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Developing Strategies for Spatially Variable Nitrogen Application in Cereals II: Wheat

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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 wheat (*Triticum aestivum*) over three seasons in two fields, Twelve Acres and Far Sweetbrier. The aim 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 in Twelve Acres with three different soil series (predominantly calcareous silty clay loam over oolitic limestone), was uniform across the field. In contrast Far Sweetbrier with uniform soil type (slightly calcareous brown clay loam), provided a more variable response. 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, which is currently the most practical commercial system, based on three years of yield data, were variable with no overall yield or economic advantages. It was concluded that that this approach may 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 there was insufficient variation in the shoot density in Twelve Acres. However, in Far Sweetbrier with the uniform soil type, applying additional N to areas with a low shoot population and maintaining the standard N rate to areas with an average shoot population resulted in an average strategy benefit of up to 0.46 t ha^{-1} compared with standard farm practice. It is necessary to combine the “real-time” data on relative crop structure, obtained by remote sensing with ground truth assessments and absolute benchmark values to successfully adjust N input levels to maximise yield.

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; 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 wheat (the subject of this paper) and barley (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 at two field sites; Twelve Acres, Gloucestershire and Far Sweetbrier, Bedfordshire, full details of which are given in Table 1.

Three distinct soil series were identified in Twelve Acres (Fig 1A) and Plate 1: Sherborne series, which consists of calcareous topsoil, typically 25 to 35 cm deep, overlying a brashy

Oolitic limestone; Moreton series, which is similar to Sherborne but deeper to limestone, typically 50 to 60 cm; and Didmarton series which is clayey throughout the profile. At Far Sweetbrier, the soil series throughout the field is Hanslope (Fig. 1B) and Plate 2, further details of all the soils can be found in Earl et al (2001).

2.2 *Experimental design*

The experiments were conducted in an a similar manner to those reported by Welsh et al (2001) for barley, using a strip-based approach similar to that of Mulla *et al*. (1992) and Kachanoski *et al*. (1996), there were, however, some differences as described in detail below. 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 10 m or 12 m wide (half tramline width) for Twelve Acres and Far Sweetbrier respectively, and ran parallel with the tramlines along the length of the field, illustrations of which are given in Figures 2 and 3. The treatment strip lengths were approximately 300 m and 350 m for the two fields respectively. This arrangement of strips was selected to allow a conventional 24 m fertiliser spreader to be used for nitrogen application working on either side of the central tramline (some adjustments were made to accommodate the 20 m tramline spacing at Twelve Acres). The 10 m or 12 m treatment width allowed one 5 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*

The estimation of the 'standard' nitrogen application rate for the field was based on previous knowledge of nitrogen response curves for comparable wheat crops on similar soil types, obtained from data collected by Arable Research Centres. This standard N rate, given in Table 2, also took account of the average soil mineral N level in Twelve Acres, which was measured (0 – 30 cm depth) annually in February. Nitrogen rates for the treatments were then either increased or decreased by 25% to 30% of the standard. This range of nitrogen rates was selected to ensure significant levels of crop response.

2.3.1 Uniform treatments.

In addition to the standard rate there were two treatment strips with uniform applications of nitrogen of plus and minus 25% to 30% of the standard along their complete length, also given in Table 2. 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 by a low N rate (40 kg N ha^{-1}) and in 1999/00 by a zero N strip. The purpose of which was 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.

2.3.2 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.

2.3.3 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. Taking the average of the three years' data then identified areas of consistently high and low yield. The 100% contour represents the three-year field mean as shown in Figs. 2 and 3 for the two fields.

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; SD=2.6%) received 25% to 30% more nitrogen; the average received the standard application rate and the low potential area (96% of field mean; SD=2.4%) received 25% to 30% less nitrogen. The converse strategy was applied to the historic yield-2 (HY2) strip. The management zones were maintained for all cropping seasons.

2.3.4 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 and 5). 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.

This is illustrated in Fig. 4(a) for Twelve Acres and Fig. 4(b) for Far Sweetbrier in 1997/98. At Twelve Acres, in the shoot density-1 (SD1) strip areas of high density received 250 kg N ha^{-1} (25% more nitrogen); the average received the standard application rate (200 kg N ha^{-1}) and areas of low shoot density received 150 kg N/ha^{-1} (25% less nitrogen). The converse was applied to the shoot density-2 (SD2) strip. For SD1 in Far Sweetbrier, areas of high shoot density received 160 kg N ha^{-1} (28% more nitrogen); the average received 125 kg N ha^{-1} and areas of low density received 90 kg N ha^{-1} (28% less nitrogen). Again, the opposite strategy was applied to SD2.

At Twelve Acres in 1998/99, the original shoot-density treatment strips were relatively uniform, so alternative strips with more variation were chosen. However, the distribution of shoot density meant that only low and average zones could be established. Along SD1, the low density zone received 150 kg N ha^{-1} and the average 200 kg N ha^{-1}. The treatments along SD2 were 250 kg N ha^{-1} in the low density and 200 kg N ha^{-1} in the average zone. At Far Sweetbrier the treatment strips remained in the same positions, but again it was only possible to define areas of low and average shoot density. These received 90 and 130 kg N ha^{-1} respectively in SD1, and 170 and 130 kg N ha^{-1} in SD2.

In 1999/00, the treatment strips in Twelve Acres were re-located back to their original positions, but as their shoot populations were uniformly low throughout they were classed simply as low density zones. The SD1 strip therefore received 150 kg N ha^{-1}, and the SD2 strip 250 kg N ha^{-1}. As in 1998/99 Far Sweetbrier was divided into low and average zones, with SD1 receiving 140 and 190 kg N ha^{-1} respectively, and SD2 receiving 240 and 190 kg N ha^{-1}.

The mean shoot density in each of the zones for each season is summarised in Table 3, with the exception of Far Sweetbrier in 1998/99 where the images of spring wheat were not ground-calibrated.

2.4 *Fertiliser application*

In all seasons the fertiliser was applied as a split programme using standard farm-scale machinery. In 1997/98, the nitrogen fertiliser (Hydro Extran) was applied using a 24m 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 1998/99 and 1999/00, liquid fertiliser was used (Chafer Nuram 37) and was applied with a Chafer sprayer using T-jet nozzles. Table 4 gives details of the fertiliser applications at Twelve Acres and Far Sweetbrier.

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 three zones, corresponding with the Sherborne, Moreton and Didmarton soil series in Twelve Acres and evenly spatially distributed in Far Sweetbrier. 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*

2.6.1 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 rainfall, Table 5 and Fig. 5, was less than the 10 year average annual rainfall of 731 mm for Twelve Acres in 1997/98 and higher in the two following years, which were virtually identical. The total annual rainfall for Far Sweetbrier was greater in all seasons than the 10 year average (571 mm) with 1997/98 receiving a lower rainfall than the following 2 years. Over the three year period Far Sweetbrier received in total 28% less rainfall than Twelve Acres.

The resulting soil moisture content data are shown in Figs. 6 and 7 together with the field capacity (FC) and permanent wilting point (PWP) moisture contents for the soils. These were estimated from the soil physical properties for each of the soil series using pedo-transfer functions (Hall et al., 1977). The results show that there are differences in both field capacity and permanent wilting point for the 3 soils at Twelve Acres, with Didmarton having a larger amount of available water in the 900 mm profile (i.e. FC-PWP = 140 mm) compared to Moreton (130 mm) and Sherborne (120 mm). The available water content at Far Sweetbrier in the Hanslope series soil is 130 mm.

The distribution of rainfall differed between seasons, and fields such that at Twelve Acres the autumn/winter period (August-November) in 1997 was siginficantly drier than the other two years. This resulted in a lower "over winter" soil moisture content which did not reach field capacity as shown in Fig. 6A. In 1998/99 and 1999/00 the soils effectively reached field capacity. Despite this initially lower available moisture content, in 1998 the soil moisture content was no lower at harvest than in the subsequent years. The drier autumn/winter period in 1997 maintained the moisture content of the Didmarton series to levels similar to Moreton, whereas, in subsequent years it was significantly higher. The changes in the profile water content in the May-June period for each year follows similar patterns for all 3 soils.

The wettest September-December period occurred in 1998, which had sufficient impact to prevent the establishment of winter wheat at Far Sweetbrier, and instead spring wheat was sown in February 1999.

The two years of data for Far Sweetbrier (Fig. 7) show a similar level of peak moisture content with an ultimately drier soil at harvest in 1997/98, after significant rainfall in June which returned the Hanslope series to field capacity.

3.2 *Local yield response to applied N*

The type of data collected by the yield monitor along the length of the uniform treatment strips is illustrated for Twelve Acres in Figure 8. From this, values can be extracted to examine the yield response to N fertiliser rate in different areas. Measurements made during the lead-in time of the combine at the start of each treatment strip, and at the boundaries between zones, were subsequently removed from the data set (shaded areas, Fig. 8).

In this case (1997/98), there was a tendency for yield to increase, moving from the Moreton soil series through to the Didmarton, and the trends were very similar for all three N rate strips. Data from the Moreton and Sherborne zones were used to produce comparative nitrogen response curves for each soil series (Fig. 9). Unfortunately, the area of Didmarton soil at the end of each strip was insufficient to allow a similar analysis, due to the lead-in time required for the combine and fertiliser spreader.

The yields obtained at Twelve Acres were lower in 1999/00 (Fig. 9C) than in either of the previous two seasons (Figs. 9A and 9B). The only notable difference in average yield between the two main soil series was in 1997/98, when the Sherborne series was marginally better. However, in both this season and in 1999/00, when the two soil series yielded similarly, the optimum N application rate was the same, and equal to standard farm practice (200 kg N/ha). In 1998/99, the Moreton series again showed little benefit from more than 200 kg N/ha, but for the Sherborne an optimum in excess of 250 kg N/ha was indicated.

In Far Sweetbrier, differences between seasons were more obvious. However, both the types of wheat crop grown, and the N application rates evaluated, differed between years. Overall yields were lower for the spring wheat crop in 1998/99 (Fig. 10B) than for the first winter wheat crop of 1997/98 (Fig. 10A) or the third winter wheat crop of 1999/00 (Fig. 10C).

Because Far Sweetbrier has a single soil type, the yield strips were simply divided along their length into three zones, forming south-western (zone 1), central (zone 2) and north-eastern (zone 3) sections. Average treated yields in zone 2 were similar to those in zone 3 in all seasons. However, at the low N rate in 1998/99 and at the zero N rate in 1999/00, the yield penalty was smaller in zone 3. Zone 1 gave equal yields to zones 2 and 3 in 1997/98, but was lower yielding in both the following seasons. The nitrogen response curve in zone 1 showed the same pattern in all three years (albeit for a different range of N rates), with the standard amount always optimum. For zones 2 and 3, a similar optimum rate was indicated in 1999/00, but in the previous two years the N response curves suggested a higher optimum than zone 1.

Interestingly, there is evidence that historically Far Sweetbrier was divided into two fields, and zone 1 equates very closely with one of these separate fields, as shown in Plate 3.

3.3 *Variable nitrogen strategies*

3.3.1 Historic yield approach.

As with the uniform treatment strips, yield data taken from each of the historic yield management zones (Fig. 11) can be used to produce N response curves (Fig. 12) for areas of low and high historic yield, and thus evaluate the various historic yield nitrogen strategies.

At Twelve Acres, the differences between zones, and between seasons, were similar to those observed with soil series (Figs. 12A-C). The optimum N application rate was effectively the same for both high and low yielding zones, and equal to the standard rate of 200 kg N/ha. However there was a more obvious decline in yield where a higher than optimum N rate was applied in the high yielding zone.

With no yield improvements resulting from an increase or decrease in the N application rate compared to the standard 200 kg N/ha, none of the historic yield nitrogen strategies (more N on the high yielding and less on the low yielding, or vice versa) gave any benefit (Table 6). Even if alternative strategies are constructed, such as applying more N on the high yielding zones only, and applying the standard rate to the remainder (HY3 in Table 6), or more N on the low yielding zones only (HY4 in Table 6), there are still no benefits.

At Far Sweetbrier, the relative responses to N application rate differed substantially between seasons. In 1997/98, there was little difference between the historic high and low yielding zones, no doubt partly due to lodging that occurred over a large part of the field (Fig. 13A). However, there was an indication of a more consistent yield increase with N rate in the low yielding zone. In 1998/99, there was little yield advantage from applying more than the standard N rate (130 kg N/ha) in the high yielding zone, but the optimum for the low yielding zone appeared to be above the maximum tested (170 kg N/ha). In 1999/00, the optimum for both the high and low yielding zones was equal to the standard rate (190 kg N/ha).

As a result of these responses, in 1997/98 and 1998/99 the HY2 strategy (less N on the high yielding areas, more on the low yielding) gave a substantial yield improvement compared to standard farm practice, although the average N rates applied were also marginally greater (Table 7). Other strategies also gave benefits in 1997/98, but these were smaller. The only other strategy to give a yield increase in 1998/99 would have been to apply more N on the low yielding areas, with the standard rate on the remainder (HY4). However, in 1999/00, none of the strategies showed a yield improvement compared to standard farm practice.

3.3.2 Shoot density approach.

Figure 14 is an example from Far Sweetbrier in 1997/98, where management zones have been assigned according to shoot density. It shows the yield along each of three treatment strips (SD1 and SD2 shoot density strategies, plus the standard for comparison) for areas of low, average and high relative shoot density. As before, data can be extracted to allow examination of the yield response to applied N in each zone. In both Twelve Acres and Far Sweetbrier, no high shoot density zones could be defined in 1998/99 or 1999/00, so the strips were divided into low and average shoot density areas only.

At Twelve Acres, there were no differences in N response between low and high shoot density zones in 1997/98, and the optimum N rate for both was the standard 200 kg N/ha (Fig. 15A). In 1998/99 and 1999/00, with no high density zones, it is not possible to compare response curves, and 200 kg N/ha was again optimum in both seasons (Fig. 15B-C). With no differences between zones, neither the SD1 shoot density strategy (more N on the high density area and less on the low) or SD2 (more on the low, less on the high) gave a yield improvement over standard farm practice (Table 8). However, in 1998/99, as there was no high density zone the average N rate applied to the SD1 strip was less than the standard, and with no real yield penalty this did represent a benefit.

At Far Sweetbrier in 1997/98 (Fig. 16A), the responses to N rate were small in both low and high shoot density zones, and there were no obvious differences between them, other than the high zone being marginally higher yielding. In 1998/99 (Fig. 16B) and 1999/00 (Fig.16C), there were no high density zones, but in the low zones yield rose sharply with increasing N, and optimum rates in excess of the highest amounts tested were indicated. In 1997/98 yield differences between the two shoot density strategies, and standard farm practice, were small. In the following two seasons, however, SD2 (more N on the low density areas, less on the high) resulted in a yield improvement compared to standard practice, giving an average yield improvement of 0.46 ha^{-1} over the three years (Table 9). However, the average amount of N applied to the SD2 strips was higher than for the standards.

3.4 *Spatial variability of yield response to applied nitrogen*

In addition to evaluating different variable nitrogen application strategies, the data can be used to examine the spatial variability in crop yield response to nitrogen application rate, using values from different locations within the field. This is illustrated for Twelve Acres over the three-year period in Figure 17, and for Far Sweetbrier in Figure 18.

In 1997/98 and 1999/00, the yield response to nitrogen rate was very similar in all areas of the field, although yield level differed slightly between locations (mostly with soil type). However in 1998/99 differences were apparent, indicating that seasonal factors were influencing whether or not there was spatial variability in yield response to nitrogen.

Despite a uniform soil type, it is clear that both actual yields and their response to N rate varied considerably between locations within Far Sweetbrier. These differences were most obvious in 1998/99 and 1999/00 (1997/98 was confounded by patchy lodging). There were a number of similarities between these two seasons, for example location 1 was lower yielding than location 5 in both, but they showed similar N responses. In contrast, the N responses in locations 2 and 4 clearly differed between the two seasons, which must be related to other factors.

4 Discussion

The local yield response data for Twelve Acres suggested that the Didmarton soil type was higher yielding than either the Moreton or Sherborne series. Yield maps from previous years under uniform management had also shown the same trend. This can be explained by the greater depth of soil to rock and higher available water capacity that distinguish the Didmarton from the other two soils. The yield difference was most obvious in 1997/98, which was the driest of the three seasons. Differences in moisture holding capacity can explain a large proportion of crop variability between soil types (Moore and Tynedale-Biscoe, 1999). Also 1997/98 was the only season that indicated a difference between the Sherborne and Moreton series. However, unexpectedly it was the Sherborne series that gave the higher yields, even though the Moreton had a greater available water capacity. In the two wetter seasons that followed, there were no differences in yield between the two soil series.

In general, a nitrogen fertiliser rate of 200 kg N/ha, which was the same as standard farm practice, appeared to be optimum for Twelve Acres, regardless of soil type or location within the field. Therefore, variable N applications in this field might be difficult to justify. There was one exception in 1998/99, which appeared to show a higher optimum rate in at least one location within the Sherborne series. This may be a seasonal effect related to rainfall, which for the May-August period was highest in 1998/99. However, this year was also unusual in that, despite autumn plant populations being higher and more uniform than in 1997/98 or 1999/00, biomass assessment at GS30 showed early growth to be poorer and more variable between locations than in the other two years.

With no substantial differences between historically low and high yielding areas, variable nitrogen strategies based on historic yield were clearly not of any benefit in Twelve Acres. Although Far Sweetbrier had a more uniform soil type than Twelve Acres, there were larger differences in both yield and optimum N rate between locations within the field. However unlike Twelve Acres, which had three very similar wheat crops (the three varieties were all comparable), there were significant changes in sowing date, previous crop, variety and range of N application rates in Far Sweetbrier, so comparison between the seasons is more complicated.

The south-western section of Far Sweetbrier was lower yielding in two out of three seasons (the exception being 1997/98 which was much drier than the other two), and it consistently failed to respond to more than the standard N rate. The fact that the remainder of the field had an optimum N rate in excess of the standard in both 1997/98 and 1998/99 might have been anticipated. In these two seasons the standard rates were reduced due to the wheat crops being a first cereal after a break crop in 1997/98, and then a spring sown-wheat in 1998/99.

With larger differences than Twelve Acres, the variable nitrogen strategies based on historic yield were more successful, in particular applying more N to the low yielding areas and less on the high yielding. This gave an average yield increase over the three years of 0.33 t ha^{-1}. However, even at Far Sweetbrier, there was no benefit in the final season, because the standard rate (which was higher than previously) was optimum even for low yielding areas. Combining the results of the two fields gave very small returns (average £3 ha^{-1}) which would be uneconomic compared to the costs of implementing precision farming management systems as given in Godwin et al (2001).

Using shoot density as the basis of variable nitrogen applications allowed the current condition of the crops to be taken in to account, rather than relying on historic trends that may be diverted by seasonal factors such as rainfall differences. As with the historic yield approach, there was a more obvious benefit at Far Sweetbrier, where the strategy of applying more N on the low shoot density areas and less on the high resulted in a yield benefit in two out of three seasons, averaging 0.46 ha^{-1}. In the first season, this was complicated by lodging, which affected a significant part of the field. Furthermore, in the following two years the average amount of nitrogen applied using this strategy was higher by 32 kg N ha^{-1}. By contrast, the only instance of a benefit at Twelve Acres was in 1998/99. Here, the strategy of applying more N on the high density shoot areas and less on the low was beneficial simply because there were no high density shoot areas, and the saving in amount of fertiliser applied to the low density areas outweighed the small reduction in yield.

Inability to define areas of high shoot density in either Twelve Acres or Far Sweetbrier in 1998/99 and 1999/00 highlighted the weakness of an approach based on relative rather than absolute differences in shoot populations. In Twelve Acres, the range of shoot populations in all three years was such that it could be argued that all areas were essentially similar, having average shoot density, and could therefore have received the standard field rate. As this was the best strategy, an approach based on absolute shoot populations would have been effective. Far Sweetbrier was again complicated by having very different wheat crops, and therefore shoot population characteristics.

A major outcome from these experiments was that it was clearly necessary to combine the "real-time" ADP data on relative crop structure, with appropriate benchmark values for different wheat crops at different stages. Publication of the Wheat Growth Guide (HGCA, 1998) provided an appropriate source of such values, and these developments enabled a second series of experiments to be conducted that examined a variable nitrogen strategy based on managing wheat crop canopies according to pre-determined targets. This is reported in Wood *et al*. (2001).

5 Conclusions

1. Whilst there was some variation between years, related to seasonal effects, at Twelve Acres there was little spatial variability in yield response to N fertiliser level, despite the presence of three soil series. By contrast, Far Sweetbrier with a uniform soil type showed more spatial variability, and this was consistent with evidence of old field boundaries.

2. Historic yield data are important for identifying consistently over or under performing areas. However, although there have been small benefits on occasions, depending on field and season, their routine use as a basis for spatially variable nitrogen applications is not reliable. Over three years at Far Sweetbrier, the average yield increase from a strategy based on applying more N to low yielding areas and less to high yielding areas was almost cancelled by a similar loss at Twelve Acres.

3. Variations in crop structure can successfully be monitored in near "real time" by remote sensing, allowing the possibility of rapid alterations in mid-season agronomy to improve crop performance.

4. The use of shoot density as a basis for spatially variable nitrogen applications was more promising than historic yield. At Twelve Acres, shoot densities were comparatively uniform across the soil series, and hence there was no yield benefit from an approach aimed at applying either more or less N to high or low density areas. At Far Sweetbrier, a strategy of applying more nitrogen to low density areas and less to high density areas (where applicable) gave an average yield increase of 0.46 t ha^{-1}, worth £30 ha^{-1}.

5. The key conclusion was that it was necessary to combine the "real-time" data on relative crop structure, obtained by remote sensing, with absolute benchmark values for similar wheat crops, and this led to the subsequent development of the experimental programme based upon managing crop canopies.

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Figure captions for:

Developing Strategies for Spatially Variable Nitrogen Application in Cereals II: Wheat

J. P. Welsh[1]; G. A. Wood[1]; R. J. Godwin[1]; J. C. Taylor;[1] R. Earl[1]; S. Blackmore[1] S.M. Knight[2]

Table 1
Site Details

	Twelve Acres	*Far Sweetbrier*
Size (ha)	8.10	7.00
OS National Grid Ref	SP 1705 0630	TL 1220 4540
Cropping History:	Continuous winter wheat	Rotation
1997/98	WW (*cv*. Hussar)	WW (*cv*. Rialto)
1998/99	WW (*cv*. Brigadier)	SW (*cv*. Chablis)
1999/00	WW (*cv*. Buster)	WW (*cv*. Rialto)
10 year average annual rainfall (mm)	731	571
Soil type	Calcareous silty clay loam over oolitic limestone	Slightly calcareous brown clay loam
Soil series	Moreton, Sherborne and Didmarton	Hanslope

Table 2
Target Nitrogen Application Rates (kg ha^{-1})

	Twelve Acres			*Far Sweetbrier*		
Year	*Standard*	*Standard +*	*Standard –*	*Standard*	*Standard+*	*Standard–*
1997/98	200	250	150	125	160	90
1998/99	200	250	150	130	170	90
1999/00	200	250	150	190	240	140

Table 3
Shoot density in the high, average and low density zones in 1997/98, 1998/99 and 1999/00.

Location and Growing Season	*Date of Image*	*Shoot Density (shoots m^{-2})*					
		High Density Zone		*Average Zone*		*Low Density Zone*	
		Mean	*Standard Deviation*	*Mean*	*Standard Deviation*	*Mean*	*Standard Deviation*
TWELVE ACRES							
1997/98	28-02-98	897	28	871	40	818	31
1998/99	14-03-99	n/a	n/a	651	53	512	48
1999/00	02-02-00	n/a	n/a	n/a	n/a	288	74
FAR SWEETBRIER							
1997/98	05-03-98	1281	113	1176	124	1134	112
1998/99	30-04-99	-	-	-	-	-	-
1999/00	05-03-00	n/a	n/a	680	163	443	158

Table 4

Dates of fertiliser applications at Twelve Acres and Far Sweetbrier.

	Twelve Acres		*Far Sweetbrier*	
	Date	*Quantity (kg N ha^{-1})*	*Date*	*Quantity (kg N ha^{-1})*
1997/98	12-Mar-98	50	07-Apr-98	90 – 160
	30-Apr-98	100 – 200		
1998/99	20-Mar-99	50	10-Apr-99	45
	13-Apr-99	67 – 133	12-May-99	45 – 125
	13-May-99	33 - 67		
1999/00	21-Mar-00	50	15-Mar-00	40
	25-Apr-00	67 - 133	29-Apr-00	60 – 127
	19-May-00	33 - 67	20-May-00	40 – 73

Table 5
Rainfall distribution at Twelve Acres and Far Sweetbrier in 1997/98, 1998/99 and 1999/00

Season	*Rainfall Distribution (mm)*			*Total (mm)*
	Sep - Dec	*Jan - Apr*	*May - Aug*	
TWELVE ACRES				
1997/98	249	232	186	667
1998/99	406	272	278	956
1999/00	396	315	247	958
FAR SWEETBRIER				
1997/98	194	221	165	581
1998/99	311	149	175	634
1999/00	160	227	247	635

Table 6
Mean yield response of the historic yield nitrogen application strategies (HY) compared with standard farm practice (S.F.P.) in Twelve Acres in 1997/98, 1998/99 and 1999/00.

	Season					
	1997-98		*1998-99*		*1999-00*	
Strategy	*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	6.85	177	7.64	175	5.41	175
HY2	7.00	222	7.63	225	5.39	225
HY3	7.14	207	7.64	202	5.82	203
HY4	7.15	224	7.79	227	5.78	226
S.F.P	7.16	200	7.68	200	5.87	200

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

Table 7
Mean yield response of the historic yield nitrogen application strategies (HY) compared with standard farm practice (S.F.P.) in Far Sweetbrier in 1997/98, 1998/99 and 1999/00

	Season					
	1997-98		*1998-99*		*1999-00*	
Strategy	*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	8.43	113	6.86	116	7.94	173
HY2	8.82	137	7.53	143	8.12	207
HY3	8.36	133	6.90	139	8.26	200
HY4	8.37	136	7.27	143	8.34	207
S.F.P	8.25	125	6.89	130	8.35	190

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

Table 8
Mean yield response of the relative shoot density N application strategies compared with standard farm practice (S.F.P.) in Twelve Acres in 1997/98, 1998/99 and 1999/00

Strategy	*Season*					
	1997-98		*1998-99*		*1999-00*	
	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 ($kg\ N\ ha^{-1}$)*
SD1	7.11	191	7.87	168	5.27	150
SD2	7.01	208	7.74	232	5.50	250
S.F.P	7.22	200	7.99	200	5.75	200

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

Table 9.
Mean yield response of the relative shoot density N application strategies compared with standard farm practice (S.F.P.) in Far Sweetbrier in 1997/98, 1998/99 and 1999/00

Strategy	*Season*					
	1997-98		*1998-99*		*1999-00*	
	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 ($kg\ N\ ha^{-1}$)*
SD1	8.58	124	5.83	105	7.54	151
SD2	8.41	126	6.91	155	8.44	228
S.F.P	8.46	125	6.02	130	7.90	190

Confidence intervals for the mean yields range between ± 0.07 – 0.09 t ha^{-1}

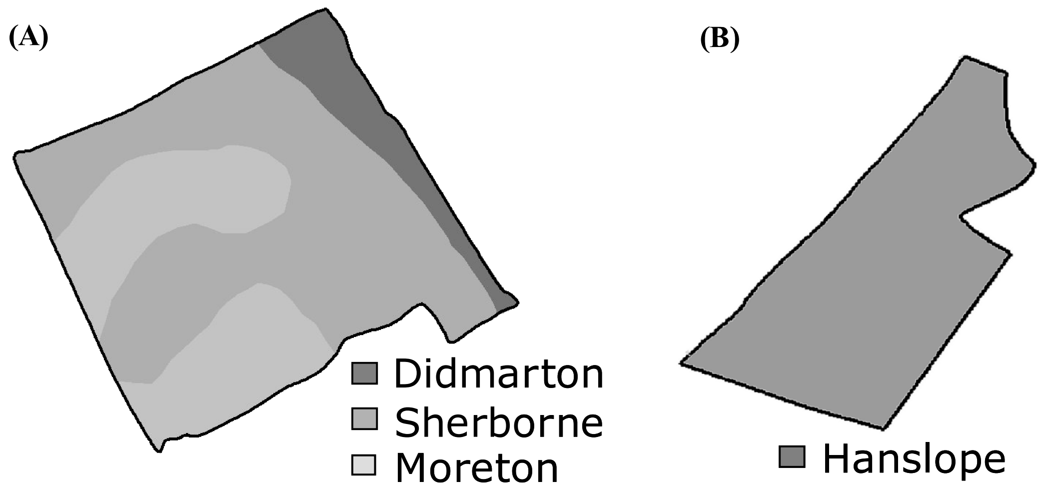


*Fig. 1. Map of (**A**) Twelve Acres and (**B**) Far Sweetbrier showing distribution of soil series. (Maps courtesy of Soil Survey and Land Research Centre)*

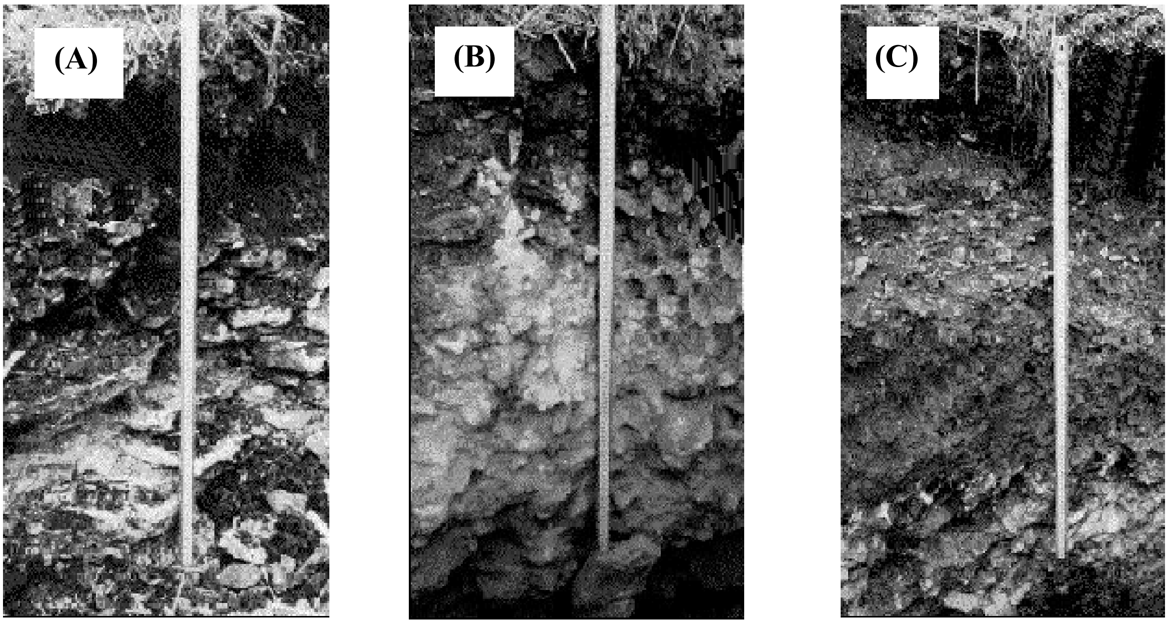


*Fig. 2. Soil profile pits in Twelve Acres showing (**A**) Moreton and (**B**) Sherborne and (**C**) Didmarton soil series*

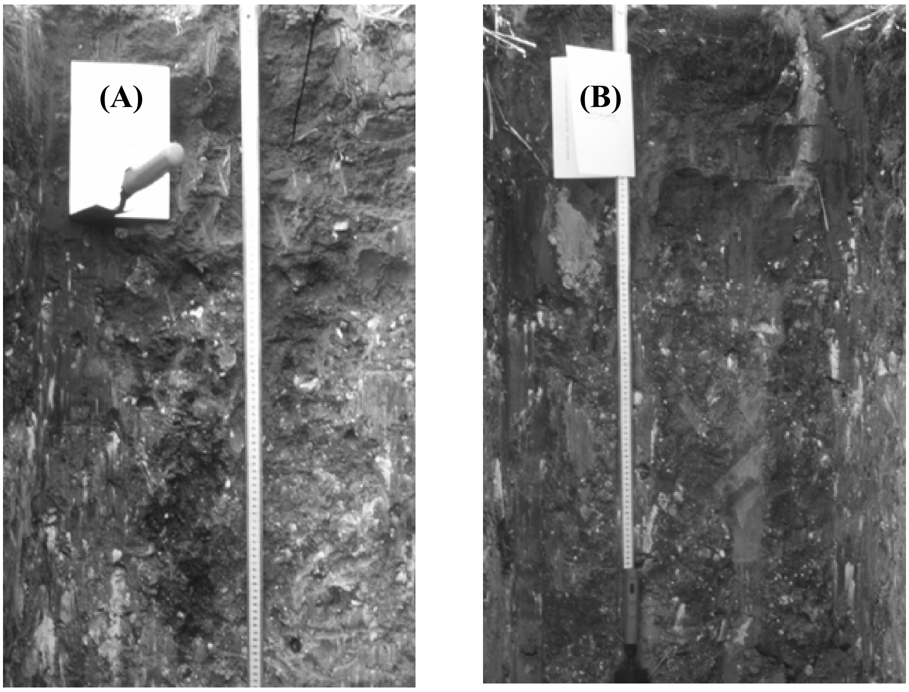


*Fig.3. Soil profile pits in Far Sweetbrier showing (**A**) and (**B**) Hanslope soil series*

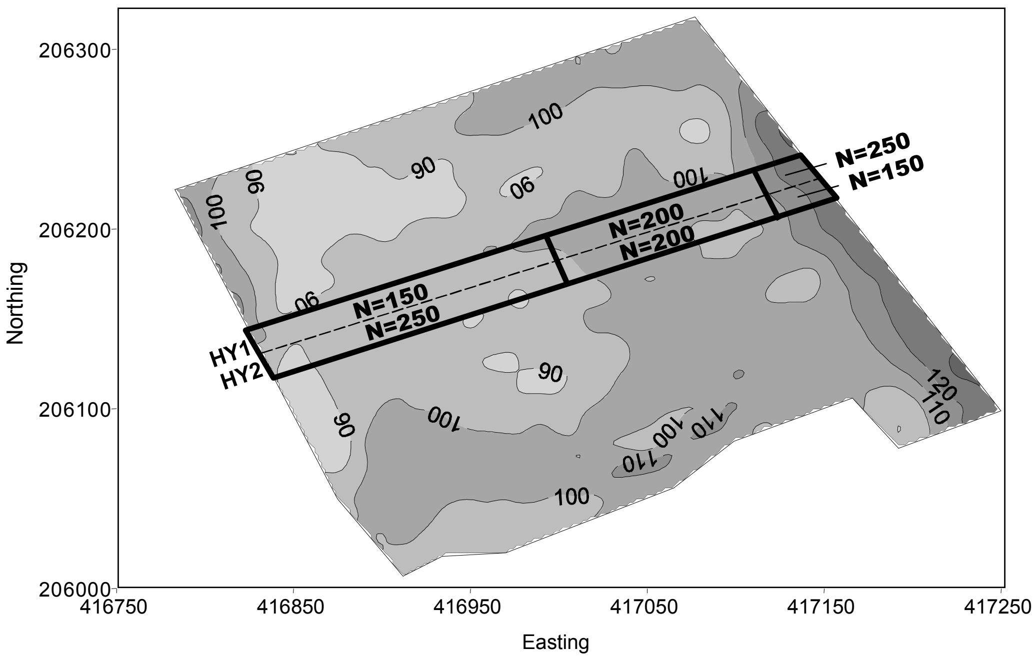


Fig. 4. Historic yield distribution in Twelve Acres expressed as a percentage of the two-year average derived from two years' of yield maps (1995 and 1996). HY1 and HY2 refer to treatment strips and N=150, 200, 250 refers to the nitrogen application rate in kg N ha^{-1}

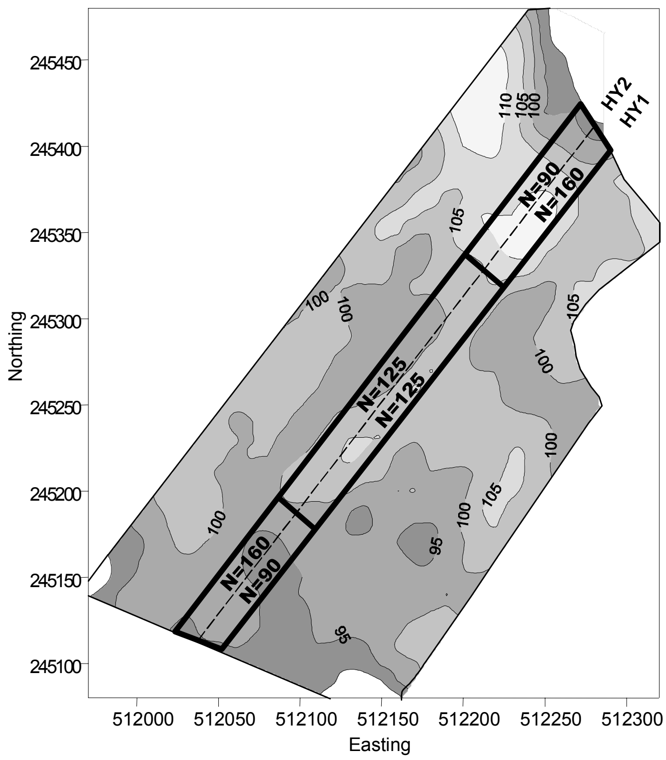


Fig. 5. Historic yield distribution in Far Sweetbrier expressed as a percentage of the three-year average derived from three years' of yield maps (1995 – 1997). HY1 and HY2 refer to treatment strips and N= 125, 160, 90 refers to the nitrogen application rate in kg N ha^{-1}

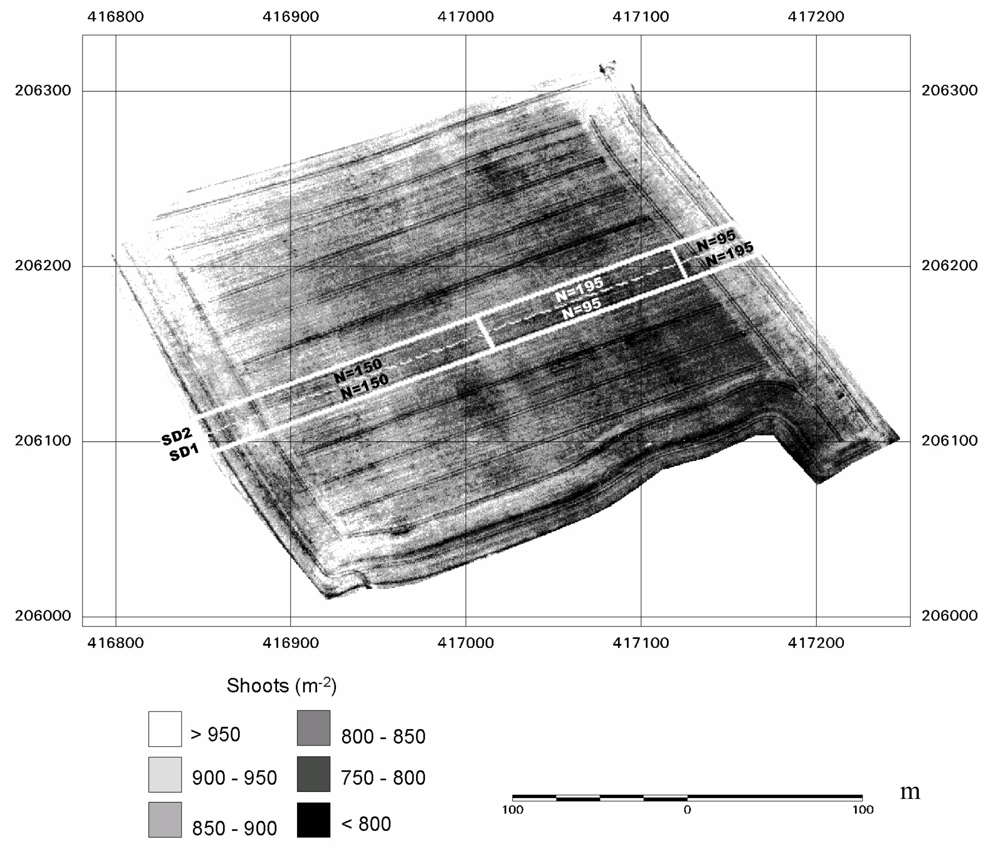


Fig. 6(a). Aerial Digital Photography (ADP)-derived shoot density map for Twelve Acres (accuracy of calibration: r^2=0.98; Standard error = 47 shoots m^{-2}) showing treatment strips and corresponding N application rates. Image acquired (28 February 1998) and N = 150, 200, 250 refers to the nitrogen application rate in kg N ha^1

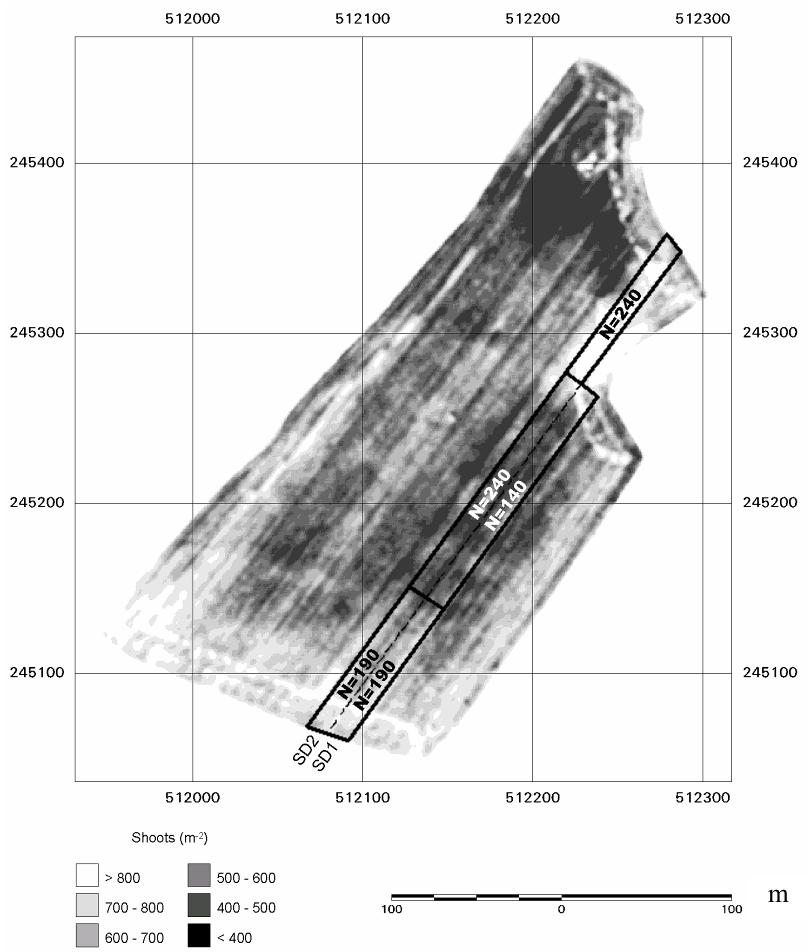


Fig. 6(b). Aerial Digital Photography (ADP)-derived shoot density map for Far Sweetbrier (accuracy of calibration: r^2=0.98; Standard error = 47 shoots m^{-2}) showing treatment strips and corresponding N application rates. Image acquired (5 March 1998) and N = 90, 125 160 refers to the nitrogen application rate in kg N ha^{-1}

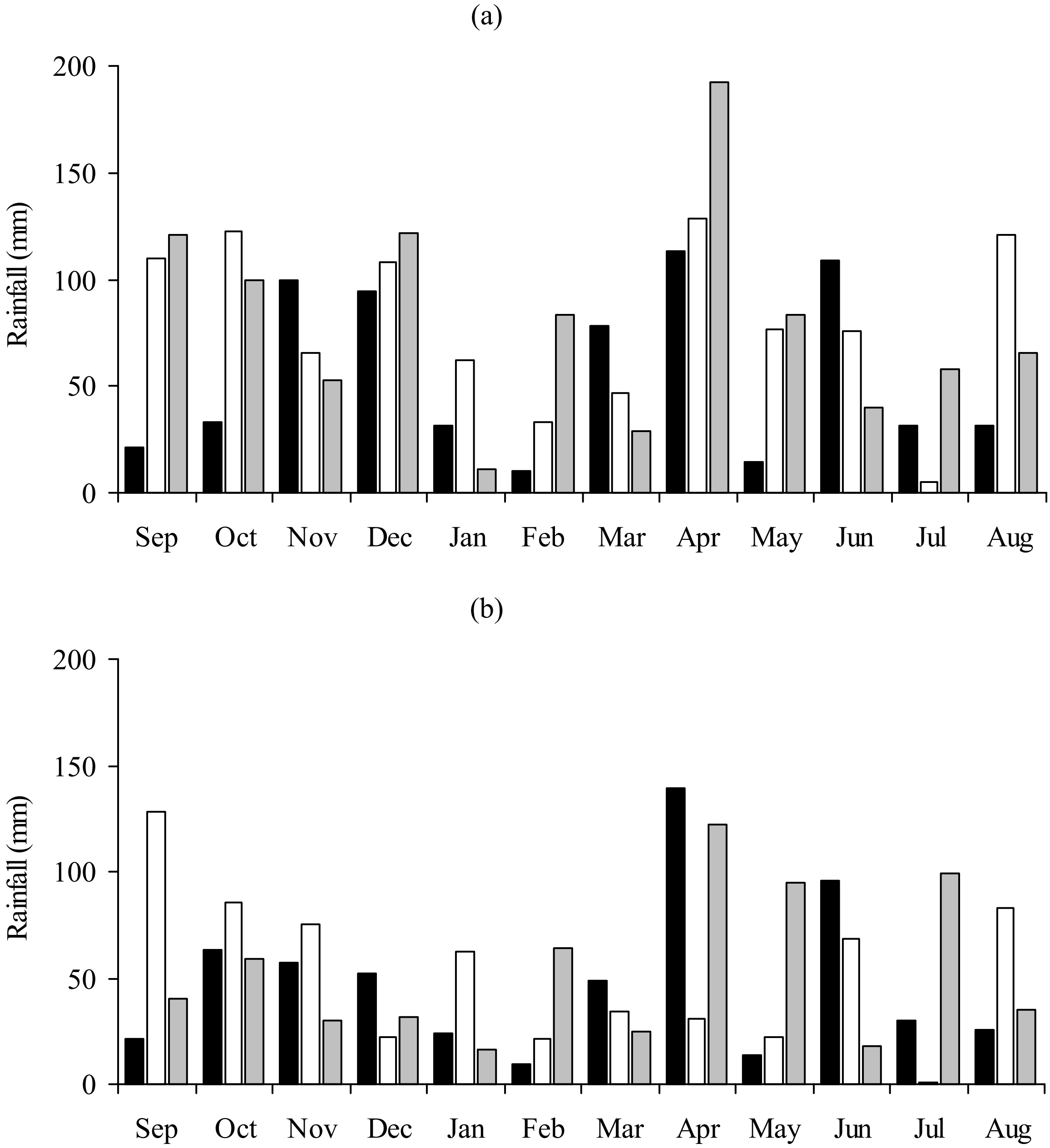


Fig. 7. Distribution of rainfall at (a) Twelve Acres and (b) Far Sweetbrier: ■, 1997/1998; □, 1998/1999; ▒, 1999/2000

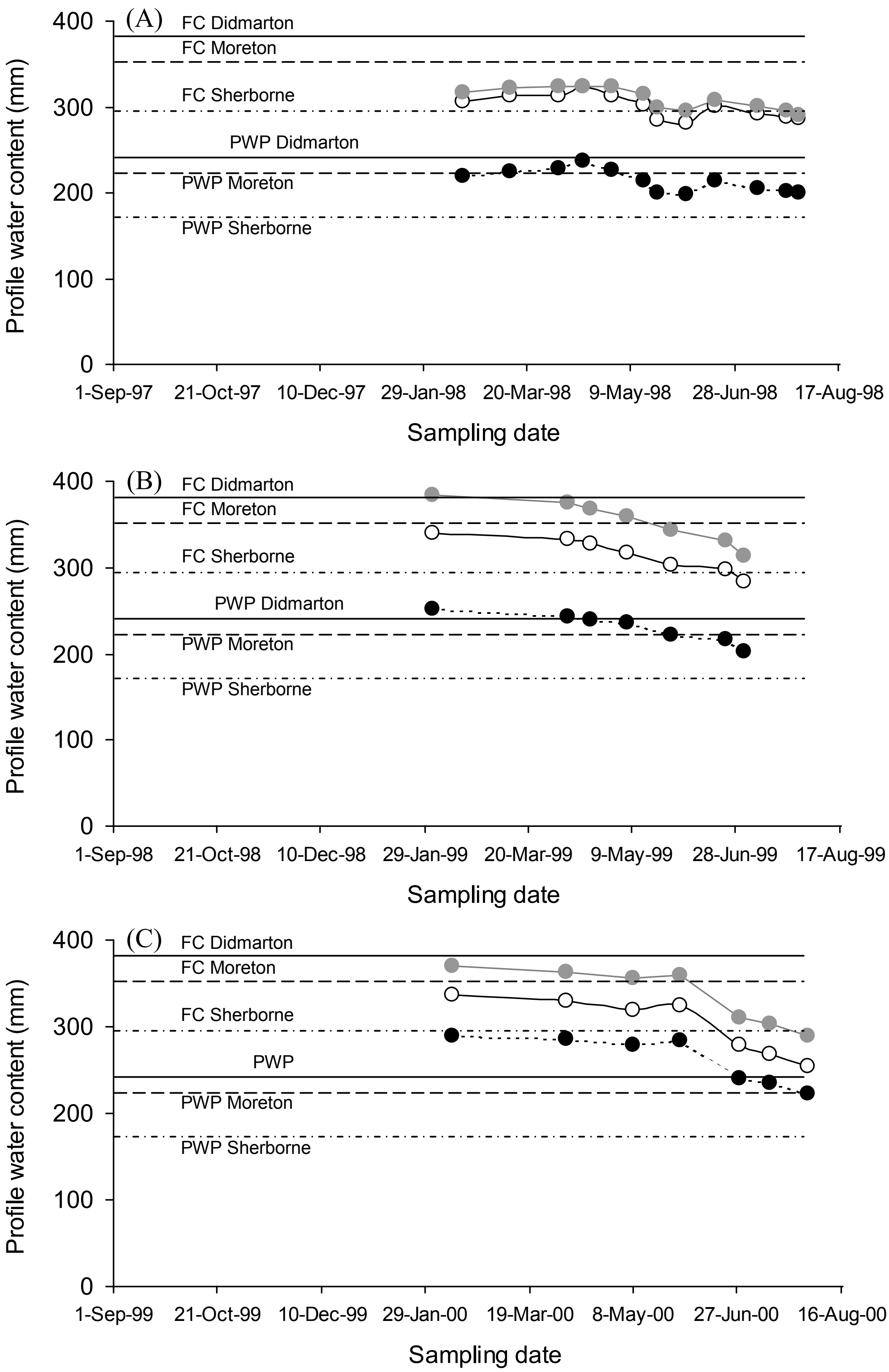
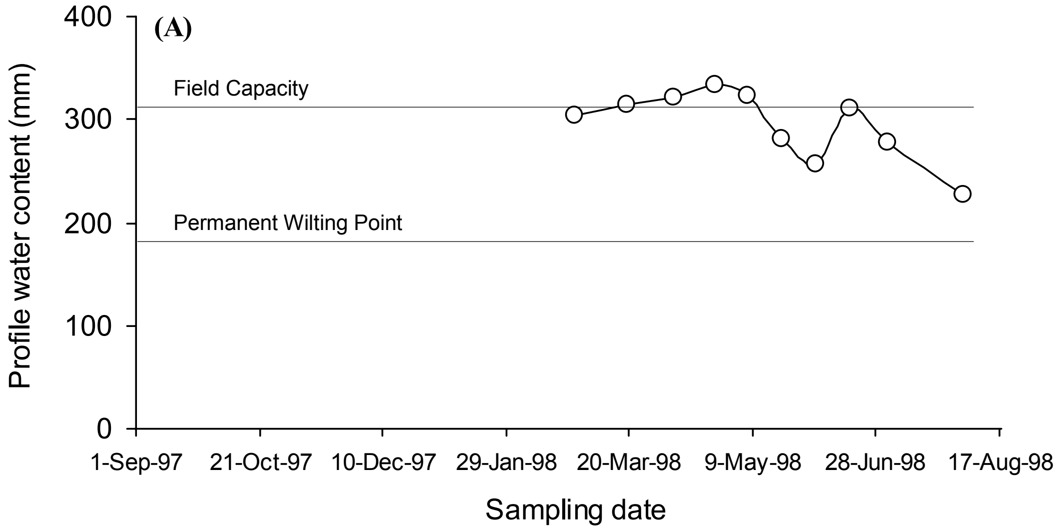


*Fig. 8. Soil moisture content (mm water in 900 mm profile) in the Moreton, Sherborne and Didmarton soil series in Twelve Acres in (**A**) 1997/98, (**B**) 1998/99 and (**C**) 1999/00. F.C. = Field Capacity; P.W.P. = Permanent Wilting Point; —○—, Moreton; -●-, Sherborne; —●—, Didmarton*



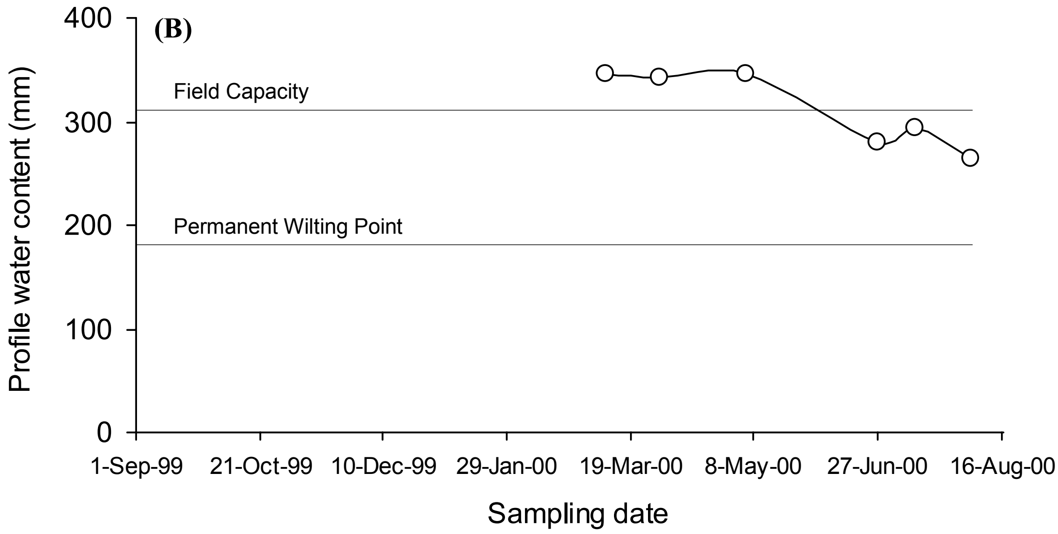


*Fig. 9. Soil moisture content (mm water in 900 mm profile) in the Hanslope soil series in Far Sweetbrier in (**A**) 1997/98, (**B**) 1999/00. (F.C. = Field Capacity; P.W.P. = Permanent Wilting Point)*

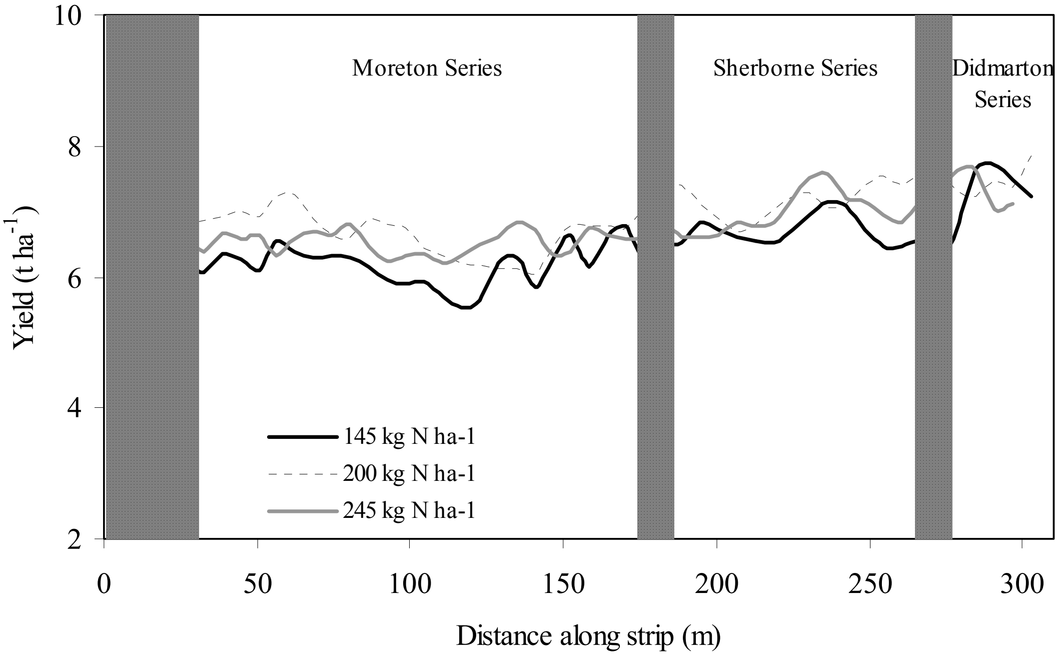


Fig. 10. Combine Yield (t ha^{-1}) of N response treatment strips in Twelve Acres in 1997/98. Shaded area represents lead-in time of combine harvester: ——, 145 kg Nha^{-1}; - - - -, 200 kg Nha^{-1}; ——, 245 kg Nha^{-1}

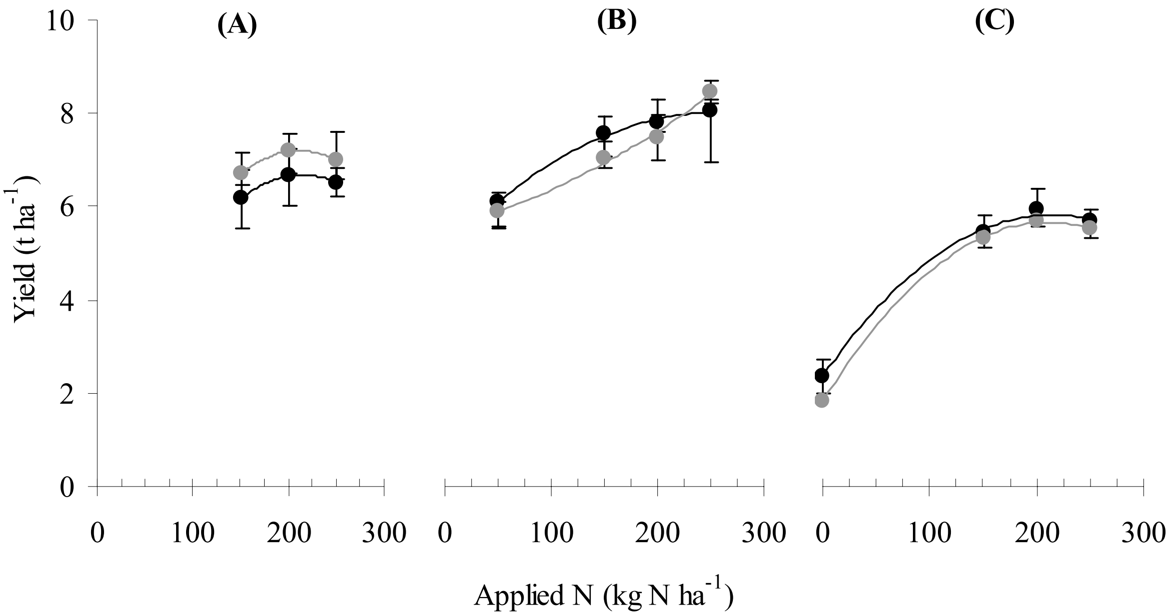


*Fig. 11. Yield response to applied N in the Moreton and Sherborne soil series zones in Twelve Acres in (**A**) 1997/98, (**B**) 1998/99 and (**C**) 1999/00. Error bars denote the yield range about the mean.* ●*, Moreton;* ●*, Sherborne*

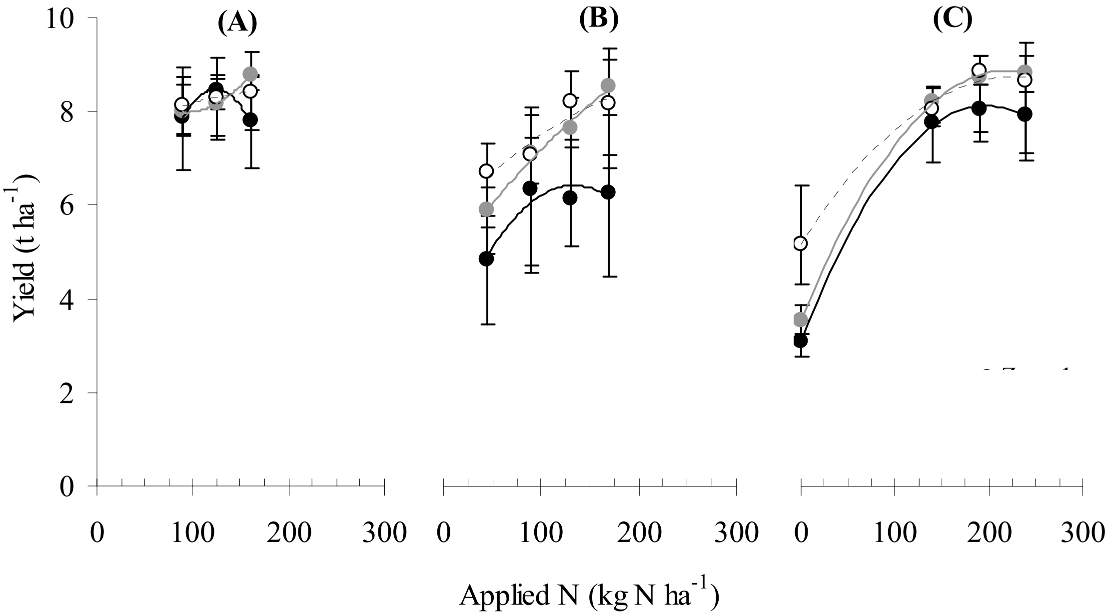


*Fig. Yield response to applied N in Zones 1, 2 and 3 in Far Sweetbrier in (**A**) 1997/98, (**B**) 1998/99 and (**C**) 1999/00. Error bars denote the yield range about the mean.* ●*, Zone 1;* ●*, Zone 2;* ○*, Zone 3*

Fig.13. Aerial photograph of Far Sweetbrier taken 18 July 1996. Image shows crop marks revealing remnants of ancient field boundaries.

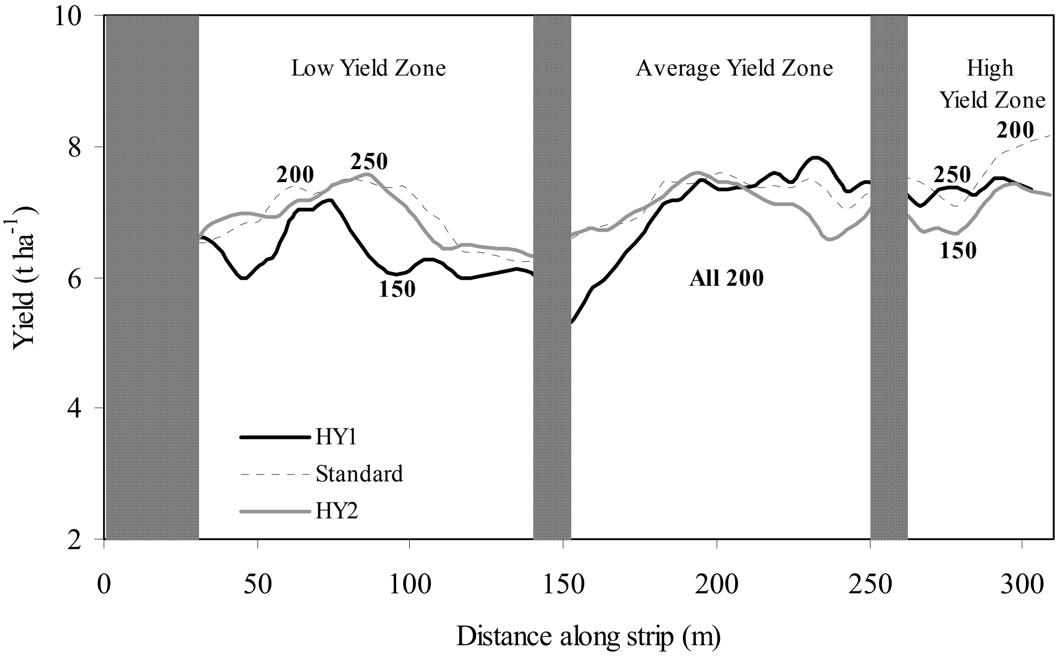


*Fig. 14. Combine Yield (t ha^{-1}) of the Historic Yield (HY) strategy treatment strips in Twelve Acres in 1997/98. Shaded area represents lead-in time of combine harvester. Numbers in bold (**150, 200, 250**) are the N application rate in kg N ha^{-1}. ——, HY1; - - - ·, Standard; ——, HY2*

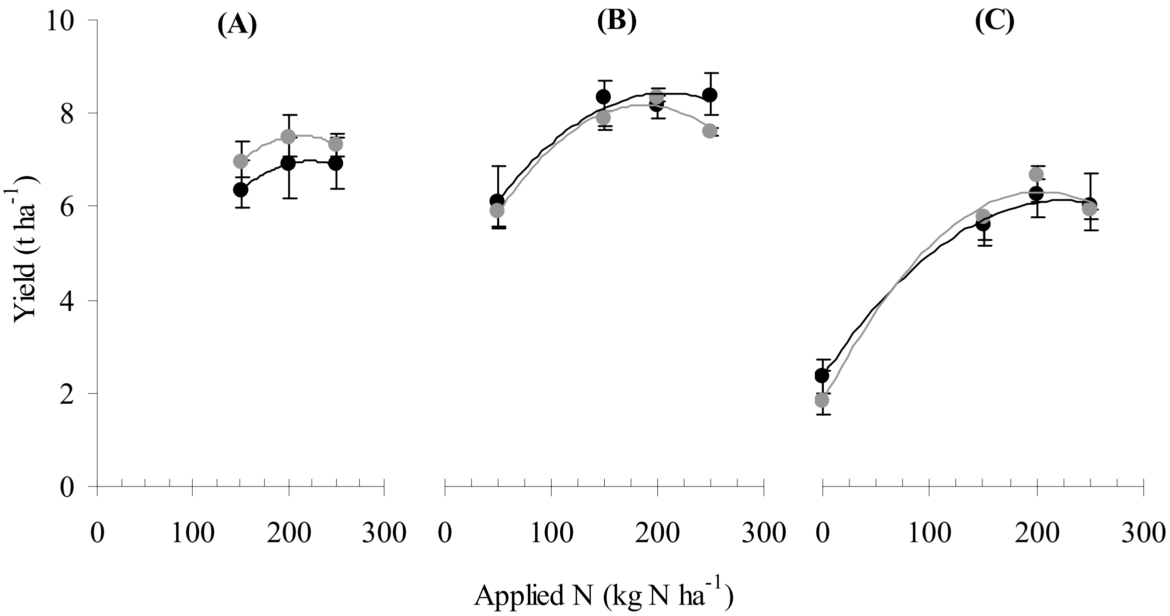


*Fig. 15. Yield response to applied N in the high and low yielding parts of Twelve Acres in (**A**) 1997/98, (**B**) 1998/99 and (**C**) 1999/00. Error bars denote the yield range about the mean yield for each N rate in each management zone.* ●*, Low yield zone;* ●*, High yield zone*

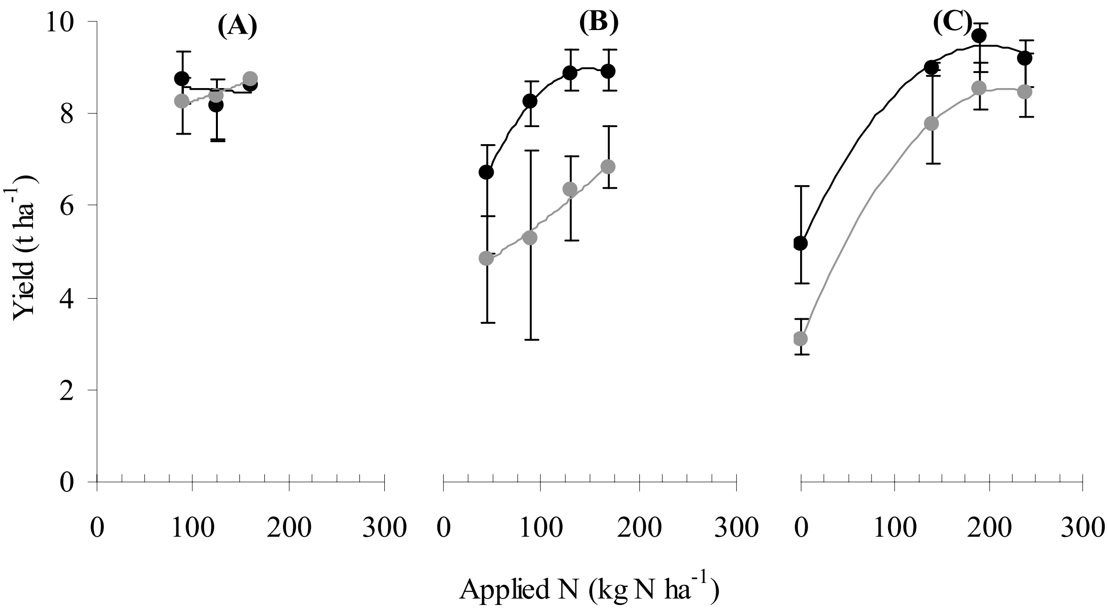


*Fig. 16. Yield response to applied N in the high and low yielding parts of Far Sweetbrier in (**A**) 1997/98, (**B**) 1998/99 and (**C**) 1999/00. Error bars denote the yield range about the mean yield for each N rate in each management zone.* ●*, Low yield zone;* ●*, High yield zone*

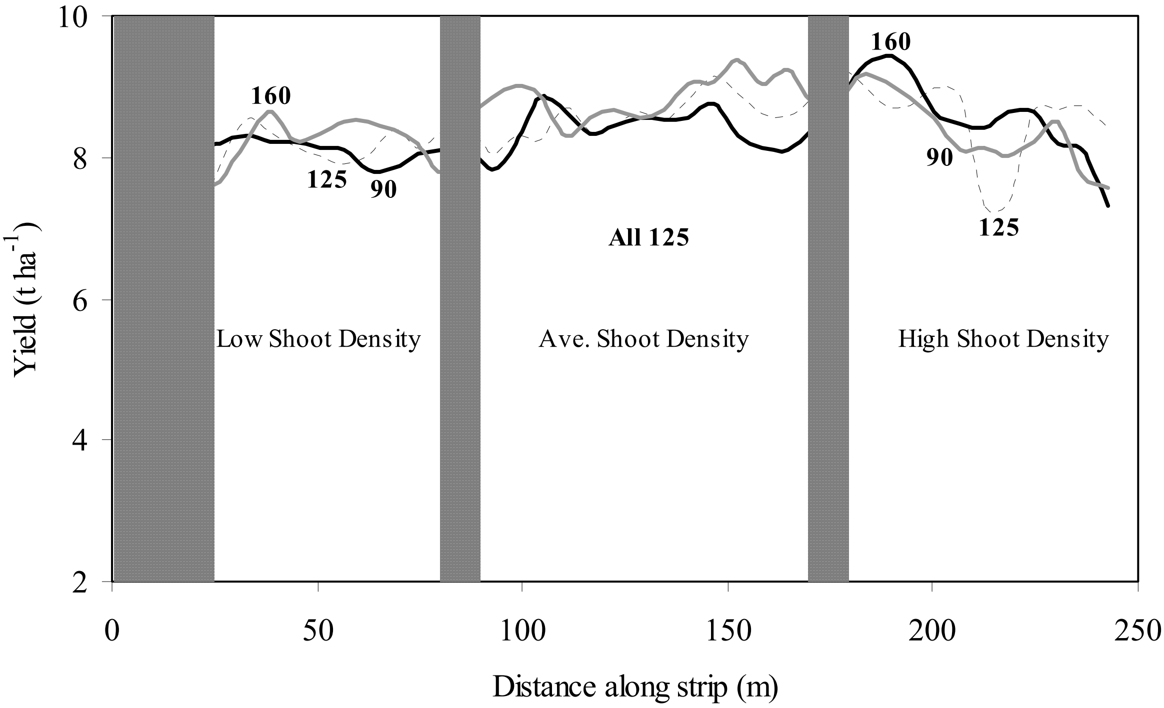


*Fig. 17. Combine Yield (t ha^{-1}) of the Shoot Density (SD) strategy treatment strips in Far Sweetbrier in 1997/98. Shaded area represents lead-in time of combine harvester. Numbers in bold (**90, 125, 160**) are the N application rate in kg N ha^{-1}.*
——, SD1; - - - ·, Standard; ——, SD2

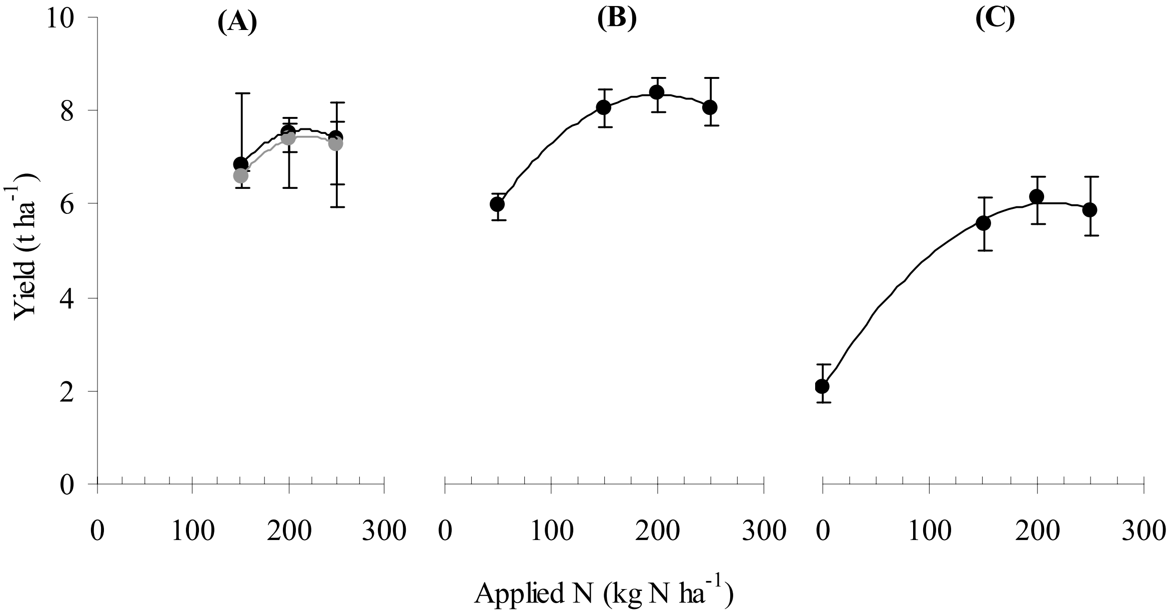


*Fig. 18. Yield response to applied N in areas of Twelve Acres with either a relatively high or low shoot density, compared with the field average in (**A**) 1997/88, (**B**) 1998/99 and (**C**) 1999/00. Error bars denote the yield range about the mean yield for each N rate in each management zone. ●, Low density zone; ●, High density zone*

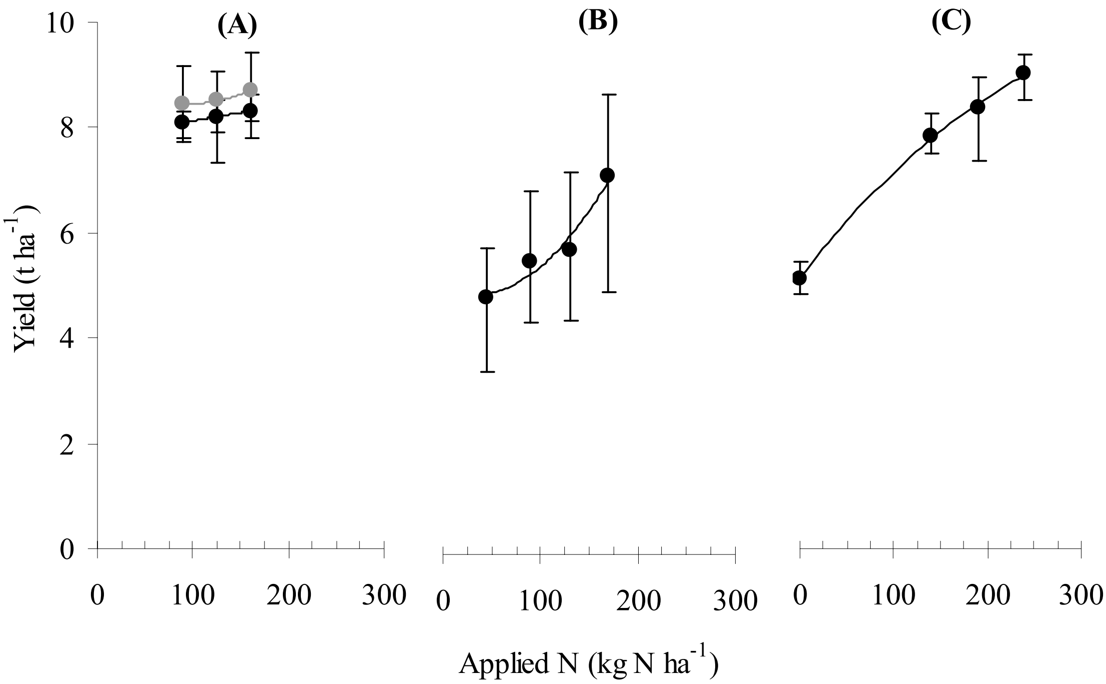


*Fig. 19. Yield response to applied N in areas of Far Sweetbrier with either a relatively high or low shoot density, compared with the field average in (**A**) 1997/88, (**B**) 1998/99 and (**C**) 1999/00. Error bars denote the yield range about the mean yield for each N rate in each management zone. ●, Low density zone; ●, High density zone*

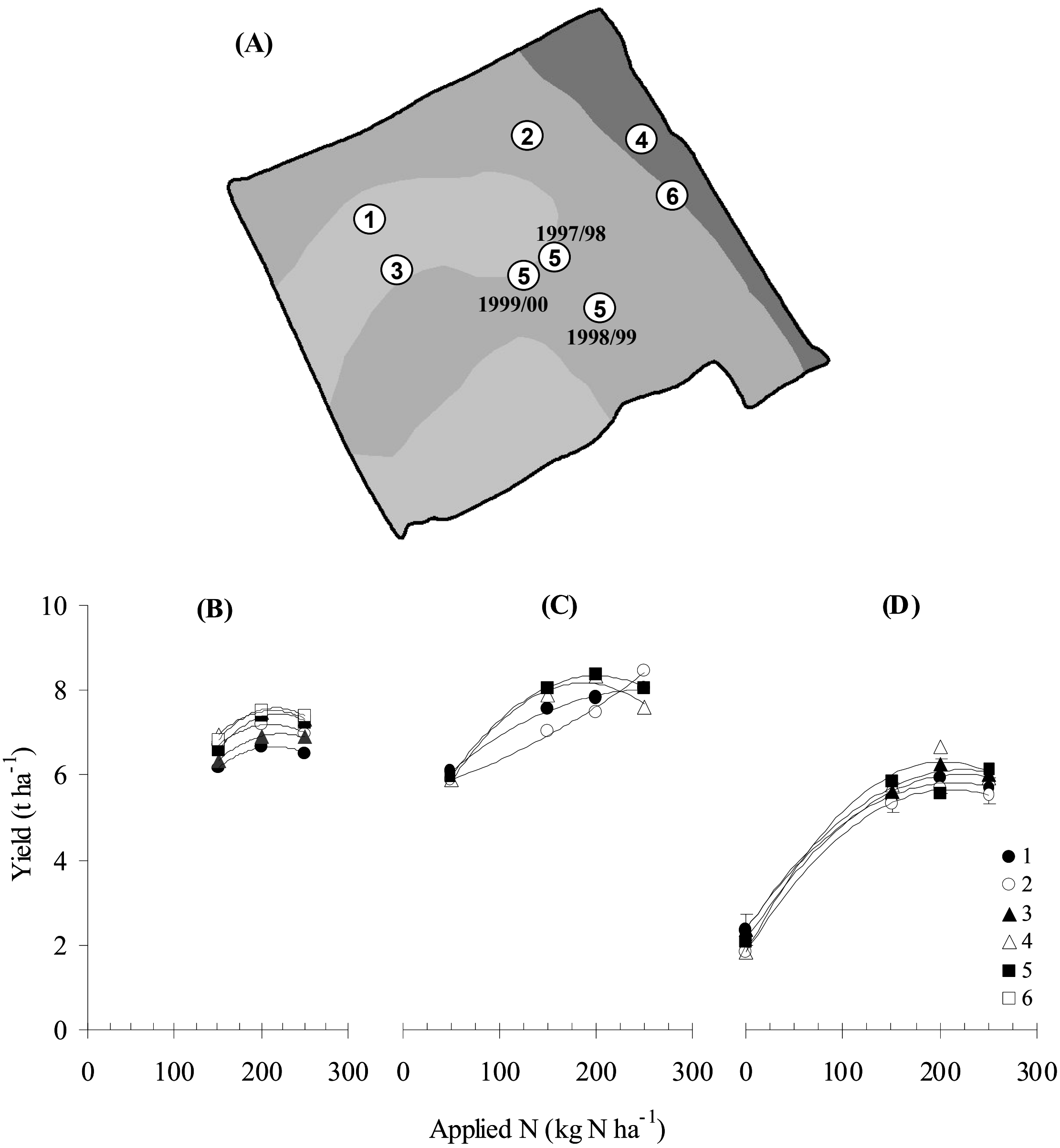


Figure 20 **(A).** Spatial locations of crop yield response to applied N in Twelve Acres in **(B)** 1997/98, **(C)** 1998/99 and **(D)** 1999/00. The numbers in **(A)** relate to areas where response curves were determined and match up with the figures legend in **(B)** – **(D):** ●, 1; ○, 2; ▲, 3; △, 4; ■, 5; □, *6*. Sampling position 5 in **(A)** occurs in three locations due to the different treatment positions in each of the seasons.

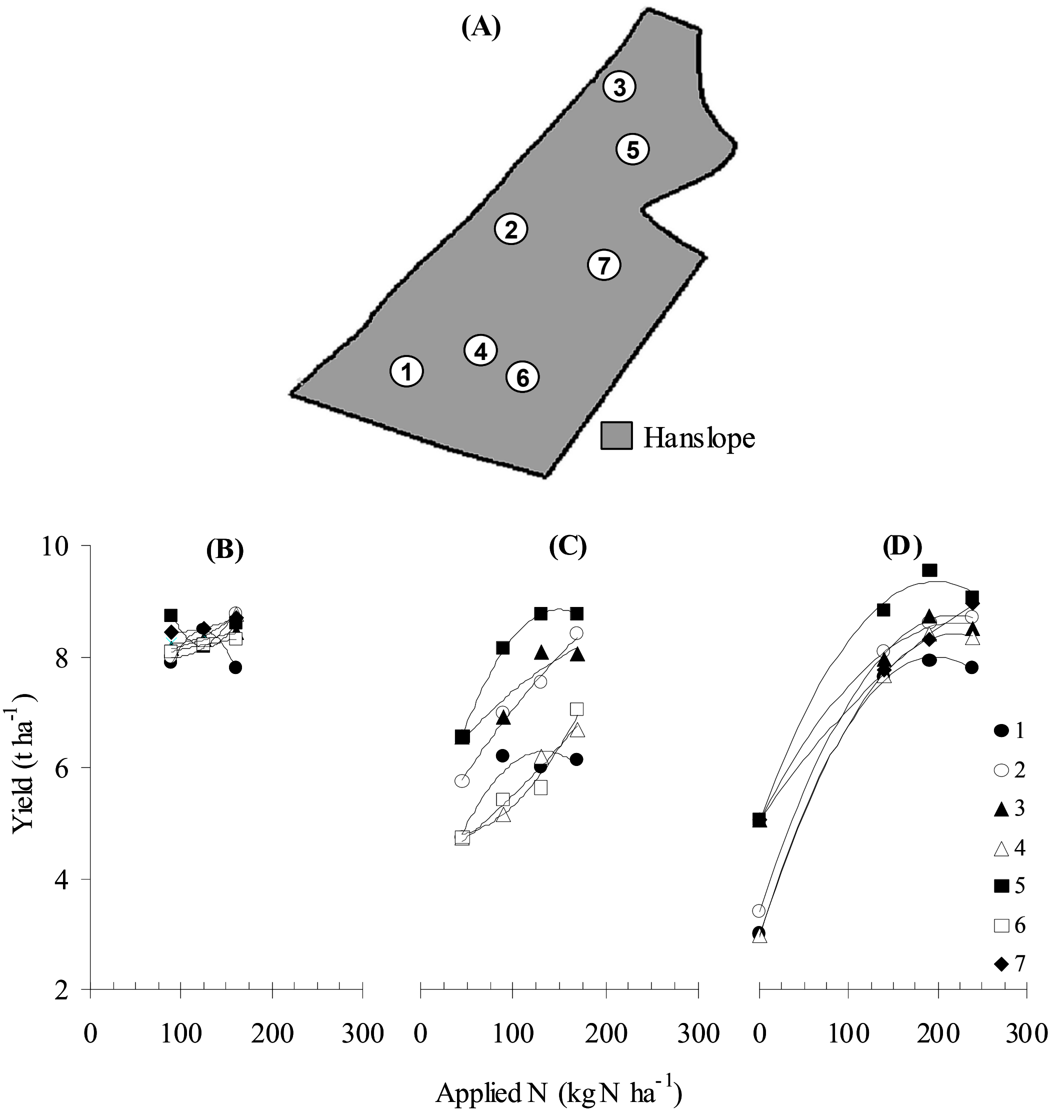


Figure 21 (**A**). *Spatial locations of crop yield response to applied N in Far Sweetbrier in (**B**) 1997/98, (**C**) 1998/99 and (**D**) 1999/00. The numbers in (**A**) relate to areas where response curves were determined and match up with the figures legend in (**B**) – (**D**):* ●, 1; ○, 2; ▲, 3; △, 4; ■, 5; □, *6;* ◆, *7*

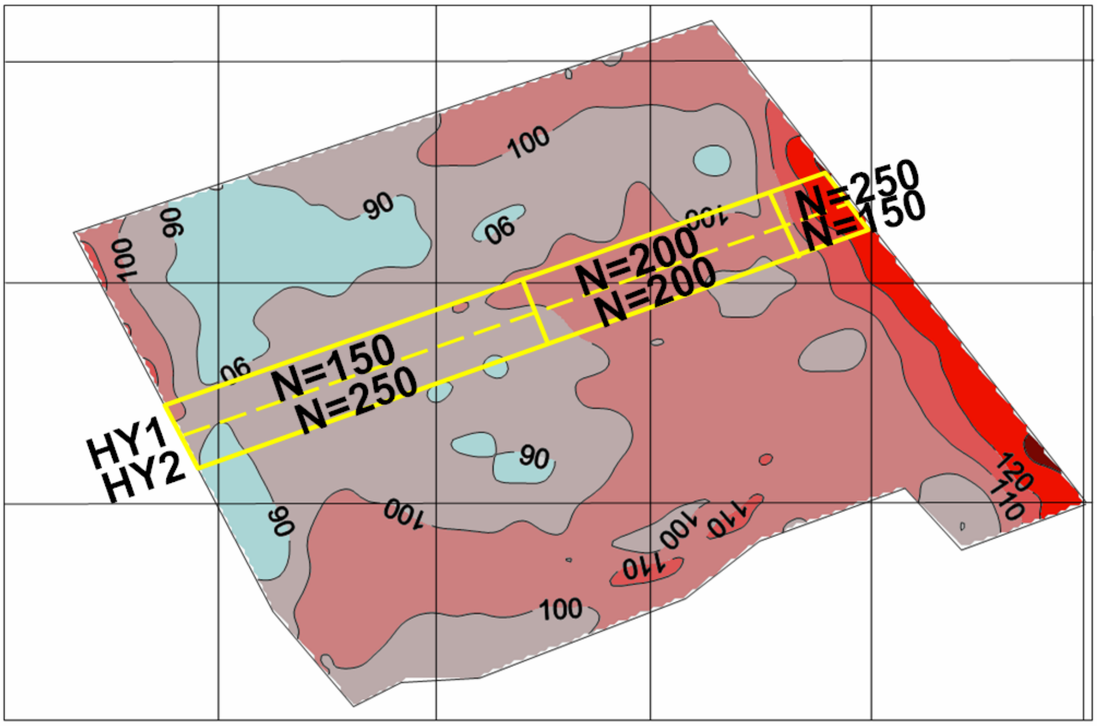


Fig. 4. Historic yield distribution in Twelve Acres expressed as a percentage of the two-year average derived from two years' of yield maps (1995 and 1996). HY1 and HY2 refer to treatment strips and N=150, 200, 250 refers to the nitrogen application rate in kg N ha^{-1}; 100 m grid spacing

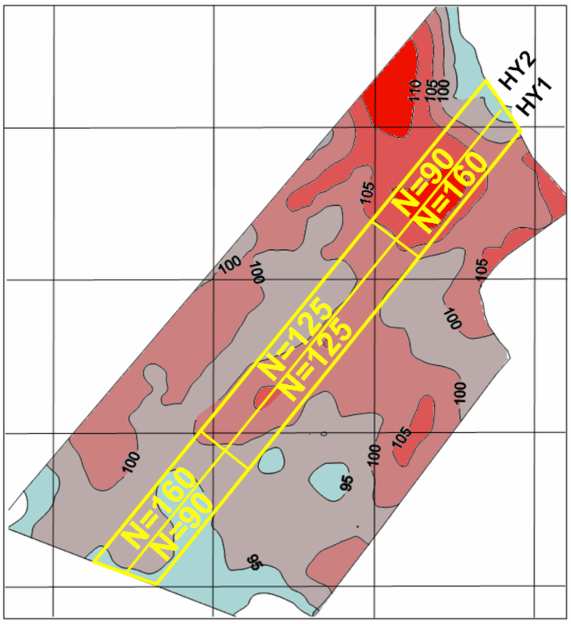


Fig. 5. Historic yield distribution in Far Sweetbrier expressed as a percentage of the three-year average derived from three years' of yield maps (1995 – 1997). HY1 and HY2 refer to treatment strips and N= 125, 160, 90 refers to the nitrogen application rate in kg N ha^{-1}; 100 m grid spacing

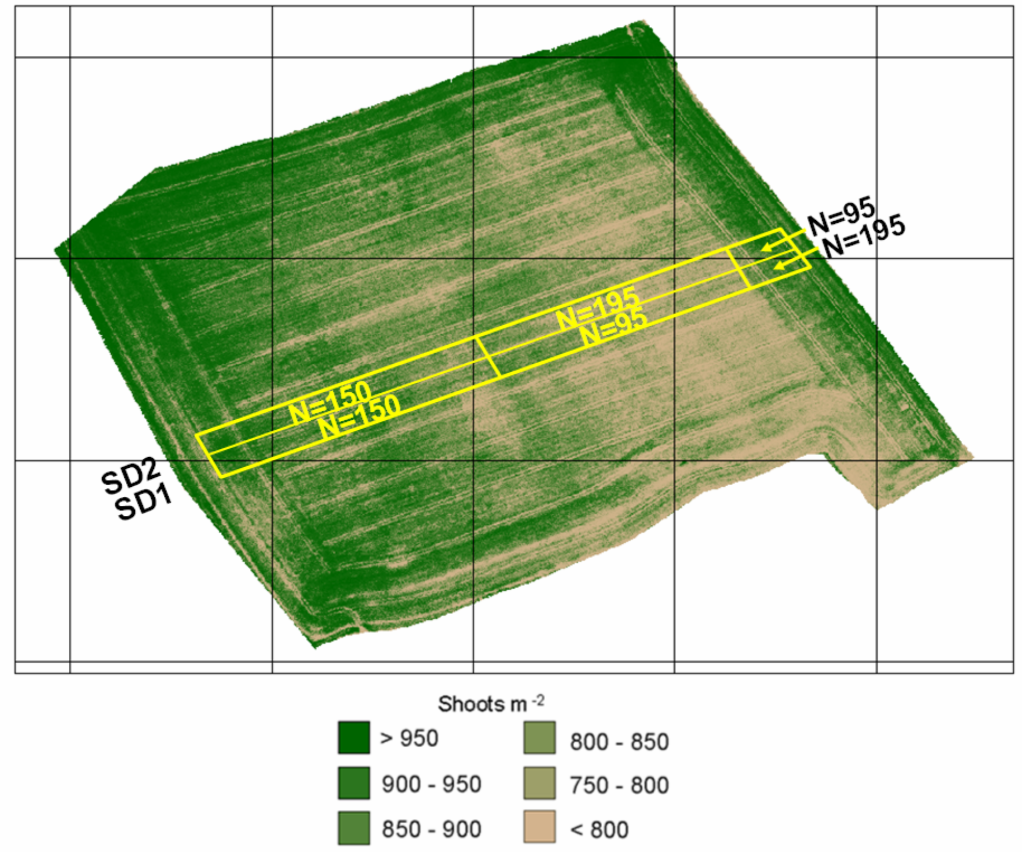


Fig. 6(a). Aerial Digital Photography (ADP)-derived shoot density map for Twelve Acres (accuracy of calibration: r^2=0.98; Standard error = 47 shoots m^{-2}) showing treatment strips and corresponding N application rates. Image acquired (28 February 1998) and N = 150, 200, 250 refers to the nitrogen application rate in kg N ha^1; 100 m grid spacing

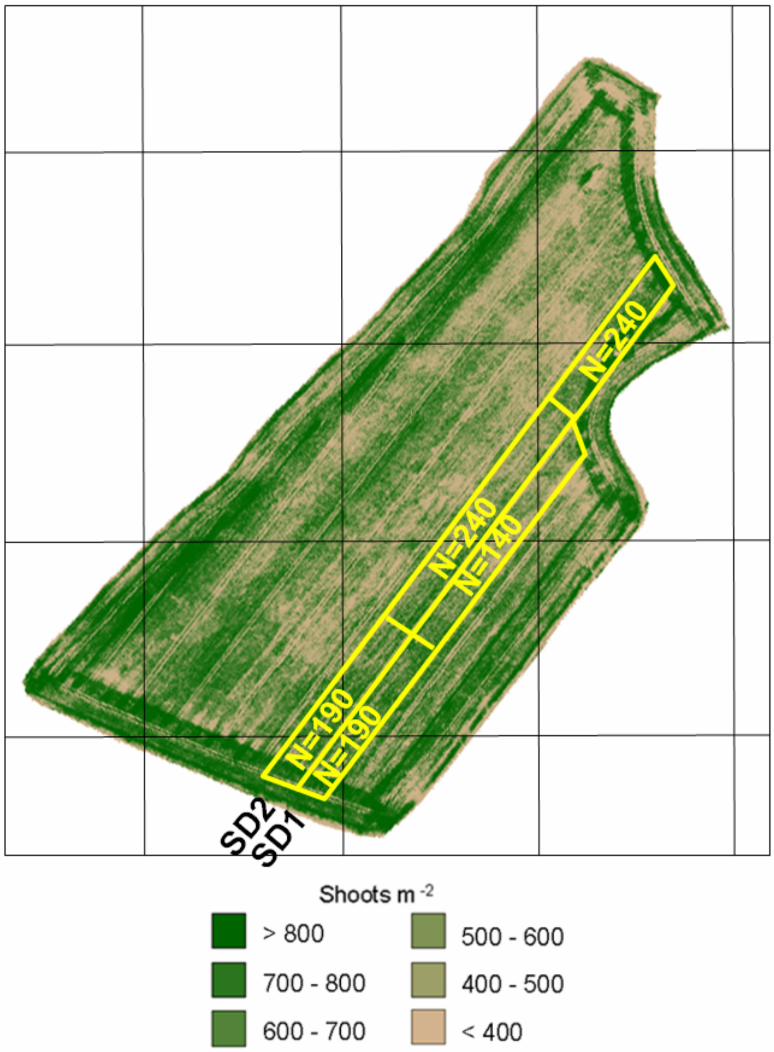


Fig. 6(b). Aerial Digital Photography (ADP)-derived shoot density map for Far Sweetbrier (accuracy of calibration: r^2=0.98; Standard error = 47 shoots m^{-2}) showing treatment strips and corresponding N application rates. Image acquired (5 March 1998) and N = 90, 125 160 refers to the nitrogen application rate in kg N ha^{-1}; 100 m grid spacing

Fig.13. Aerial photograph of Far Sweetbrier taken 18 July 1996. Image shows crop marks revealing remnants of ancient field boundaries.