.

The field has a cropping history of continuous winter barley and an average annual rainfall of 773 mm. The soil type is a silty clay loam over chalk and comprises two soil series: Andover series, which is a shallow, freely draining silty clay loam soil over chalk, with a topsoil of between 25 and 35 cm; and Panholes series, which is similar to Andover series but with a greater depth of soil overlying chalk, typically 40 to 60 cm (Fig. 1 and Fig. 2). The disturbed area in Fig. 1 relates to a disused railway siding that has subsequently been filled-in with imported rubble and topsoil, further details of which can be found in Earl *et al* (2001).

2.2 *Experimental design*

The experiments were completed using a strip-based approach similar to that of Mulla *et al.* (1992) and Kachanoski *et al.* (1996). The experimental design comprised five non-replicated variable N treatment strips, two non-replicated uniform N treatment strips and five standard N application rate strips (controls) to give a total of twelve strips. The strips were 12 m wide (half tramline width) and ran parallel with the tramlines along the length of the field, illustrations of which are given in Figs. 4 and 5. The treatment strip lengths ranged from 230 to 300 m depending on their position within the triangular-shaped field. This arrangement of strips was selected to allow a conventional 24 m pneumatic fertiliser spreader to be used for nitrogen application. The 12 m width also allowed one 6 m wide swath to be harvested by the combine without the inclusion of the area of the tramline wheel marks.

The standard nitrogen strips were inter-leaved with the variable nitrogen treatments, the purpose of which was threefold:

- (1) To enable the interpolation of a yield map based on the yield of the standard strips, which will indicate the inherent field variability.
- (2) To allow treatment comparisons to be made, since classical experimental design and statistical analyses with replicated plots is not possible.
- (3) To produce a spatial range of crop yield response curves from the yield response of adjacent non-standard nitrogen rate strips and the mean of their adjacent standard strips.

2.3 *Treatments*

Managing barley for low N malting quality requires that nitrogen application rates are optimised for grain nitrogen concentration rather than for maximum yield. The result of this is that the treatments will tend to be on the sensitive part of the nitrogen response curve as opposed to the plateau at maximum yield. The estimation of the ‘standard’ nitrogen application rate for the field (125 kg N ha^{-1}) was based on previous knowledge of nitrogen response curves for the same variety of malting barley (*cv.* Fanfare) on similar soil types, obtained from data collected by Arable Research Centres. This standard N rate also took account of the average soil mineral N level in Trent field, which was measured (0 – 60 cm depth) annually in February. Nitrogen rates for the treatments were then either increased or decreased by 30% of the standard. This range of nitrogen rates, based on the nitrogen response curves for this variety of barley on similar soil types, was selected to ensure significant levels of crop response. In the 1999/00 season, a decision was taken by the farmer to manage the crop for general market rather than for low nitrogen malting quality. This resulted in an increase of the “standard” rate from 125 kg N ha^{-1} to 160 kg N ha^{-1} .

Uniform treatments.

In addition to the standard rate there were two treatment strips with uniform applications of nitrogen of plus and minus 30% of the standard (i.e. in 1997/98 and 1998/99 the rates were 160 kg N ha⁻¹ and 90 kg N ha⁻¹, whilst in 1999/00 the rates were 205 kg N ha⁻¹ and 115 kg N ha⁻¹) along their complete length. The purpose of this was to provide an indication of the crop response to different levels of nitrogen in the high, average and low yield potential areas of the field. The location of the treatment strips was maintained for both cropping seasons, with the exception of one of the standard strips, which was replaced in 1998/99 and 1999/00 by a zero N strip to allow the calculation of apparent fertiliser N recovery rates and to provide an additional data point on the yield response to applied N response curve.

Variable treatments.

In order to address the question posed earlier, two nitrogen application strategies were tested:

- (1) More N on the 'good' areas, and less N on the 'poor' areas
- (2) Less N on the 'good' areas, and more N on the 'poor' areas

Before these strategies could be implemented, however, yield potential had to be estimated to define 'good' and 'poor' areas. This was achieved using two different approaches; historic yield and shoot density.

2.3.1 *Historic Yield (HY) approach.*

Variability in yield potential can be estimated from the analysis of a time series of historic yield maps, in this case, for the period 1995 to 1997.

Yield data from the combine harvester were first corrected for systematic errors (Blackmore and Moore, 1999) and then used to study the spatial and temporal stability trends

in yield within the field. To remove any seasonal effects, each annual yield map was normalised by expressing the yield as a percentage of the field mean. Areas of consistently high and low yield were then identified by taking the average of the three years' data. The 100% contour represents the three-year field mean (Fig. 3).

Having identified areas of consistently high, average and low yield, experimental strips were established to test the nitrogen application strategies 1) and 2). On historic yield-1 (HY1) the high potential area (>110% of field mean) received 30% more nitrogen; the average received the standard application rate and the low potential area (<90% of field mean) received 30% less nitrogen. The converse strategy was applied to the historic yield-2 (HY2) strip. The management zones were maintained for all cropping seasons.

2.3.2 *Shoot Density (SD) approach.*

Yield potential can also be estimated from shoot density maps (Wood and Taylor, 2001) derived from airborne digital photographic (ADP) images, taken immediately prior to the application of nitrogen (Figs. 4, 5 and 6). The Normalised Difference Vegetation Index (NDVI) was used as a surrogate to extrapolate ground measurements of crop structure (Taylor *et al.*, 1997).

Once the images had been acquired and calibrated with ground observations of shoot density, the treatment strips were divided into management zones of high, average and low shoot density. The decision on whether areas were high or low was based on relative differences in shoot density compared with the field average in each season.

In 1997/98, along the shoot density-1 strip (SD1) the areas of high shoot density received 160 kg N ha⁻¹ (30% more nitrogen); the average received the standard application rate

(125 kg N ha⁻¹) and the areas of low shoot density received 90 kg N ha⁻¹ (30% less nitrogen). The converse strategy was applied to the shoot density-2 (SD2) strip, as shown in Fig. 4.

In 1998/99, the original shoot-density treatment strips were relatively uniform and so alternative strips with considerably more variation were chosen. Furthermore, due to the distribution of shoot density, only high and average shoot density zones were established. Along shoot density-1 (SD1), the high-density zone received 160 kg N ha⁻¹ and the average zone received 125 kg N ha⁻¹. The treatments along shoot density-2 (SD2) comprised 90 kg N ha⁻¹ in the high-density zone and 125 kg N ha⁻¹ in the average zone (Fig. 5).

In 1999/00, the treatment strips were re-located back to their original 1997/98 positions. Along shoot density-1 (SD1), the high-density zone received 205 kg N ha⁻¹, the average zone received 160 kg N ha⁻¹ and the low-density zone received 114 kg N ha⁻¹. The treatments along shoot density-2 (SD2) comprised 115 kg N ha⁻¹ in the high density zone, 160 kg N ha⁻¹ in the average zone and 205 kg N ha⁻¹ in the low-density zone (Fig. 6).

The mean shoot density in each of the management zones for each season is summarised in Table 1.

2.4 *Fertiliser application*

In all seasons, the fertiliser was applied using standard farm-scale machinery. In 1998, the nitrogen fertiliser (Hydro Extran) was applied on 13 March using a Kuhn Aero pneumatic

spreader to ensure an even application rate. The results of the calibration study of fertiliser distribution along the boom gave a coefficient of variation (CV) of 11.5%, which confirms a very uniform distribution in comparison with other spreaders where CV's in excess of 20% are not uncommon (Culpin, 1992). In 1999, the fertiliser (Hydro Extran) was applied on 24 March using a Nodet pneumatic spreader. The Nodet had a very similar CV for fertiliser distribution along the boom (12.0%) compared with the Kuhn Aero. In 1999/00, a split programme of liquid N (Chafer Nuram 37) was applied with a Chafer sprayer using T-jet nozzles on 16 March and 25 April.

2.5 *Assessments*

In addition to the NDVI images acquired prior to N application, spatial plant and shoot population analyses were conducted, as described by Wood and Taylor, (2001), to calibrate NDVI images acquired throughout the growing season in December, March and May. On the basis of the soil and yield maps, neutron probe access tubes were installed in two zones, broadly corresponding with the Andover soil series in the west and Panholes soil series in the east. Volumetric soil moisture measurements were made on a regular basis using a neutron probe. Crop structure, plant tissue, grain quality and soil nutrient parameters were also measured.

The crop response to the standard and variable nitrogen applications was measured by harvesting along each of the strips and recording the final yield using a Massey Ferguson 38 combine equipped with a yield mapping system.

2.6 *Statistical analysis - accuracy of yield comparisons.*

The yield comparisons in this study are arithmetic means of sequences of consecutive yield monitor observations made whilst harvesting the whole plot with the combine at ‘steady state’ (i.e. after the appropriate ‘lead in’ to the plot) and using the full operational width of cut. Therefore, the errors in the estimated average plot-yields result from the error characteristics of the yield monitor and not from sampling, as in the case of quadrat observations. Moore (1998) measured the performance of the type of yield monitor used in the combine and showed that the monitor underestimated the average yield of fields by approximately 20 kg ha⁻¹ with the standard error of individual observations being equivalent to 155 kg ha⁻¹. Confidence intervals for the plot yields were then calculated for each of the sections; these ranged from ± 70 to ± 90 kg ha⁻¹, depending upon the number of yield observations in each of the sections.

Yield variation within each of the sections (e.g. high-yield zone) was expressed as the yield range about the mean yield for that section.

3 **Results**

3.1 *Rainfall and soil water*

The total annual rainfall in all seasons was considerably greater than the long-term average for this site (773 mm) (Table 2).

Also, the distribution of rainfall differed between seasons, such that the autumn/winter period (August – November) in 1997 was significantly drier than those of 1998 or 1999. The

spring/summer period (April – July) in 2000 was considerably wetter than both of the previous spring periods (Fig. 7 and Table 2).

Field capacity (FC) and permanent wilting point (PWP) were estimated from the soil physical properties for each of the soil series using pedo-transfer functions (Hall *et al.*, 1977), and, in the case of the Andover series, from experimental data of actual soil moisture release curves (Thomasson *et al.*, 1989). From this, estimates of the available water capacity (AWC) for each of the soil series were calculated (FC – PWP). The results showed that the Andover series (259 mm water in 1100 mm profile) had a considerably greater AWC than the Panholes series (196 mm water in 1100 mm profile). The total amount of water in the soil profile, to a depth of 1.1 m, determined from the clusters of access tubes in the east (Panhole series) and west (Andover series) of the field is given in Fig. 8.

In 1997/98, the profile water content for the Andover series remained within 70 mm of field capacity (maximum deficit = 27% of AWC), whilst the Panholes series dropped to 121 mm below field capacity (maximum deficit = 62% of AWC) towards the end of May (Fig. 7A). Therefore, although both soil series remained well above the permanent wilting point, it is likely that the crop in the Panholes series would have experienced greater moisture stress than that in the Andover series.

In contrast to 1997/98, both soil series in 1998/99 remained close to field capacity throughout the season (Maximum deficit: Andover = 8% of AWC; Panholes = 16% of AWC) (Fig. 7B).

In 1999/00, both series remained at field capacity until mid-June and then dropped to a maximum deficit of 22% of AWC in the Andover series and 25% of AWC in the Panholes series (Fig. 7C). Given the similarity in deficit in both soil series, it is unlikely that the crop would have experienced any difference in moisture stress between the soils. These results are compatible with the above-average rainfall that occurred in all of the cropping seasons (Fig. 7).

3.2 *Local yield response to applied N*

An example of the type of data collected by the yield monitor along the length of the treatment strip is given in Fig. 9. Data can be extracted to examine the yield response to different N levels in different parts of the treatment strips. In this case, the yield data from the Andover and Panholes soil series zones was extracted to produce response curves for each of the soil series (Fig. 10). It can be clearly seen that the yield shows some improvement through additional N in the Andover series zone, whilst in the Panholes series the standard N rate (dashed line) appears to be closer to the optimum, in terms of maximum yield. The yield data included the measurements made during the lead-in time of the combine as it filled with grain at the start of the treatment strips. These data were subsequently removed from the analysis (shaded area, Fig. 9).

Overall, the yields in 1998/99 (Fig. 9B) were considerably lower than those achieved in 1997/98 and 1999/00 (Figs. 9A and 9C). Fig. 9A illustrates a considerable difference in the optimum N application rate between the Andover and Panholes soil series zones. The Andover series zone shows the optimum (in terms of maximum yield) N rate is in excess of 160 kg N ha^{-1} , whilst in the Panholes zone, the optimum is closer to 125 kg N ha^{-1} . In the following seasons (Figs. 9B and 9C), however, the yield response in both zones is broadly

similar with an optimum N application rate in excess of 160 kg N ha⁻¹ in 1998/99 and 205 kg N ha⁻¹ in 1999/00. Given the similarity in yield response, it was not surprising to find that crops in both soil series zones had similar apparent fertiliser N recovery rates of 0.7.

3.3 *Variable nitrogen strategies*

Historic yield approach.

Using the same method as for the uniform treatment strips, yield data can be extracted from each of the historic yield management zones (Fig. 11) to provide yield response to applied nitrogen curves (Fig. 12).

In all seasons, the yield response to applied N was broadly similar in both the historically high and low yield zones, although different optimum N application rates were observed between seasons. In 1997/98, the optimum N application rate for maximum yield was in excess of 160 kg N ha⁻¹ in both zones (Fig. 11A). In 1998/99, the crop showed a much flatter response to increasing N application rate (Fig. 11B), with the optimum N rate being closer to 160 kg N ha⁻¹ in both zones. In 1999/00, the optimum N application rate for maximum yield was in excess of 205 kg N ha⁻¹ for both zones (Fig. 11C). From the shape of the response curves, however, it appears the low yield zone would probably have a lower optimum N rate than the high yield zone (Fig. 11C).

Therefore, there was no opportunity to reduce the N application rate below the standard rate for the field without suffering a yield penalty in any of the seasons. In terms of the nitrogen application strategies being tested, neither showed any benefit compared to a uniform application of N at the standard rate. This is summarised in Table 3. However, from

the data, it is possible to construct alternative strategies. For example, HY3 represents applying 30% additional N to the high yield zone, whilst applying the standard N rate to both the average and low yield zones. Alternatively, HY4 represents applying 30% additional N to the low yield zone whilst maintaining the standard N rate on the other areas. Both of these strategies result in a yield improvement compared with standard farm practice (Table 3). This suggests the best strategy would have been to increase the N rate uniformly along the strips. This is not surprising since the N application rates were selected to achieve low N malting quality rather than maximum yield.

Shoot density approach.

In contrast to the historic yield approach, assigning management zones according to shoot density appeared to offer much greater potential for applying variable N rates. Fig. 13 illustrates the yield along each of the treatment strips (TD1, Standard and TD2), which can be extracted to examine yield response to applied N in each of the management zones where different N rates were applied (Fig. 14).

In 1997/98, yield response to increasing N rates differed between the management zones (Fig. 13A). In the high shoot density zone, yield showed an inverse relationship to increasing N rate, whilst the opposite was true of the low-density zone. This result was due to crop lodging in the high shoot density areas, such that applying higher N rates tended to accentuate lodging. Therefore, in the high shoot density zone, the optimum N rate for maximum yield was approximately 90 kg N ha⁻¹, whilst in the low density zone the optimum rate was greater than 160 kg N ha⁻¹.

In 1998/99, when only two management zones were established, high and average shoot density, there was a positive yield response to increasing N rates in the high shoot density zone, with an optimum N application rate in excess of 160 kg N ha⁻¹ (Fig. 13B).

In 1999/00, three management zones were established, high, average and low shoot density. However, in contrast to 1997/98, the yield response to applied N was similar in both the high and low shoot density zones, with the optimum N application rate for maximum yield in excess of 205 kg N ha⁻¹ (Fig. 13C).

The mean yield response of the N application strategies are summarised in Table 4. In 1997/98, SD2 (30% additional fertiliser to the low shoot density area, 30% less fertiliser to the high density area and a standard application to the average areas) resulted in a benefit over standard farm practice of c. 0.21 t ha⁻¹. In 1998/99, however, the opposite strategy, SD1, resulted in the greatest benefit, such that yield in the high shoot density zone benefited from 30% additional fertiliser. The overall yield benefit of adopting the shoot density-1 strategy (SD1) was c. 0.32 t ha⁻¹ compared with standard farm practice. Similarly, in 1999/00, the shoot density-1 strategy (SD1) was also the most beneficial in terms of yield compared with standard farm practice; with a mean yield improvement of 0.36 t ha⁻¹.

3.4 *Spatial variability of yield response to applied nitrogen*

As well as testing a set of variable nitrogen application strategies, the data can be used to illustrate the spatial variability in crop yield response to applied nitrogen, as the data are taken from a number of locations within the field (Fig.15).

It is clear from this that yield response to applied N can vary within the field (Fig. 14B). However, this variation is highly dependent on season such that in 1998/99 (Fig. 14C) and 1999/00 (Fig. 14D) the yield response to nitrogen was almost identical in all areas of the field.

3.5 *Grain quality*

One of the key quality parameters for malting barley is the concentration of nitrogen in the grain. The ideal concentration of N in the grain is dependent on the market for which the barley is intended. The greatest premiums are paid for barley that has a grain N concentration of between 1.55 and 1.75% (HGCA, 2001). A lesser premium would be paid for barley with a grain N concentration of between 1.75% and 1.85%. Above this level, the barley would be sold for general market only. Also, a grain N concentration of below 1.55% would receive a reduced premium.

Fig. 16 shows the effect of nitrogen application rate on grain nitrogen concentration. In all seasons, the grain nitrogen concentrations remained below the 1.85% maximum threshold, even at the highest N rates. However, in only three cases would the barley have achieved its maximum premium. This suggests that the N application rates used could have been increased.

4 **Discussion**

From the local N response data, it is clear that there can be different optimum N application rates in different parts of the field. This, however, is highly dependent on seasonal variations. In 1997/98, the optimum N application rate for maximum yield on the Andover soil series was in excess of 160 kg N ha⁻¹, whilst on the Panholes series the optimum

was closer to 125 kg N ha⁻¹. In the following seasons, however, the yield in both areas exhibited similar responses to applied N. This may be attributed to differences in the quantity and distribution of rainfall and the influence this has on soil moisture. A large proportion of crop variability between soil types is explained by differences in moisture holding capacity (Moore and Tyndale-Biscoe, 1999). In 1997/98, there were considerable differences in soil moisture deficit between the soil series such that the crop in the Panholes series would have experienced greater moisture stress than that in the Andover series. The result of this can be seen in the final yields achieved in the different soil series zones, where the maximum yield in the Panholes zone was approximately 1 t ha⁻¹ lower than that in the Andover zone. In 1998/99 and 1999/00, however, the soil moisture deficits were generally lower than 1997/98 and, within each season, both soil series had similar soil moisture deficits. This is reflected in the similarity of N response and maximum final yields achieved in both soil series.

Using historic yield trends as the basis for varying N rates produced inconsistent results. In general, the most effective strategy would have been a uniform application of N, regardless of previous yield. It might be argued that the relative differences in yield between the management zones were too small and that the crop would not have been expected to differ given this range. However, a more fundamental argument against using this approach for determining an N application strategy would be that no account is taken of the conditions in the current crop. It is clear that season to season variation in climatic conditions (e.g. Fig. 7) can be large, which will have an effect on crop development and performance (e.g. Table 1), but this approach tends to “smooth” out this variation, relying instead on an average performance figure (i.e. the mean values from a series of yield maps). Therefore, for this reason, the use of historic yield data as a basis for varying N application rates is not recommended. This result is compatible with the findings of Dampney *et al.*, 1999 and Davis

et al., 1996. Historic yield data may be more useful as a basis for applying other inputs, such as P and K, where a replenishment strategy could be employed, having first established that the nutrients are not deficient. In addition, historic yield maps may provide a suitable basis for stratifying fields to identify targeted sampling positions for the assessment of soil physical or chemical parameters.

The shoot density approach offers considerably more potential as a basis for varying N rates as it takes account of conditions in the current crop. In 1997/98, the SD2 strategy (less on the ‘good’, more on the ‘poor’) resulted in a benefit of approximately 0.21 t ha⁻¹ compared with standard farm practice. This negative response to increasing N rate in the ‘good’ or high shoot density area was due to crop lodging. The very high shoot density is likely to have resulted in poorer rooting, a situation that would have been further aggravated by high N rates which tend to increase the canopy size and weaken the stems (HGCA, 1999). The combination of these factors resulted in the observed lodging. By reducing the N rate in this ‘good’ zone, canopy size was restricted and the lodging risk reduced. In the following seasons, however, it appeared that the opposite strategy was best, with the SD1 strategy resulting in a benefit of 0.32 t ha⁻¹ in 1998/99 and 0.36 t ha⁻¹ in 1999/00. These conflicting results may be explained by the way that the management zones were defined. In this series of experiments, the shoot density zones were defined as high or low relative to the field average in each season, figures for which are given in Table 1. This resulted in a situation where, in one season, high density was defined as being a shoot population of *c.* 1650 shoots m⁻², whilst in another, 1024 or 1270 shoots m⁻² were regarded as “high”. If the criteria for defining shoot density in 1997/98 had been applied to 1998/99 and 1999/00, the entire strips would have been re-classified as low density and, as such, the recommendation would have been a uniform application of N at the higher N rate (30% additional N). This would have

meant that the SD2 strategy would have been the most effective. The lower shoot populations encountered in 1998/99 and 1999/00 probably resulted from poorer establishment as a consequence of seedbed and subsequent growing conditions being adversely affected by the relatively high rainfall during this time.

The logical progression of the shoot density approach is to use more objective criteria for defining whether a shoot population is high or low. For winter wheat, the Wheat Growth Guide (HGCA, 1998), provides guidelines for managing shoot populations and canopy development, and so provides the basis for defining management zones. Unfortunately, there is not a similar publication for barley, although, given some experience of managing a crop in this way, it is possible to elucidate where the boundaries between high, average and low shoot populations should be. From our limited data, i.e. only one site over three seasons, it would appear that the boundaries for winter barley (*cv* Fanfare), when assessed in March, would be:

Low shoot density	< 1300 shoots m ⁻²
On-target	1300 – 1600 shoots m ⁻²
High shoot density	> 1600 shoots m ⁻²

This, however, is likely to be highly dependent on climatic conditions, e.g. rainfall, and other crop management inputs such as crop growth regulators.

In terms of both grain quality and final yield, it is clear that the standard N application rate (125 kg N ha⁻¹) used in the first two seasons was probably too low (but at the time considered correct for the grain quality that existed) and that 160 kg N ha⁻¹ would have been more

appropriate. However, from the first season's data it was found that increasing N rates to 160 kg N ha⁻¹ had the potential to result in crop lodging. Therefore, based on this, it seemed logical to maintain the standard N rate for the next season. Following this, it was very apparent that there was scope to apply more N without adversely affecting grain yield or grain quality and so in the final season a higher standard N rate was applied. This highlights an important problem for managing nitrogen. The approaches that have been employed can assist in determining how the nitrogen should be distributed within the field. They do not provide an optimum N application rate, which is affected by a range of factors including climatic conditions and other crop management inputs.

Overall, it is clear, that given significant seasonal differences, it is essential that “real-time” information, such as airborne digital photographic images, be used for managing inputs of nitrogen, where account can be taken of growing conditions in that particular season. With these responses the return from variable management of nitrogen should outweigh the costs for farmed areas of 250 ha or greater as shown in Godwin et al (2001).

5 Conclusions

The crop response to applied nitrogen can vary spatially within the field when there is a significant difference in soil moisture deficit between soil series. When soil moisture deficits are similar, this variation is not present. Therefore, crop response to applied N is highly dependent on the distribution and total quantity of rainfall in any given season.

Variations in crop structure can be monitored in near “real time” by remote sensing, which enable mid-season agronomic decisions to improve crop performance.

Historic yield data are important for establishing areas of consistent over and under, performance and provide a means to target investigations and sampling. Their use, however, as a basis for applying spatially variable nitrogen is not proven.

According to the shoot density approach, applying additional N to areas of low shoot density and reducing N to areas of high density is the most effective strategy. Using this approach, yield benefits in the region of 0.3 t ha⁻¹ were achieved in comparison with standard farm practice.

The economic benefits resulting from the shoot density approach ranged from £14 to £23 ha⁻¹ compared with standard farm practice, once adjustments are made for the quantities of N used.

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Figures for:

**Developing Strategies for Spatially Variable Nitrogen Application in
Cereals I: Winter Barley**

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Knight²

Table 1
Shoot density in the high, average and low-density zones in 1997/98 (10-Mar-98),
1998/99 (15-Mar-99) and 1999/00 (15-Mar-00)

<i>Season</i>	<i>Shoot Density (shoots m⁻²)</i>					
	<i>High Density Zone</i>		<i>Average Density Zone</i>		<i>Low Density Zone</i>	
	<i>Mean</i>	<i>Standard Deviation</i>	<i>Mean</i>	<i>Standard Deviation</i>	<i>Mean</i>	<i>Standard Deviation</i>
1997/98	1650	93	1400	95	1300	110
1998/99	1024	64	950	75	n/a	n/a
1999/00	1270	171	1070	174	760	184

Table 2
Rainfall distribution at Trent Field in 1997/98, 1998/99 and 1999/00

<i>Season</i>	<i>Rainfall Distribution (mm)</i>			<i>Total (mm)</i>
	<i>Aug - Nov</i>	<i>Dec - Mar</i>	<i>Apr - Jul</i>	
<i>1997/98</i>	349	314	303	966
<i>1998/99</i>	412	269	249	930
<i>1999/00</i>	416	274	456	1146

Table 3.
The mean yield response of the historic yield nitrogen application strategies
compared with standard farm practice (S.F.P.) in 1997/98, 1998/99 and 1999/00

<i>Strategy</i>	<i>Season</i>					
	<i>1997-98</i>		<i>1998-99</i>		<i>1999-00</i>	
	Yield (t ha ⁻¹)	Ave. N Rate (kg N ha ⁻¹)	Yield (t ha ⁻¹)	Ave. N Rate (kg N ha ⁻¹)	Yield (t ha ⁻¹)	Ave. N Rate (kg N ha ⁻¹)
HY1	7.76	124	6.44	124	8.02	159
HY2	7.60	126	6.57	126	7.84	161
HY3	8.01	133	6.59	133	8.47	170
HY4	8.05	135	6.71	135	8.52	173
S.F.P	7.87	125	6.57	125	8.29	160

Confidence intervals for the mean yields range between $\pm 0.07 - 0.09$ t ha⁻¹.

Table 4
The mean yield response of the relative shoot density N application strategies
compared with standard farm practice (S.F.P.) in 1997/98, 1998/99 and 1999/00.

<i>Strategy</i>	<i>Season</i>					
	<i>1997-98</i>		<i>1998-99</i>		<i>1999-00</i>	
	<i>Yield</i> <i>(t ha⁻¹)</i>	<i>Ave. N Rate</i> <i>(kg N ha⁻¹)</i>	<i>Yield</i> <i>(t ha⁻¹)</i>	<i>Ave. N Rate</i> <i>(kg N ha⁻¹)</i>	<i>Yield</i> <i>(t ha⁻¹)</i>	<i>Ave. N Rate</i> <i>(kg N ha⁻¹)</i>
SD1	7.13	110	6.92	142	8.27	177
SD2	7.79	140	6.51	108	7.81	143
S.F.P	7.58	125	6.60	125	7.91	160

Confidence intervals for the mean yields range between $\pm 0.07 - 0.09 \text{ t ha}^{-1}$.

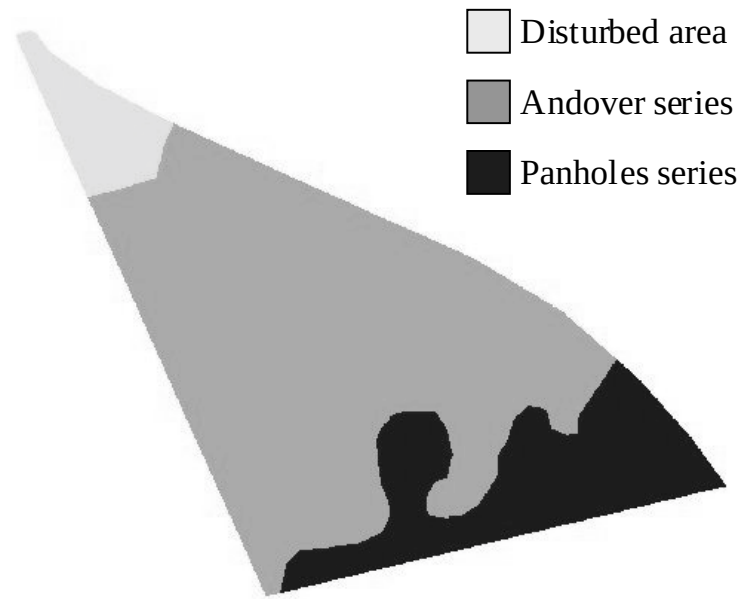


Fig. 1. Map of Trent field (8.76 ha) showing distribution of soil series. (Map courtesy of Soil Survey and Land Research Centre, Silsoe)

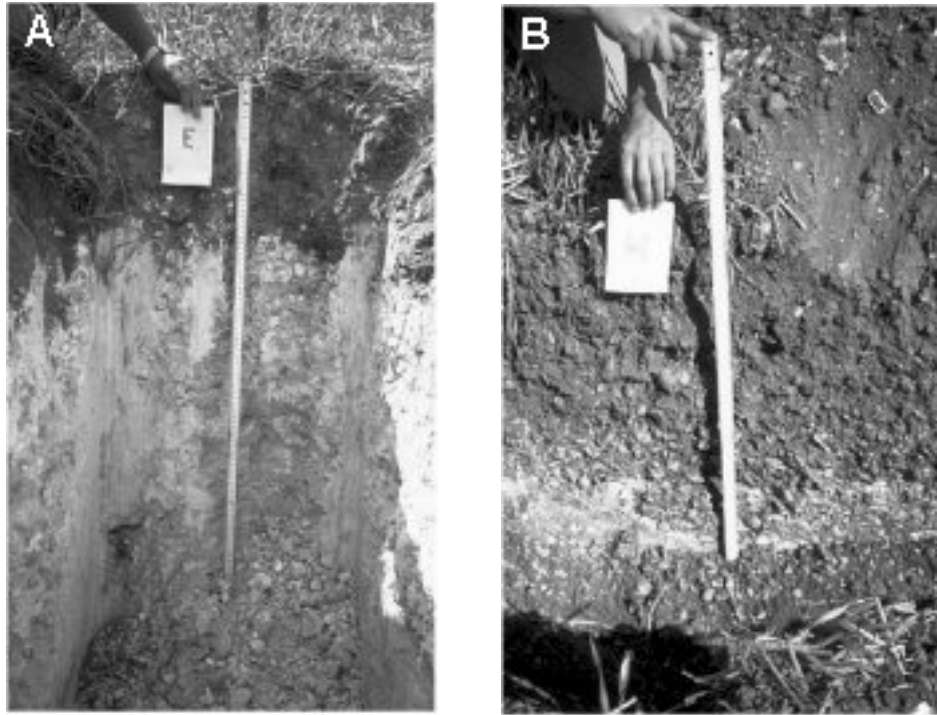


Fig. 2. Soil profile pits showing (A) Andover and (B) Panholes soil series

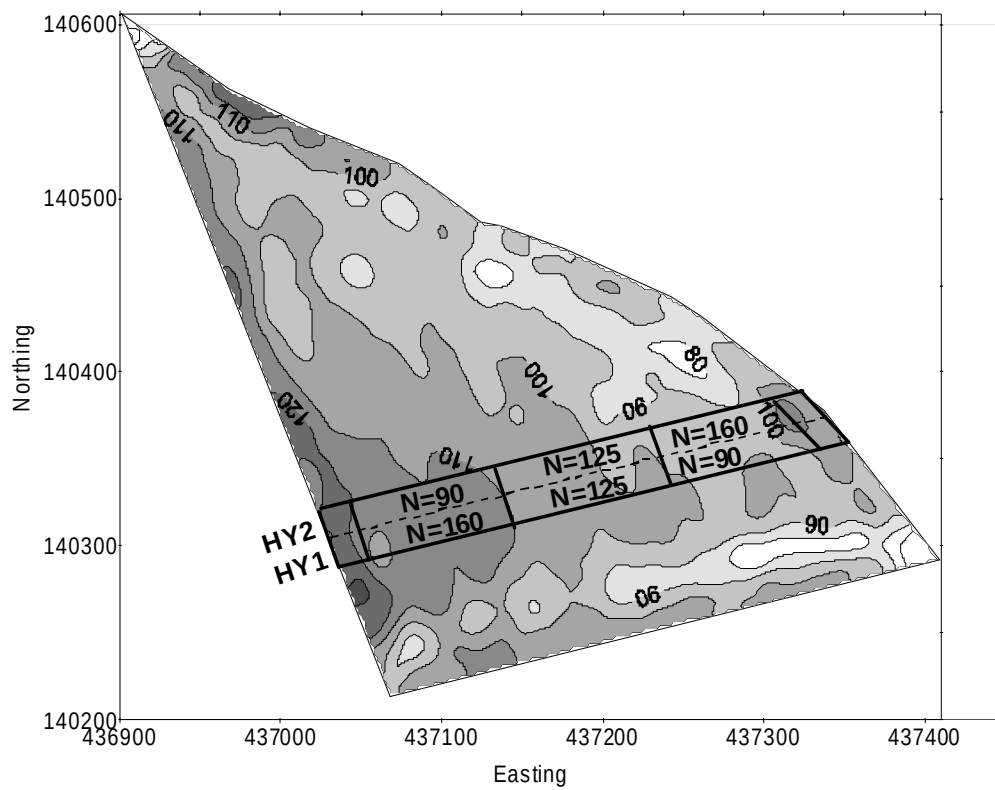


Fig. 3. Historic yield distribution in Trent field expressed as a percentage of the three-year average derived from three years' of yield maps (1995 – 1997). HY1 and HY2 refer to treatment strips and N=90, 125, 160 refers to the nitrogen application rate in kg N ha^{-1}

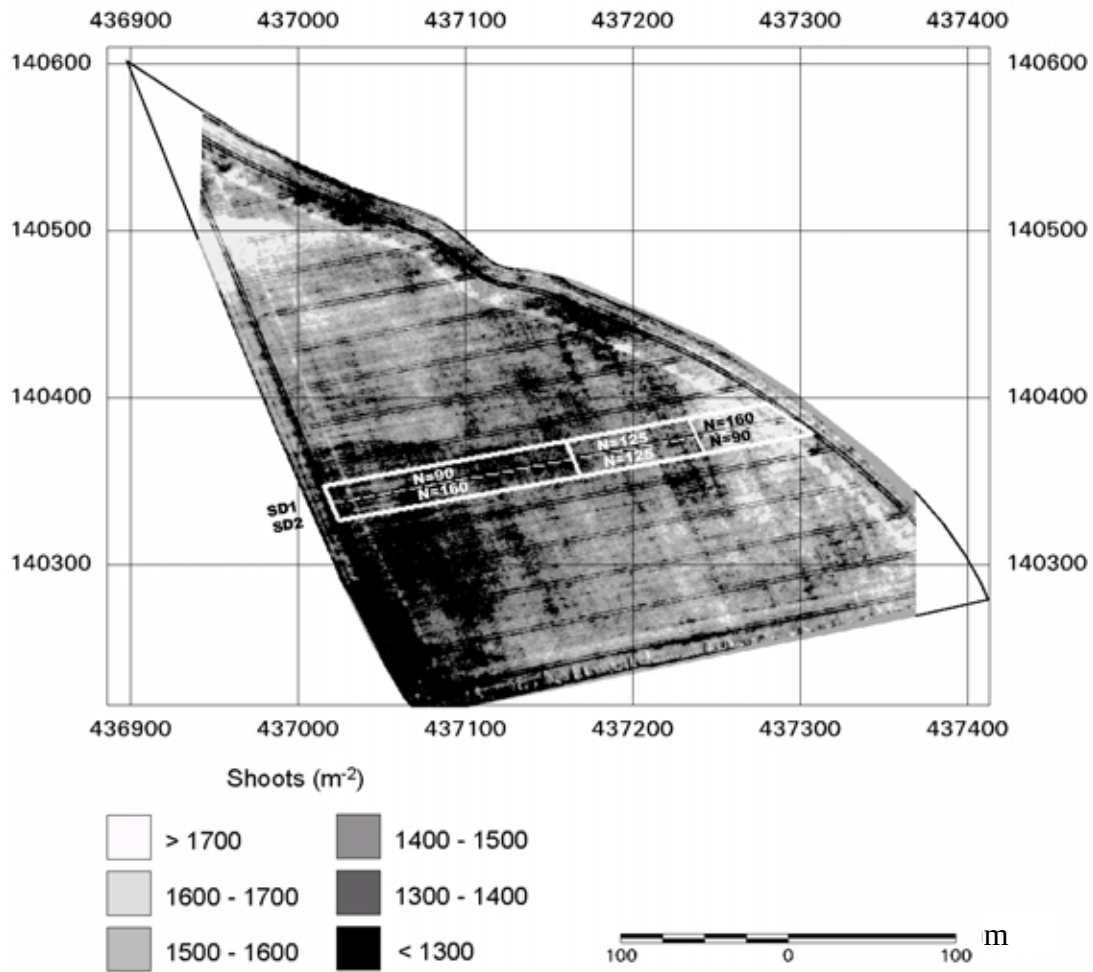


Fig. 4. Aerial Digital Photography (ADP)-derived shoot density map (accuracy of calibration: $r^2 = 0.98$; Standard error = 47 shoots m^{-2}) showing treatment strips and corresponding N application rates. Image acquired 05 March 1998 (calibrated 10 March 1998). 90, 125, 160 refers to the nitrogen application rate in $kg\ N\ ha^{-1}$

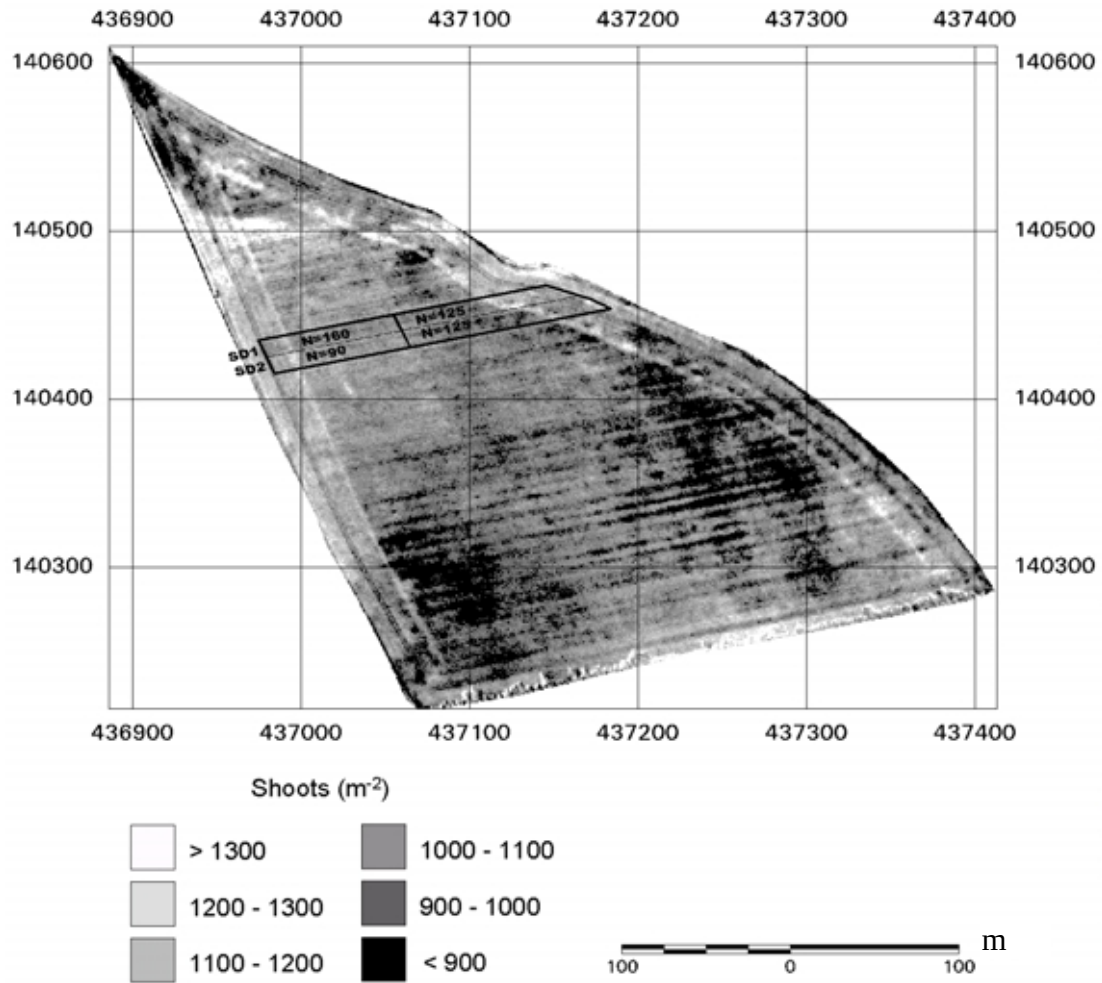


Fig. 5. Aerial Digital Photography (ADP) -derived shoot density map (accuracy of calibration: $r^2 = 0.9$; Standard error = 89 shoots m^{-2}) showing treatment strips and corresponding N application rates. Image acquired 14-Mar-1999 (calibrated 15 March 1999). 90, 125, and 160 refers to the nitrogen application rate in kg N ha^{-1}

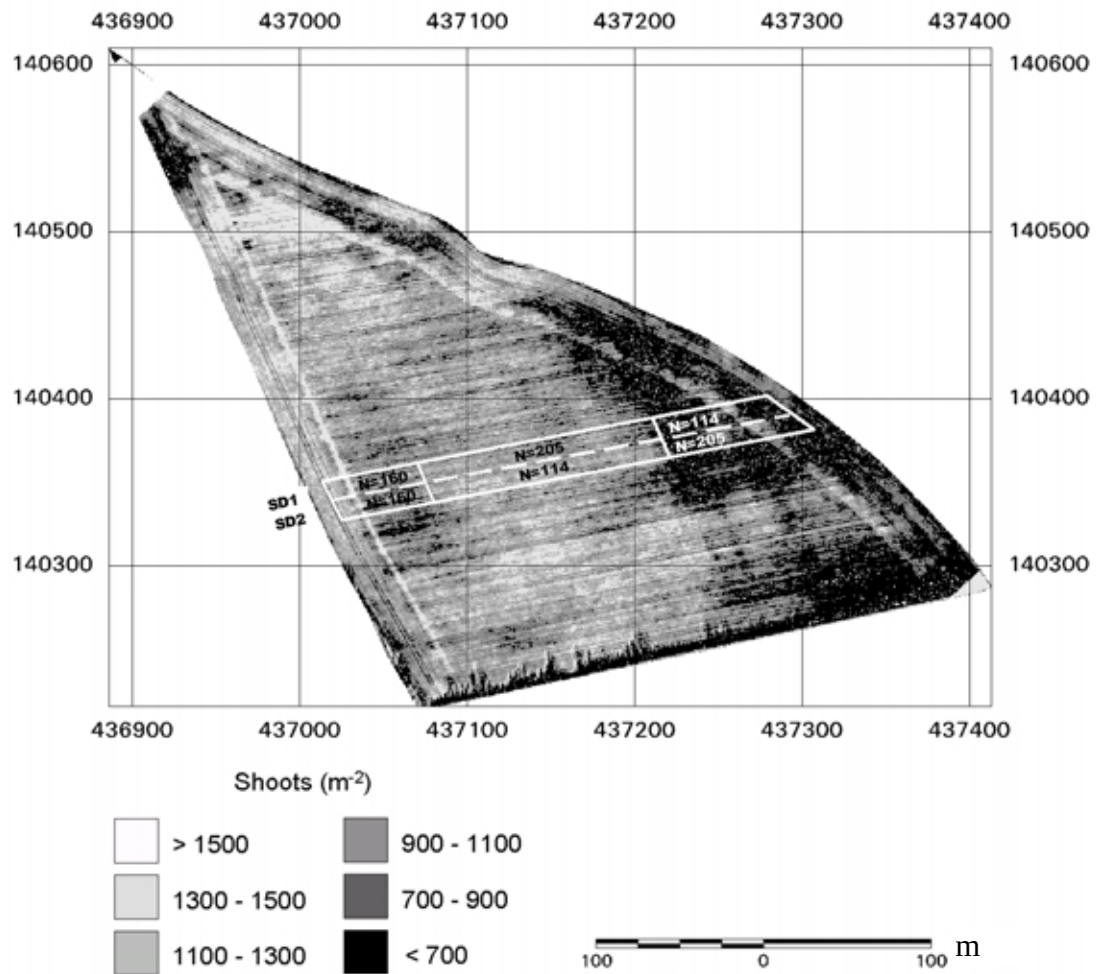


Fig. 6. Aerial Digital Photography (ADP) - derived shoot density map (accuracy of calibration: $r^2 = 0.5$; Standard error = 360 shoots m^{-2}) showing treatment strips and corresponding N application rates. Image acquired 02 Feb 2000 (calibrated 11 Feb 2000). 114, 160, and 205 refer to the nitrogen application rates in kg N ha^{-1}

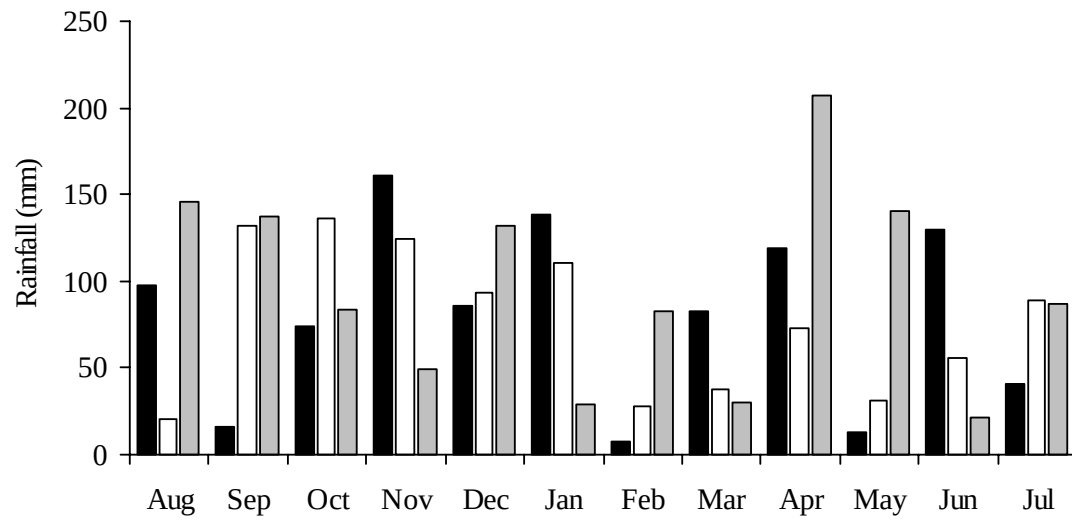


Fig. 7. Distribution of rainfall at Trent Field in 1997/98, 1998/99 and 1999/00: ■, 1997/1998; □, 1998/1999; ▒, 1999/2000

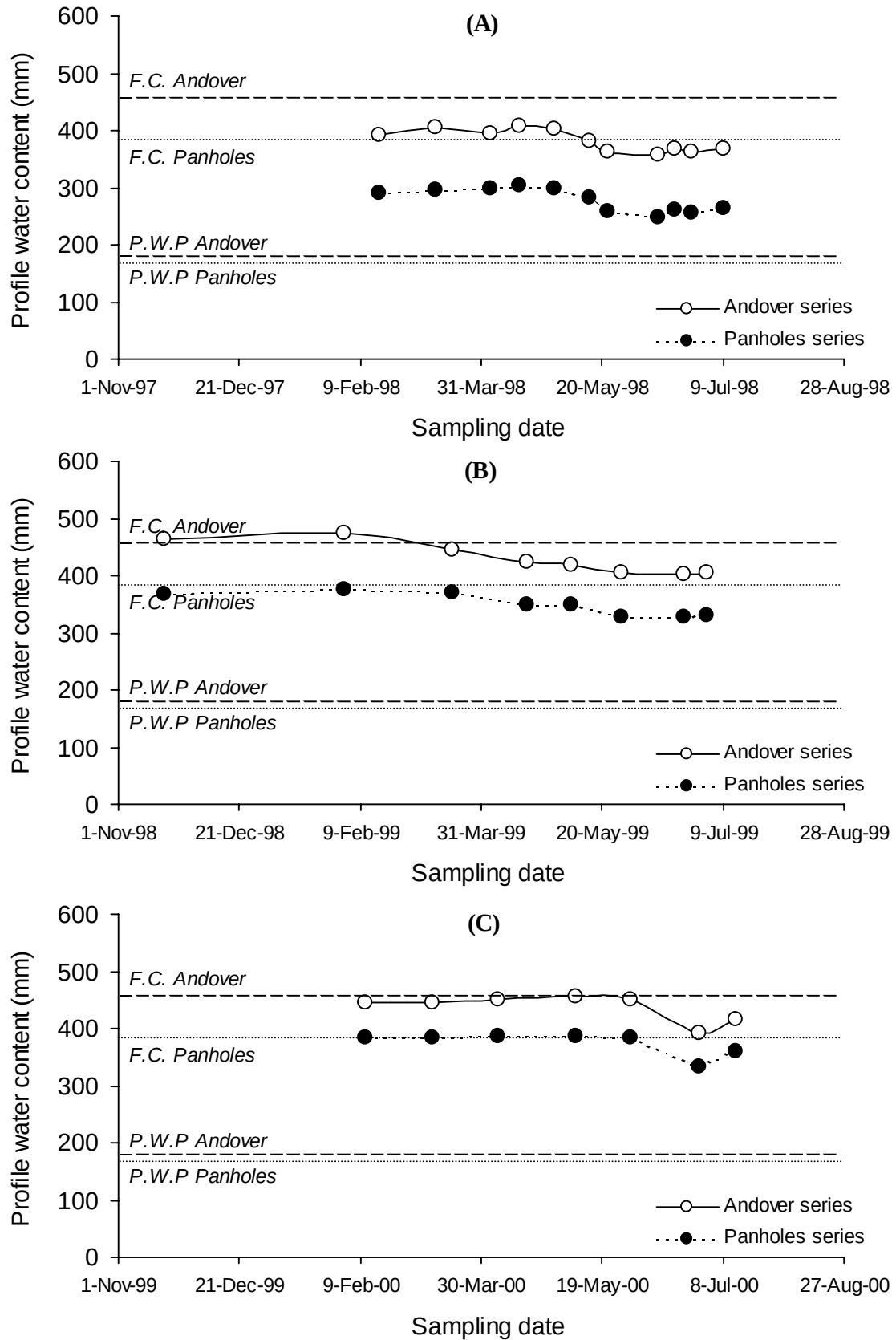


Fig. 8. Soil moisture content (mm water in 1.1 m profile) in the Andover and Panholes soil series in Trent field in (A) 1997/98, (B) 1998/99 and (C) 1999/00: -●-, Andover series; -○-, Panholes series; F.C. = Field Capacity; P.W.P. = Permanent Wilting Point

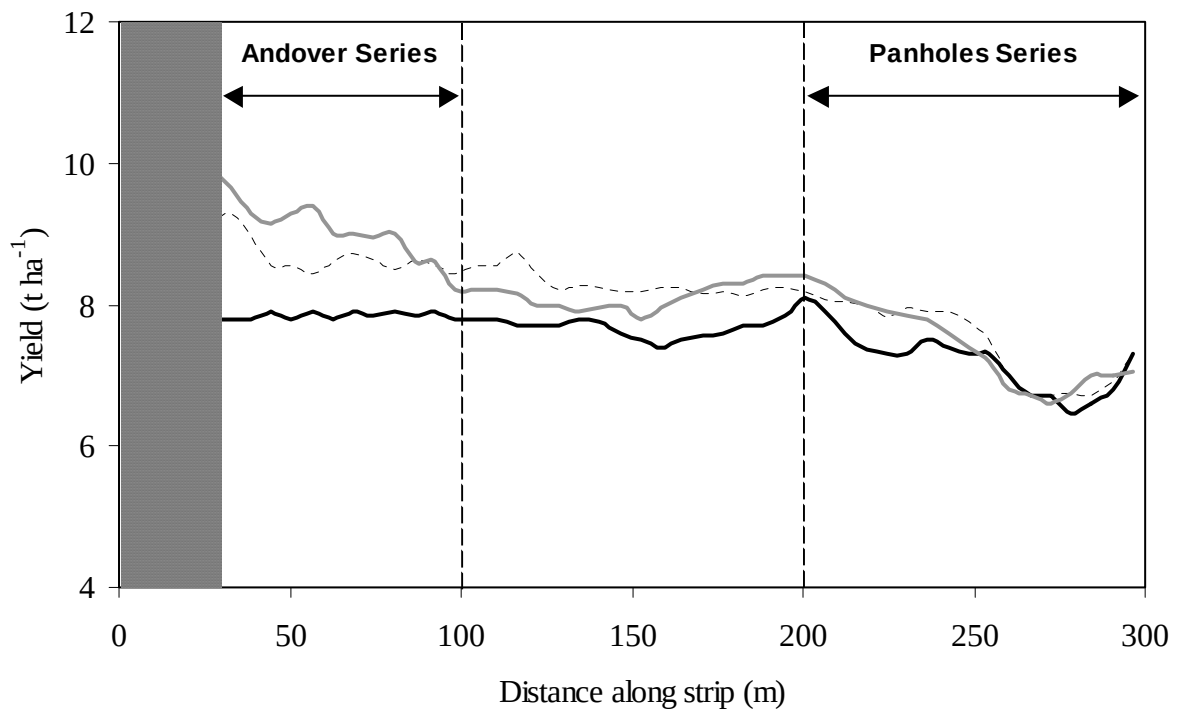


Fig. 9. Combine Yield (t ha^{-1}) of N response treatment strips in 1997/98. Shaded area represents lead-in time of combine harvester: —, 90 kg N/ha; -----, 125 kg N/ha; —, 160 kg N/ha

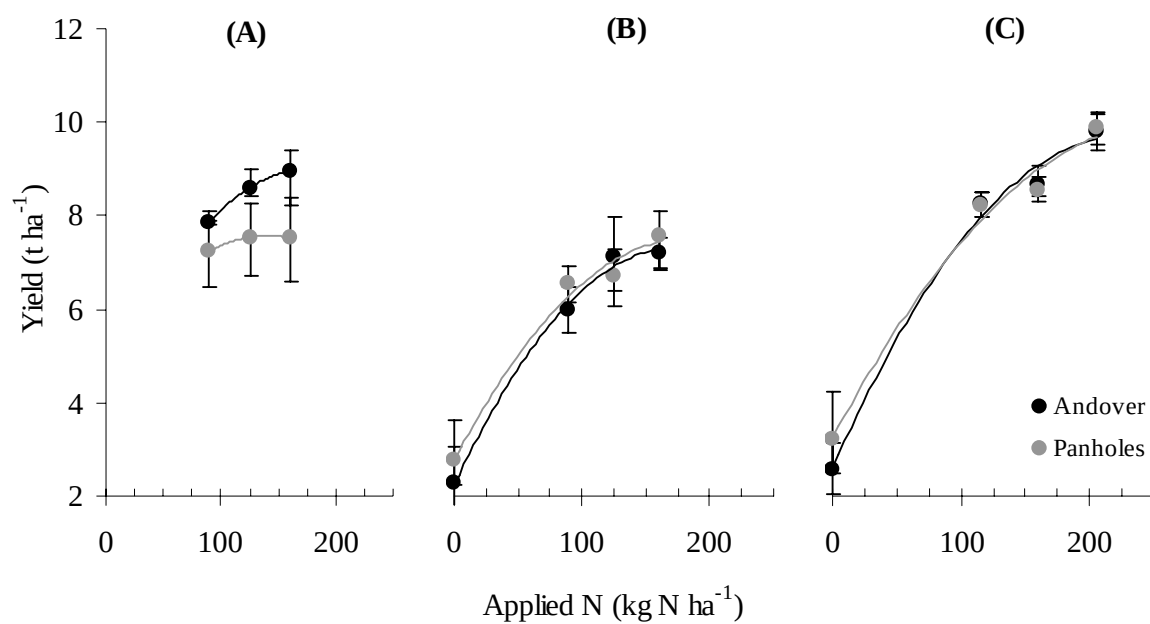


Fig. 10. Yield response to applied N in the Andover and Panholes soil series zones in (A) 1997/98, (B) 1998/99 and (C) 1999/00. Error bars denote the yield range about the mean: ●, Andover; ●, Panholes

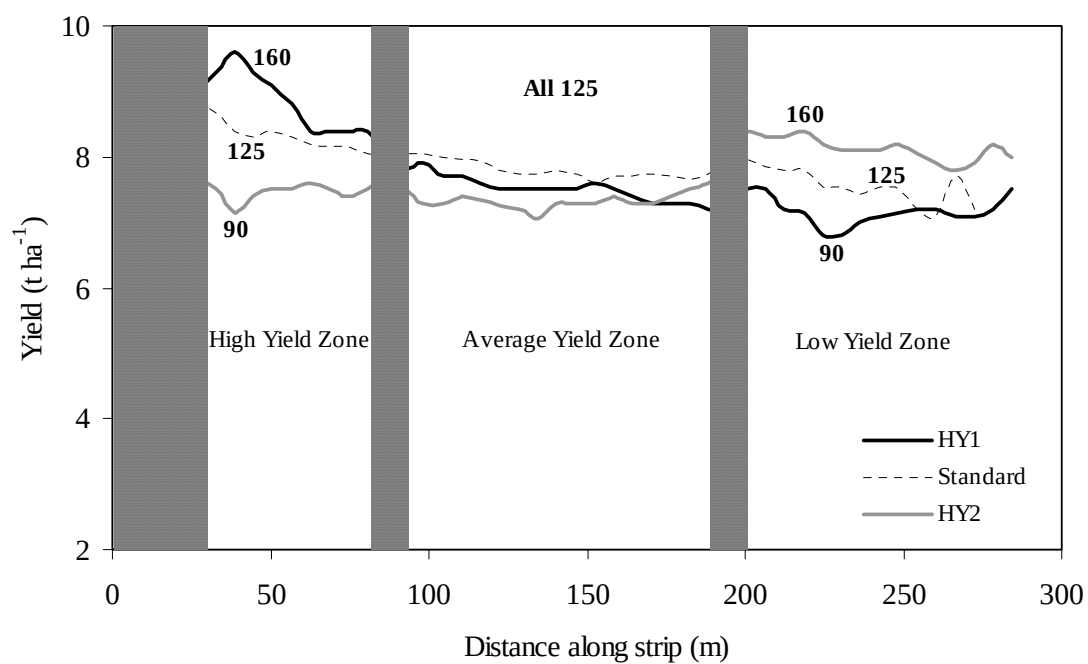


Fig. 11. Combine Yield (t ha^{-1}) of the Historic Yield (HY) strategy treatment strips in 1997/98. Shaded area represents lead-in time of combine harvester. Numbers in bold (90, 125, 160) are the N application rate in kg N ha^{-1} : —, Historic yield 1; - - - - - , Standard; — , Historic yield 2

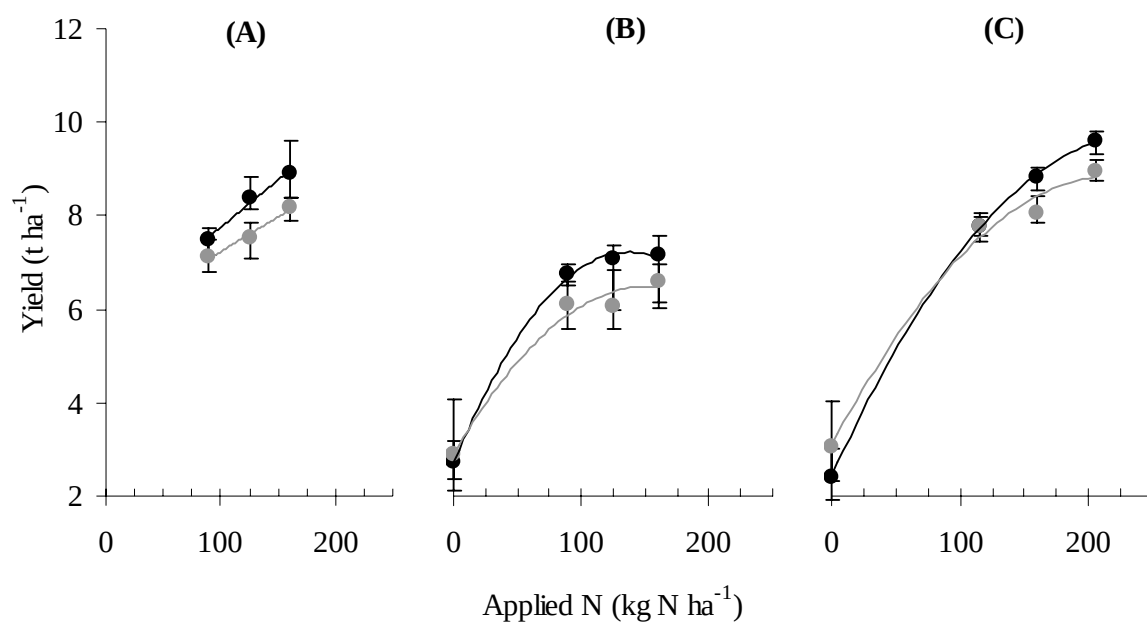


Fig. 12 Yield response to applied N in the high and low yielding parts of the field in (A) 1997/98, (B) 1998/99 and (C) 1999/00. Error bars denote the yield range about the mean yield for each N rate in each management zone: ●, High yield zone; ●, Low yield zone

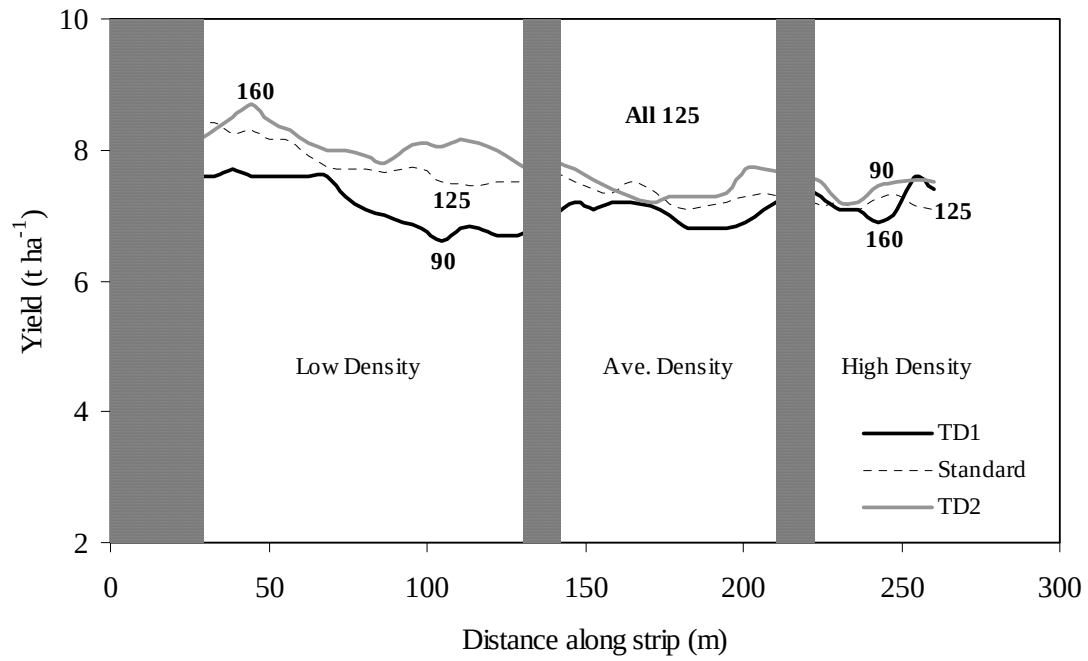


Fig. 13 Combine Yield (t ha^{-1}) of the Historic Yield (HY) strategy treatment strips in 1997/98. Shaded area represents lead-in time of combine harvester. Numbers in bold (90, 125, 160) are the N application rate in kg N ha^{-1} : —, “Strip TD1”; -----, Strip “Standard”; —, “Strip TD2”

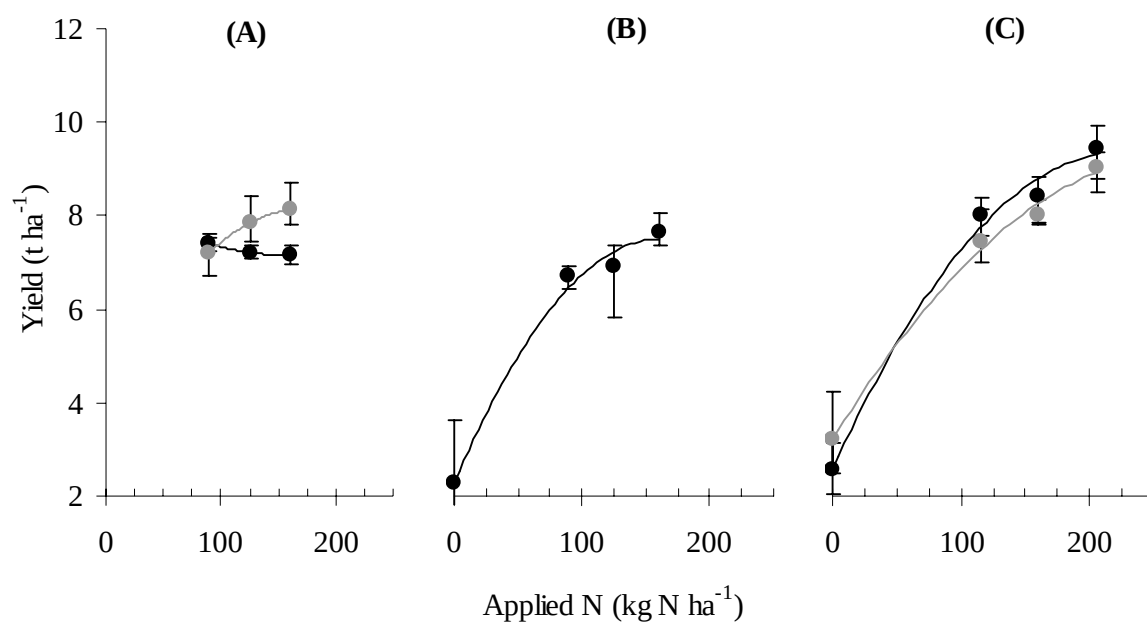


Fig. 14 Yield response to applied N in areas of the field with either a relatively high or low shoot density, compared with the field average in (A) 1997/88, (B) 1998/99 and (C) 1999/00. Error bars denote the yield range about the mean yield for each N rate in each management zone: ●, High yield zone; ●, Low yield zone

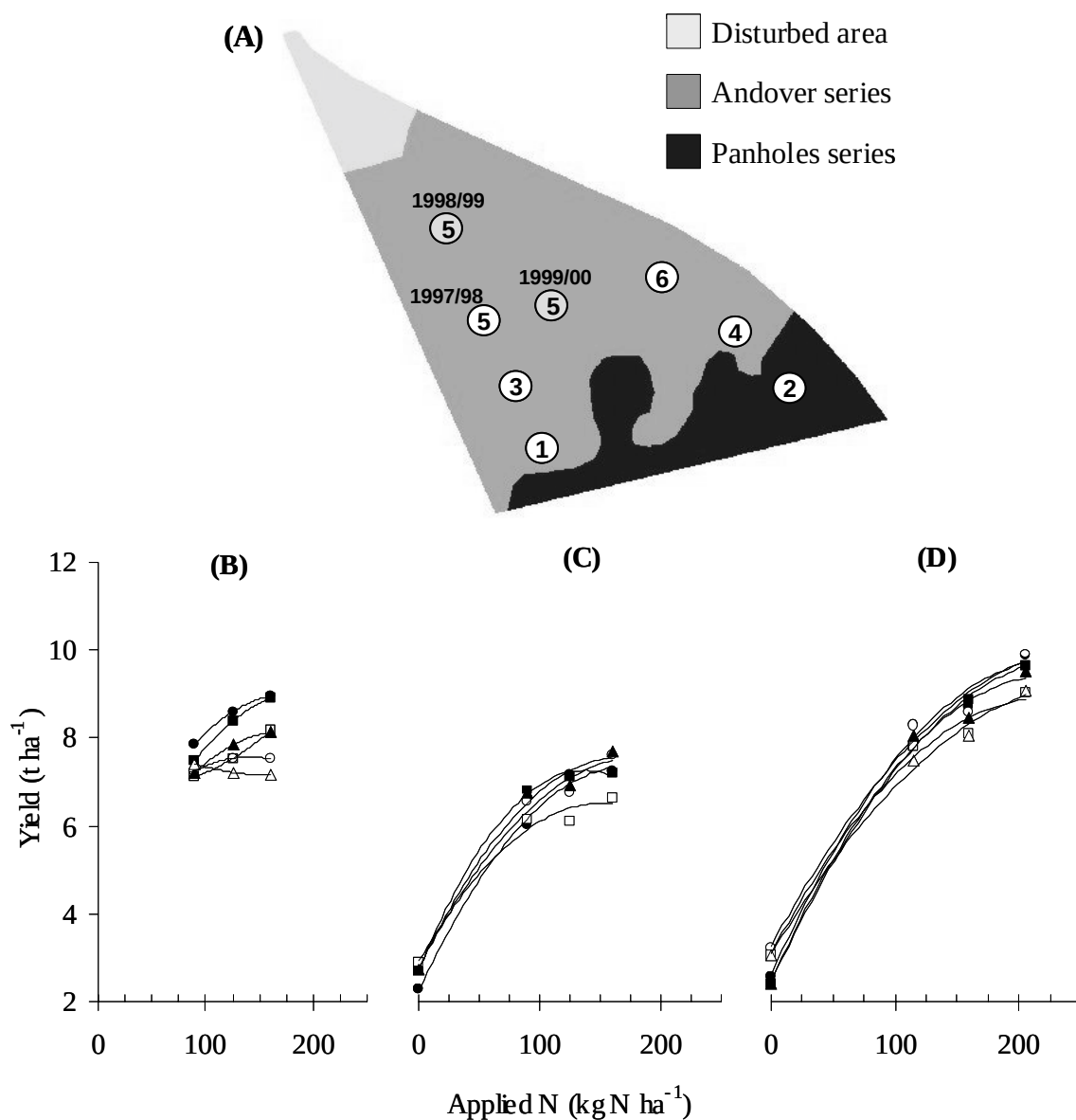


Fig. 15 Spatial variability in crop yield response to applied N in (A) Trent Field in (B) 1997/98, (C) 1998/99 and (D) 1999/00. The numbers in (A) relate to areas where response curves were determined and match up with the curves: ●, 1; ○, 2; ■, 3; □, 4; △, 5; ▲, 6. Sampling position 6 in (A) occurs in three locations due to the different treatment positions in each of the seasons

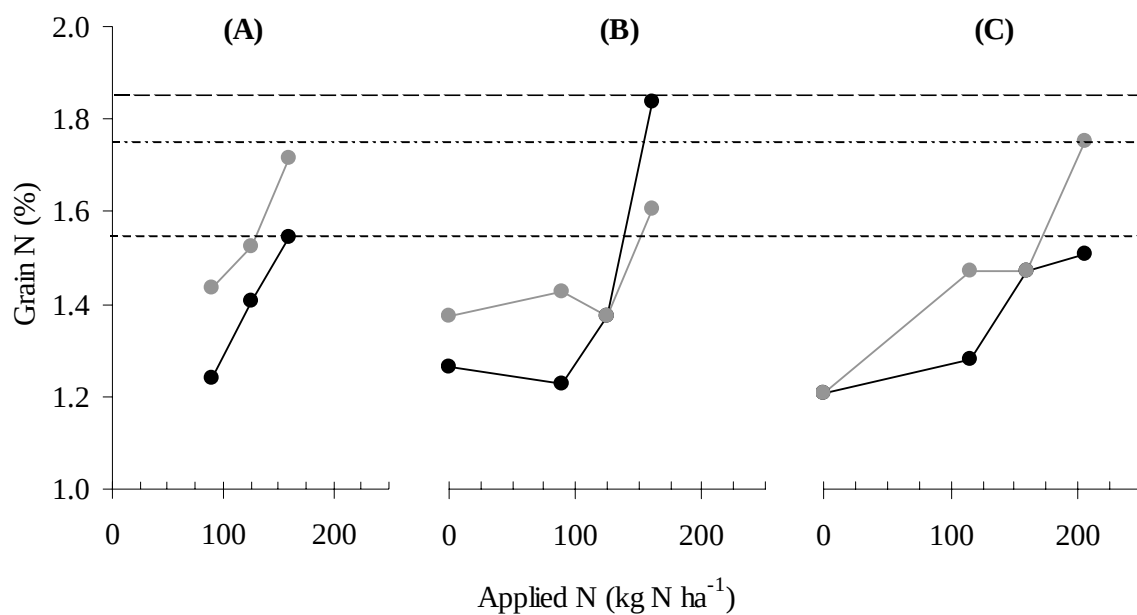


Fig. 16 The effect of increasing N rate on grain nitrogen concentration in the Andover and Panholes soil series zones in (A) 1997/98, (B) 1998/99 and (C) 1999/00. Broken lines indicate thresholds for various malting barley markets: ●, Andover; ●, Panholes

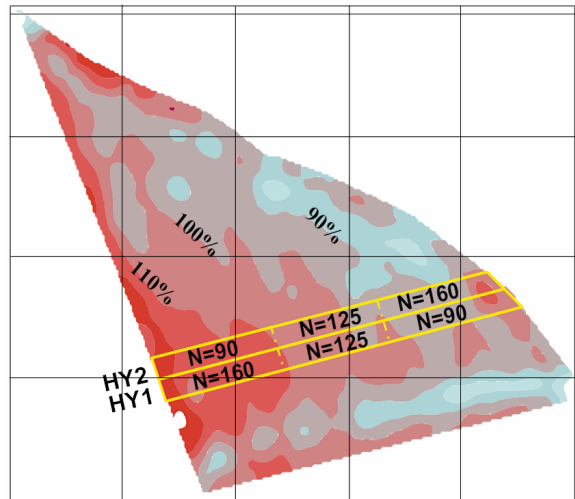


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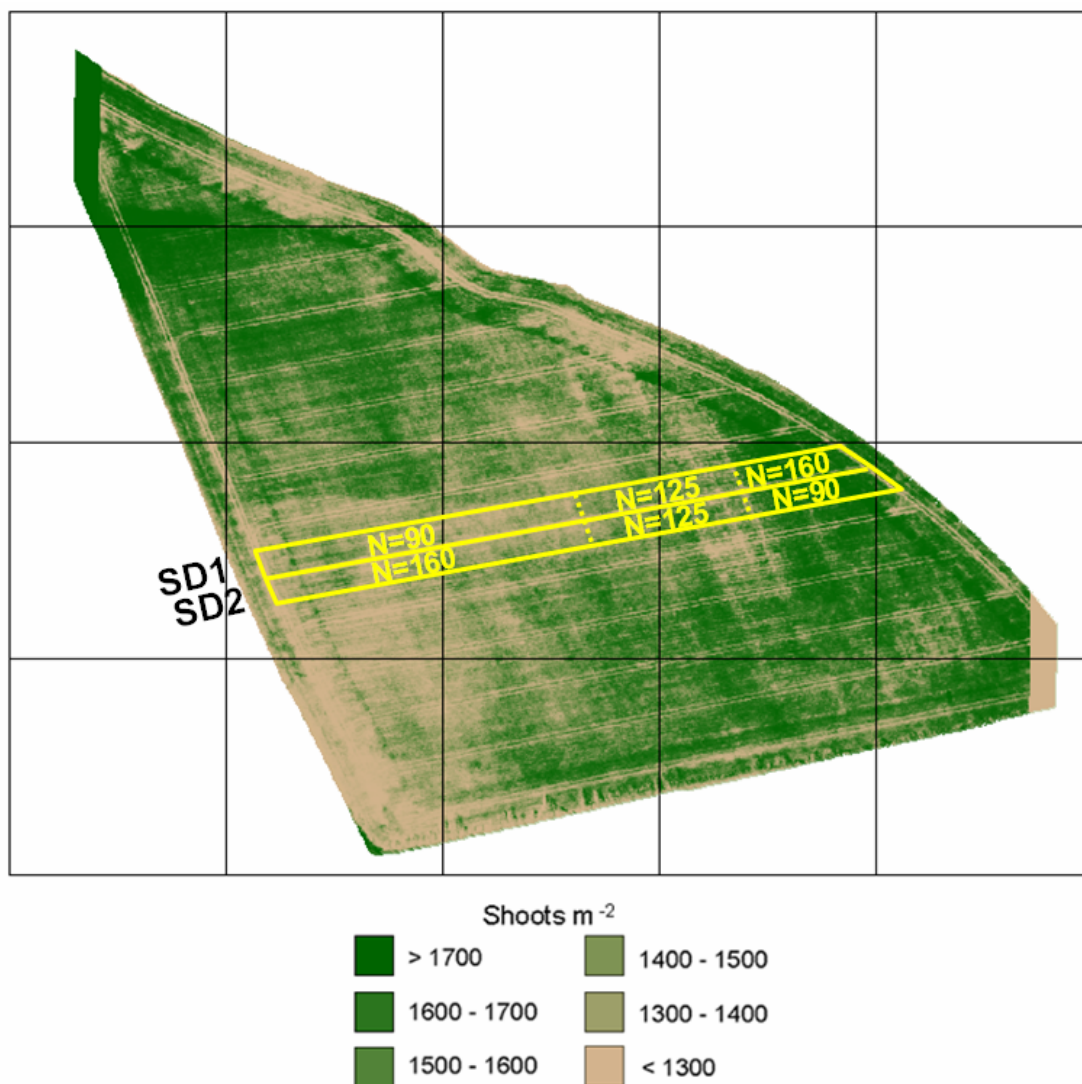


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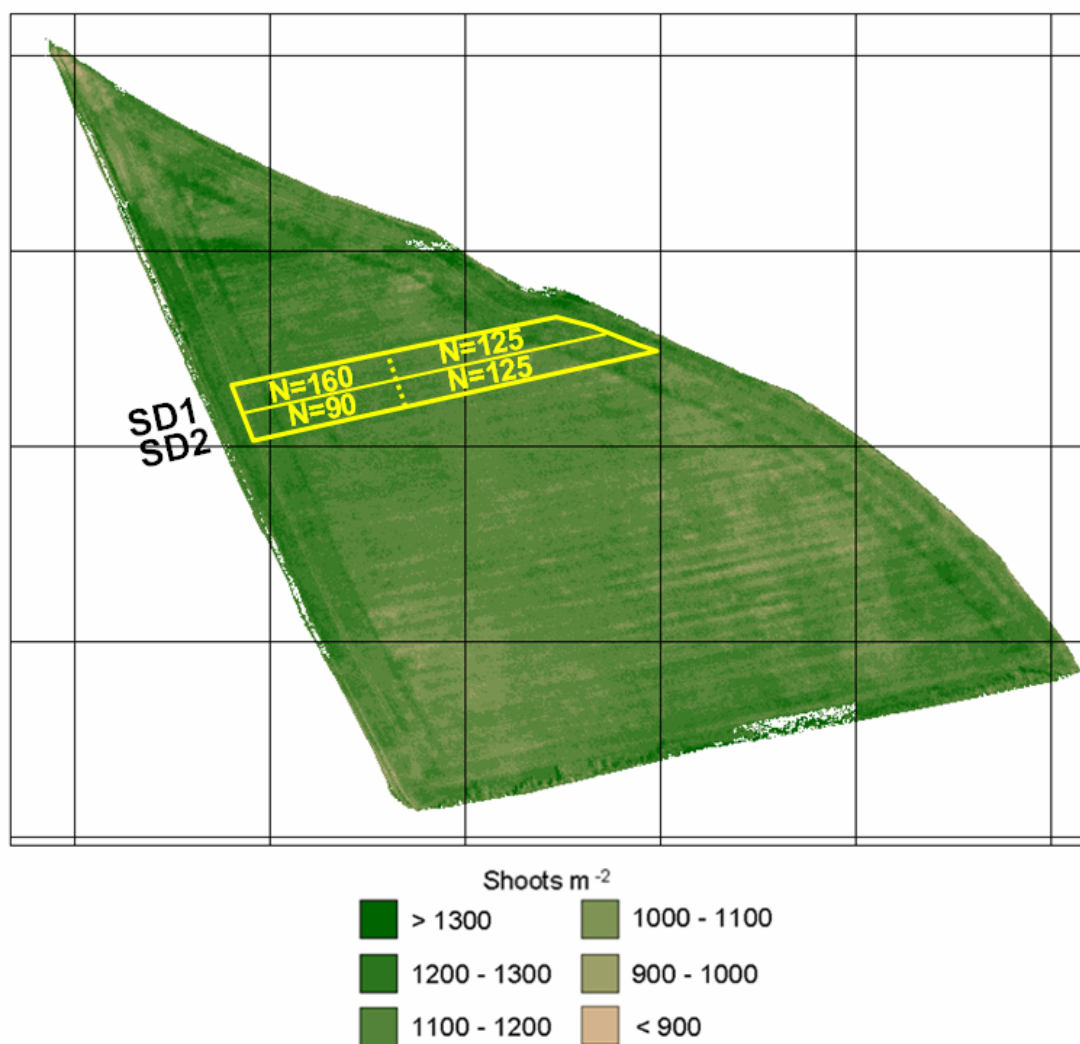


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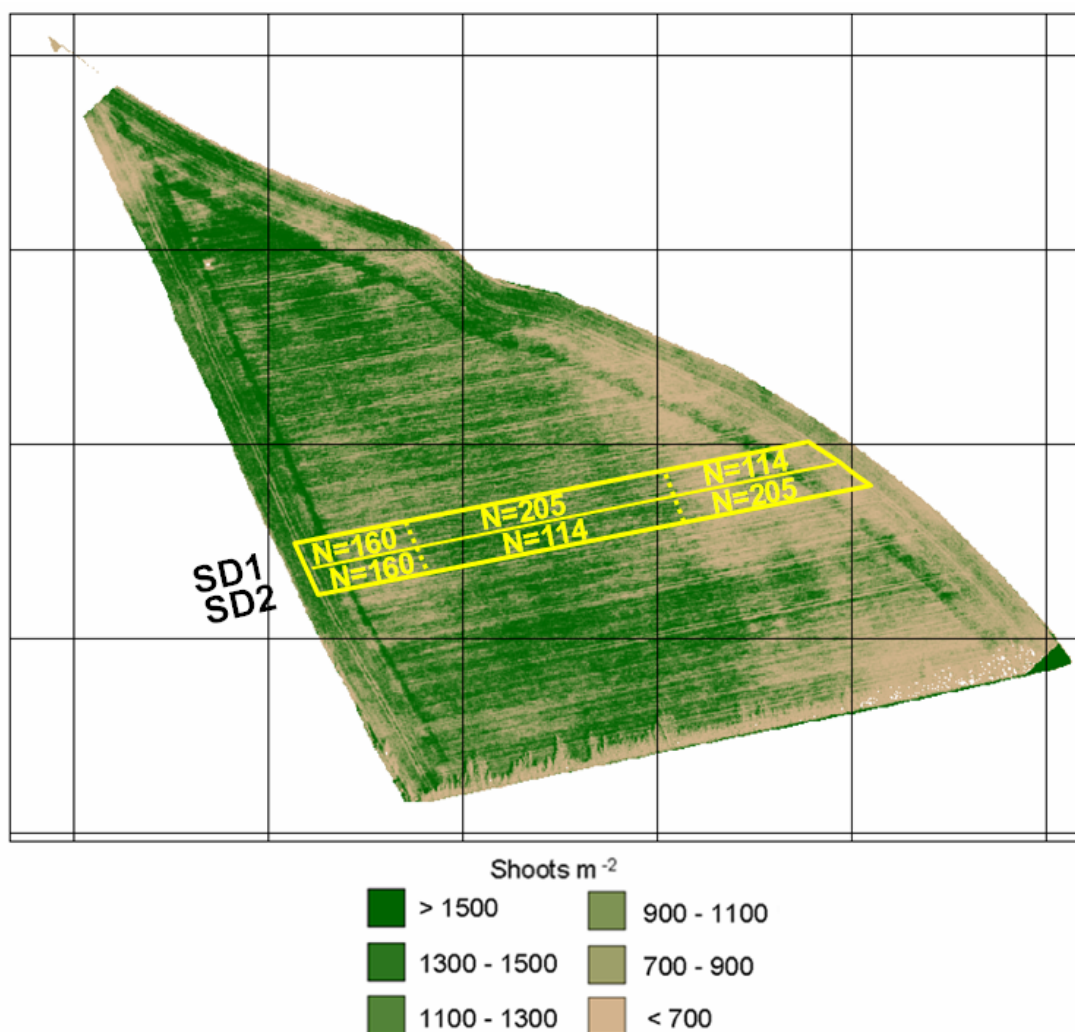


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