PROJECT REPORT No. 267

'PRECISION FARMING' OF CEREAL CROPS: A FIVE-YEAR EXPERIMENT TO DEVELOP MANAGEMENT GUIDELINES

JANUARY 2002

Price £4.10

PROJECT REPORT No. 267

by

R J GODWIN, R EARL, J C TAYLOR, G A WOOD, R I BRADLEY
J P WELSH, T RICHARDS, B S BLACKMORE

National Soils Resource Institute, Cranfield University at Silsoe, Silsoe, Bedfordshire MK45 4DT

M J CARVER

Arable Research Centres, Manor Farm, Daglingworth, Cirencester, Gloucestershire GL7 7AH

S KNIGHT

ARC Eastern, Shuttleworth College, Old Warden Park, Biggleswade, Bedfordshire SG18 9DX

B WELTI

Shuttleworth Trust, Old Warden Park, Biggleswade, Bedfordshire SG18 9DX

This is the final report of a 63-month project that started in April 1996. The work was funded by a grant of £729,739 from HGCA (Project No. 1743). Further support was provided by Massey-Ferguson (in kind as machinery) and Hydro Agri (UK) (£210,000).

CONTENTS

ABSTRACT

Precision Farming is the term given to a method of crop management by which areas of crop within a field may be managed with different levels of input. The benefits of so doing are three-fold:

i. the economic margin from crop production may be increased by improvements in yield or a reduction in inputs,

ii. the risk to environmental pollution from agrochemicals applied at greater levels than those required by the crop can be reduced,

iii. greater assurance from precise targeting and recording of field applications to improve traceability.

It is an excellent example of where both economic and environmental considerations are working together.

This five-year study, principally involving five fields in Southern and Eastern England, covered a total of thirteen soil types that represented approximately 30% of the soils producing arable crops in England and Wales. The overall aim of the project was to determine guidelines to maximise profitability and minimise environmental impact of cereal production using precision farming. The objectives were:

i. To develop a methodology for identifying the causes of within-field variation in crop performance.

ii. To develop practical guidelines required to implement precision farming technology to achieve best management practice.

iii. To explore possibilities of using remote sensing methods to enable decisions to be made in "real time" during the growth of the crop.

iv. To determine potential economic benefits of using precision farming technology for cereal production.

v. To collaborate with a range of farmers with interests in precision farming to ensure that research findings are appropriate for adoption.

The study concentrated on the interaction between soil/water variability and nitrogen applications. The harvest years 1995-97 (which included a harvest before the formal start of the programme) concentrated on identifying the in-field variability and the development of the "real time" sensing techniques. Studies in harvest years 1998-2000 compared spatially controlled inputs with uniform agronomic practice. A number of techniques were used to decide upon the variable application strategy. These included information on:

i yield variability from historic yield maps,

ii variability in shoot density in the spring, and

iii variability in the subsequent development of the canopy (green area index);

the latter two enabling the development of the concept of "real-time" agronomic management.

The major outcomes of the project were as follows:

i. Yield maps are indispensable for targeting areas for investigation and treatment by precision farming practices and subsequent monitoring of results. They provide a valuable basis for estimating replenishment levels of P and K fertilisers. However, they do not provide a useful basis for determining a variable nitrogen application strategy to optimise management in a particular season.

ii. The possible extent and potential causes of yield variability can be determined using low capital cost yield mapping systems together with electro-magnetic induction techniques to assess variation in soil factors such as texture and water-holding capacity. An objective methodology has been developed to use these techniques to determine within-field management zones. Both individually and together these systems provide a means for assessing the degree of variability within a field and provide a basis for targeting soil and crop sampling points, which is the only cost-effective method for commercial use.

iii. The spatial variation in canopy development within a field can be estimated using an aerial digital photography (ADP) technique developed by Cranfield University for this project for "real-time" agronomic management. This technique can be extended from field-scale to farm-scale for crops of similar varieties and planting dates. The processing of data from cameras mounted in light aircraft is sufficiently fast to enable application rate plans to be produced and implemented in near real-time. The technique can be used as a basis for determining the most appropriate application rate for nitrogen, and as a guide for herbicide and plant growth regulator application. It is feasible to adapt the system for use with tractor-based systems.

iv. The application of nitrogen in a spatially variable manner can improve the efficiency of cereal production through managing variations in the crop canopy. Depending upon field and year, between 12% and 52% of the area of fields under investigation responded positively to this approach. In 2000 seven out of eight treatment zones gave positive economic returns to spatially variable nitrogen with an average benefit of £22 ha^{-1}.

v. Simple nitrogen balance calculations have shown that in addition to a modest increase in yield, the spatially variable application of nitrogen can have an overall effect on reducing the nitrogen surplus by approximately one third.

vi. Common problems, such as water-logging and fertiliser application errors, can result in significant crop yield penalties. Precision farming can enable these problems to be identified, lost revenue to be calculated and resultant impact on cost-benefit to be determined. This provides a basis from which informed management decisions can be taken. It is critical that these problems are corrected prior to the spatial application of fertilisers and other inputs.

vii. At current prices, benefits from spatially variable application of nitrogen outweigh costs of the investment in precision farming systems for cereal farms greater than 75 ha if basic systems costing £4,500 are purchased, and greater than 200-300 ha for more sophisticated systems costing between £11,500 and £16,000.

viii. Integrating the economic costs with the proportion of the farmed area that has benefit potential enables the break-even yield increase to be estimated. Typically a farmer with 250 ha of cereals where 20% of the farmed area could respond positively to spatially variable nitrogen would need to achieve a yield increase of 1.1 t ha^{-1} on that 20% to break even.

ix. The net effect of combining the benefits of spatially variable application of nitrogen (£22 ha^{-1}) with the benefits from both the spatial application of herbicides (up to £20 ha^{-1}) and fungicides (up to £20 ha^{-1}), found from other studies, should provide valuable returns from the adoption of precision farming concepts. However, this should not be considered as a simple sum of maximum levels quoted.

These economic advantages linked to the environmental benefits should improve the longer term sustainability of cereal production.

SUMMARY

Introduction

Precision Farming is the term given to a method of crop management by which areas of land or crop within a field are managed with different levels of input in that field. The potential benefits are:

i. the economic margin from crop production may be increased by improvements in yield or a reduction in inputs, and
ii. the risk of environmental pollution from agrochemicals applied at levels greater than optimal can be reduced.
iii. greater assurance from precise targeting and recording of field applications to improve traceablilty.

These benefits are excellent examples of where both economic and environmental considerations are working together.

This report provides an overview of a 5 year study funded by the Home-Grown Cereals Authority, Hydro Agri and AGCO Ltd, with the aim of developing practical guidelines for implementing precision farming technology for the UK cereal industry by:

i. developing a methodology for identifying causes of within-field variation,
ii. exploring the use of remote sensing methods to enable management decisions to be made in "real-time" during growth of the crop,
iii. determining potential economic benefits of precision farming,
iv. collaborating with farmers to ensure that research findings are appropriate for adoption.

The emphasis of this work was placed on the development of guidelines to assist management of ever-increasing sizes of enterprise when economic margins are under great pressure. It is the technology that assists in recognising the spatial boundaries together with equipment for yield recording and the variable application of agronomic inputs that has re-kindled the interest in the approach to farming in recent years. The main catalyst for this was the advent of affordable differential global positioning systems that enabled a number of yield mapping systems to appear on the market from 1990.

Whilst there have been, and still are, challenges to be addressed relating to the hardware and software aspects of the precision farming system, the single greatest challenge is in interpreting information from yield maps, crop performance records (both historic and "real time") and soil analysis into practical strategies for the variable application of crop treatments for an individual field.

Approach

A summary of factors that could influence the yield of crops in a given location is presented in Table 1. Whilst little control can be exercised over factors on the left of the table, they have to be considered as they can have major effects upon yield. The factors on the right, however, can be manipulated in a spatially variable manner and could lead to economic benefits from either (i) yield improvements due to changes in input or (ii) savings in input costs without an adverse effect upon crop yield.

Table 1. Factors influencing yield variation

Little control	Possible control	
Soil texture	Soil structure	pH levels
Climate	Available water	Trace elements
Topography	Water-logging	Weed competition
Hidden features	Macro nutrients	Pests and diseases

The duration of the main HGCA-funded study was planned to extend over 5 cropping seasons and include the harvests in 1996-2000. The fields detailed in Table 2 were selected to provide a range of case studies and included soils typical of approximately 30% of the land used for arable production in England and Wales. These fields had predominantly been in cereals for several years prior to the experimental work. To aid this long term study, AGCO Ltd. harvested crops and produced yield maps for the fields during the 1995 harvest and, therefore, provided an opportunity for studying the extent and degree of inherent within-field variation present before the outset of the main project.

Table 2. Field details and location

Field name	Location	Soil Series*	Cropping Pattern
KEY FIELDS – ALL YEARS			
Far Sweetbrier	Old Warden, Bedfordshire	Hanslope	Winter Wheat, Oilseed Rape rotation
Onion Field	Houghton Conquest, Bedfordshire	Denchworth/Oxpasture / Evesham	Continuous Winter Wheat
Trent Field	Goodworth Clatford, Hampshire	Andover / Panholes	Continuous Winter Barley
Twelve Acres	Hatherop, Gloucestershire	Sherborne / Moreton / Didmarton / Haselor	Continuous Winter Wheat
SUPPLEMENTARY FIELDS FOR 1998/99 AND 1999/2000			
Shortwood 1998/99	Gamlingay, Cambridgeshire	Hanslope / Denchworth	Winter Wheat
Far Highlands 1999/2000	Old Warden, Bedfordshire	Wickham / Evesham	Winter Wheat

*after: Jarvis et al. (1984) and Hodge et al. (1984)

At the outset it was agreed that the reasons for any underlying field variation needed to be established prior to managing the crop in a spatially variable manner. Hence, uniform 'blanket' treatments were applied in the 1995-6 and 1996-7 seasons. Yield maps for these two seasons, together with those from the 1995 harvest, provided an indication of crop yield variation both in space and time. Since the 1997-8 cropping season, effects of variable inputs were studied on all fields shown in Table 2.

A number of fields planted with uniform seed rate were subjected to variable inputs of nitrogen. An additional two fields, Onion Field and Far Highlands, had variable nitrogen inputs applied across a range of seed rates that had been sown to create different crop canopy structures.

Inherent Variability

Crop yield

Typical variations in crop yield are presented in Figure 1, which shows that there is some similarity over the three-year period. The spatial trend map (average yield) for the period shows that, on average, the yield range for this particular field is in excess of ?20% of the mean, with the higher yielding zones to the west and the lower yielding zones to the east of the 100% (or mean) contour. These maps have been corrected using algorithms to compensate for field operational artifacts associated with combine harvester grain filling at the headlands and crop harvesting widths of less than the full width of the combine harvester cutter bar. The variation in yield for the 4 main fields averaged between ±25% of the mean yield with a range of ±20% to ±33%.

An important outcome of this project was the development and refinement of spatial yield maps that are now in use in the industry.

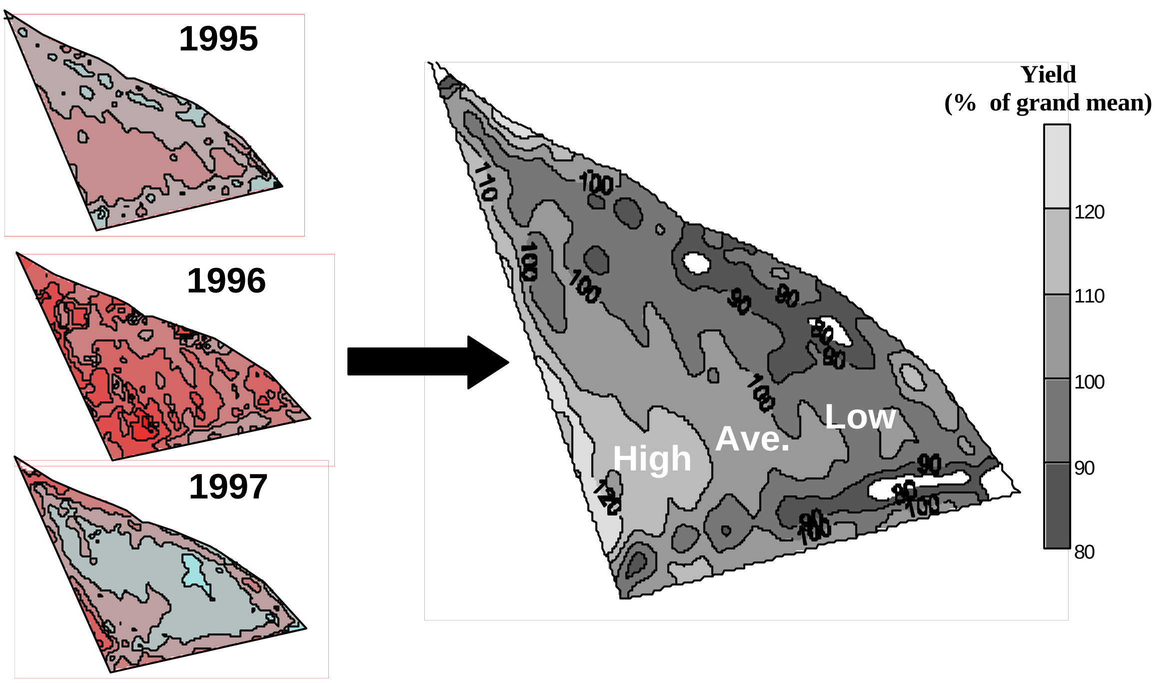


Figure 1. Spatial trend (average yield) map for yield at Trent Field, 1995 - 1997

Soil types

The fields were initially surveyed at a commercial detail level of approximately 1 auger hole/ha to provide an overview of soil textural and profile variation. These were complemented by "targeted" profile pit descriptions. The location of the profile pits were selected to encompass:

i the range of yields observed in the yield maps of 1994/95 and 1995/96,

ii the density of the crop from aerial digital photography (see Section 3.4) captured in May 1996, and

iii soil maps based on auger sampling at a 100 m grid spacing.

The soil profile pits, 3 m long x 1 m wide x 1.5 m deep, were excavated to provide detailed information for soil classification, on crop rooting depth and soil drainage status. Excavations such as these, should be viewed as a one-off investment since photographs taken of geo-referenced soil profiles can be passed on to successive generations and have a greater impact than traditional written profile descriptions.

Further studies with soil coring apparatus (to a depth of 1 m) and electromagnetic induction (EMI) equipment increased the resolution to define soil textural boundaries. The latter technique is particularly useful for differentiating soil textures as shown in Figure 2, where the higher levels of conductivity indicate higher moisture content soils, which, if conducted at field capacity, would indicate greater clay content.

Objective techniques, using cluster analysis, have been developed which enable potential management zones to be determined using historic yield and EMI data. Differences in soil nutrient levels have been identified between the management zones and, hence, form a basis for targeted sampling of soil nutrient status.

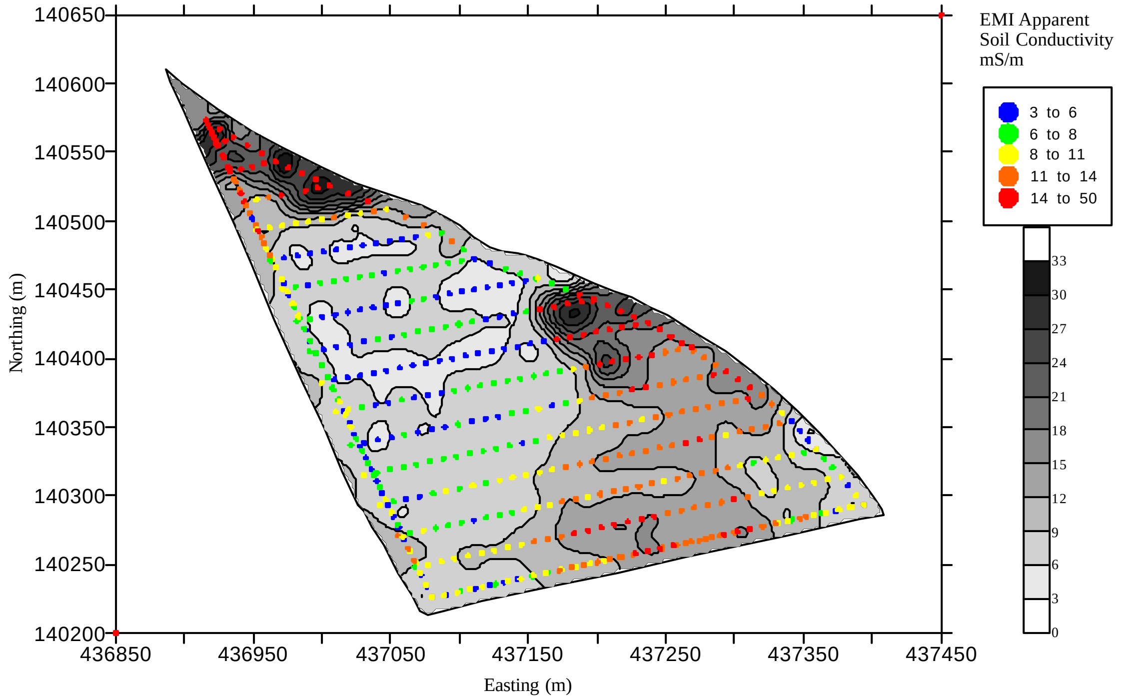


Figure 2. EMI conductivity Trent Field 2nd February 1999

Soil fertility and crop nutrition

Detailed analyses of macro- and micro-nutrients in both soil water extracts and plant tissue were conducted at approximately 50 m grid spacings together with soil pH. These indicated that there was variation in nutrient levels in each of the fields. However, with the exception of isolated areas with low pH, the levels were above the commonly accepted agronomic limits.

Crop canopy

Variations in crop canopy occur both in space and time in the same field. In order to obtain consistent and reliable data for monitoring crop development for 'real time' management and to explain field differences, a light aircraft was equipped with two digital cameras fitted with red (R) and near infra red (NIR) filters. Field images obtained from aerial digital photography (ADP) from a height of 1000 m give a pixel resolution of 0.5 m x 0.5 m. Normalised Difference Vegetation Index (NDVI) values were estimated from the following equation:

$$\text{NDVI} ? \frac{\text{NIR} ? \text{R}}{\text{NIR} ? \text{R}}$$

The resulting images, such as Figure 3, show the effect of variations in crop development immediately prior to the first application of nitrogen. These images are (i) immediately valuable in discerning patterns of field variability, and (ii) provide detailed spatial data on crop tillers/shoot density. These data, when calibrated against detailed agronomic measurements at targeted locations, were used in near "real time" to estimate crop condition and potential nutritional requirements. Extension of this principle to farm scale operations results in effective calibration between the crop indicators and NDVI using 8 sampling points. The cost of extending this technique to commercial practice has been estimated at £7/ha for 3 flights/year, during the January to April period, for areas of 1500 ha/flight. It has also been possible using this system to identify areas in need of spatially variable application of herbicides and plant growth regulators.

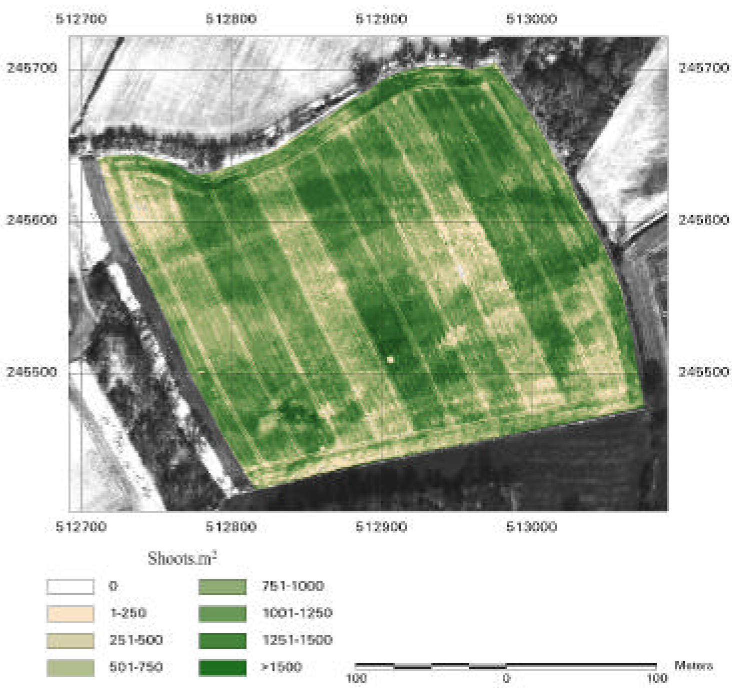


Figure 3. A calibrated NDVI image of Far Highlands indicating shoot density.

Conclusions from the field variability studies

The major long-term causes of yield variation in the study fields were attributable to soil and its associated water holding capacity. In the fields selected, whilst there was variation in the availability of plant nutrients, potassium, phosphorus and the micro-nutrients were not limiting. Stable patterns in yield were observed over the sequences of annual yield maps. The ADP system specified for this project allowed variations in crop yield components to be mapped in near "real time".

Variable Application of Nitrogen

Experimental design

One of the aims of this project was to develop an experimental methodology that could be employed by farmers to determine an optimal application strategy for a given input in any particular field, in this case nitrogen. To achieve this, it was important to use standard farm machinery for the experiments. This resulted in a move away from the traditional small plot randomised block experimental design.

The proposed design comprised a series of long strips, which ran through the main areas of variation within each field, an example of which is presented in Figure 4, where the treatment strip is interlaced with the field standard. The width of each strip was dependent upon the existing tramline system and/or the working width of the machinery available. The treatment strips were, therefore, half the width of a tramline. The fertiliser was applied using a pneumatic or liquid fertiliser applicator that was capable of operating the left and right booms independently. The strip widths used allowed the experiments to be harvested by the combine harvester without the inclusion of the tramline wheel marks. The combine was equipped with a radiometric yield sensor with a mean instantaneous grain flow error of 1%.

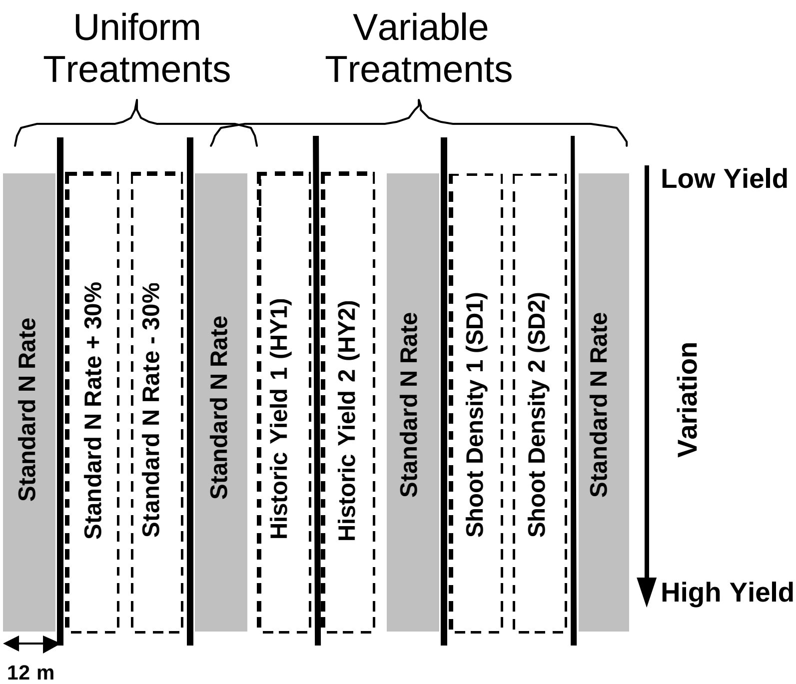


Figure 4. Plan of field experiments

Nitrogen response studies

These treatment strips had different rates of nitrogen applied uniformly along their complete length. The purpose of this was to provide an indication of the crop response to different levels of nitrogen in the various zones of the field, from typically low to high yielding areas. These were conducted with a uniform seed-rate of 300 seeds m^{-2} in 1997/98, 1998/99, and 1999/00 in Far Sweetbrier, Trent Field and Twelve Acres.

Historic yield and shoot density studies

These treatment strips were established to test the following strategies in the same fields used in the nitrogen response studies.

i Increasing the fertiliser application to the higher, or potentially higher, yielding parts of the field whilst reducing the application to the lower yielding parts.

ii Reducing the fertiliser application to the higher, or potentially higher, yielding parts of the field whilst increasing the application to the lower yielding parts.

However, before these strategies could be implemented, the high, average and low yielding zones had to be identified. Two methods were used:

i historic yield data, as shown in Figure 2.

ii shoot density data, estimated from NDVI data, as shown in Figure 3.

Using this approach, experimental strips (Figure 4) were established to give the following treatments:

Historic Yield 1 (HY1). High yield zone received 30% more nitrogen; average yield zone received the standard nitrogen rate; and the low yield zone received 30% less nitrogen.

Shoot Density 1 (SD1). High shoot density zone received 30% more nitrogen; average shoot density zone received the standard nitrogen rate; and the low shoot density zone received 30% less nitrogen.

Historic Yield 2 (HY2). High yield zone received 30% less nitrogen; average yield zone received the standard nitrogen rate; and the low yield zone received 30% more nitrogen.

Shoot Density 2 (SD2). High shoot density zone received 30% less nitrogen; average shoot density zone received the standard nitrogen rate; and the low shoot density zone received 30% more nitrogen.

Standard N rate strips were located adjacent to each of the variable treatment strips to allow treatment comparisons to be made, since classical experimental design and statistical analyses with replicated plots was not possible.

Crop canopy management studies

The methodology for these studies was developed over three years in Onion Field, but was extended to include Far Highlands in the final season. Seed rates of 150, 250, 350 or 450 seeds m^{-2} were used to establish 24 m wide strips of wheat with a range of initial crop structures. In 1997/98, the impact of seed rate on subsequent variation in canopy structure, yield components and grain yield was studied separately, with a standard dose of nitrogen fertiliser applied uniformly to all strips. In the second and third years, the strips were then subdivided into two 12 m wide sections. One section received a standard field rate of nitrogen fertiliser (200 kg N ha^{-1}), and the other received a variable amount dependent upon crop growth. Observations were made in near "real time" using the ADP technique and crop canopy measurements as described above. Appropriate flights were made prior to each of the three nitrogen application timings in the February to May period, and crop growth (shoot populations at tillering and canopy green GS30-31 and GS33) compared with benchmarks from the HGCA Wheat Growth Guide. A default nitrogen strategy was calculated using canopy management principles for areas of the variable strips where growth was on target, and application rates were then increased or decreased along each strip, where growth was above or below target respectively.

Results

Nitrogen response studies

Typical examples of the nitrogen response curves for the uniform treatments for the winter barley crop in Trent Field are given in Figure 5 for the three years of the experiment. This shows a significant difference in the nitrogen response curve and the optimum application rate between the two soil types in 1997/98 when the Panholes series had the greater soil moisture deficit. In the following two seasons the soil moisture deficits were lower and both soil types were similar, resulting in common yield response curves.

Three consecutive winter wheat crops of feed varieties were grown in Twelve Acres with two main soil series. Crops grown on Sherborne series soil produced higher yields than those on Moreton, but the optimum nitrogen rate was the same for both, and equal to the standard (200 kg N ha^{-1}). At Far Sweetbrier with the uniform Hanslope series soil the strips were arbitrarily divided into three equal zones, with Zone 1 being in the south-west part. The results of the winter/spring/winter wheat crop rotation indicated that Zone 1 had a yield maximum at the field standard rate of nitrogen, the yield maximum was less than the other two zones in 1998/99 and 1999/00. The other two zones behaved in a similar manner and indicated yield benefits from additional nitrogen. This difference may be explained by evidence that Zone 1 was historically part of another field which could have received a different long-term management regime.

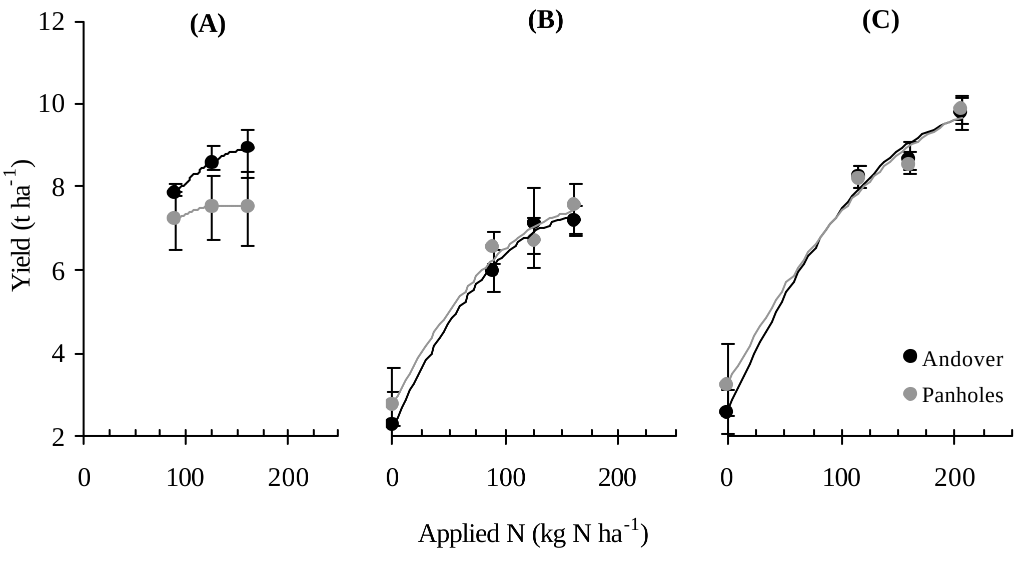


Figure 5. Yield response to applied N in the Andover and Panholes soil series zones in (A) 1997/98, (B) 1998/99 and (C) 1999/00. Error bars denote the yield range about the mean.

Historic yield and shoot density studies

An example of the yield distribution along the variable treatment yield strips is presented in Figure 6 for the HY1 and HY2 strategies. The effect of both increasing (160 kg N ha^{-1}) and decreasing (90 kg N ha^{-1}) the nitrogen application rates to the high and low yielding zones in comparison with the field standards can be clearly seen. This shows that for Trent Field in 1997/98 there were advantages of adding fertiliser to both the high and low yielding zones and penalties for reducing the rate. The results in Table 3, which summarises all the alternative scenarios in comparison with a standard application rate, indicate that there are no economic benefits from HY1 and HY2 in Trent Field or Twelve Acres. The reason for this is due to the reduction in nitrogen application rate causing a significant yield loss in both the high and low yielding zones, which are not compensated for by savings in nitrogen costs. The winter, spring, winter wheat sequence of crops at Far Sweetbrier produced benefits from the historic yield (HY2) strategy, which was due to the benefit of adding nitrogen to the poorer yielding areas which also coincided with an area of low shoot density in 1998/99 which is in agreement with the SD2 strategy and canopy management principles.

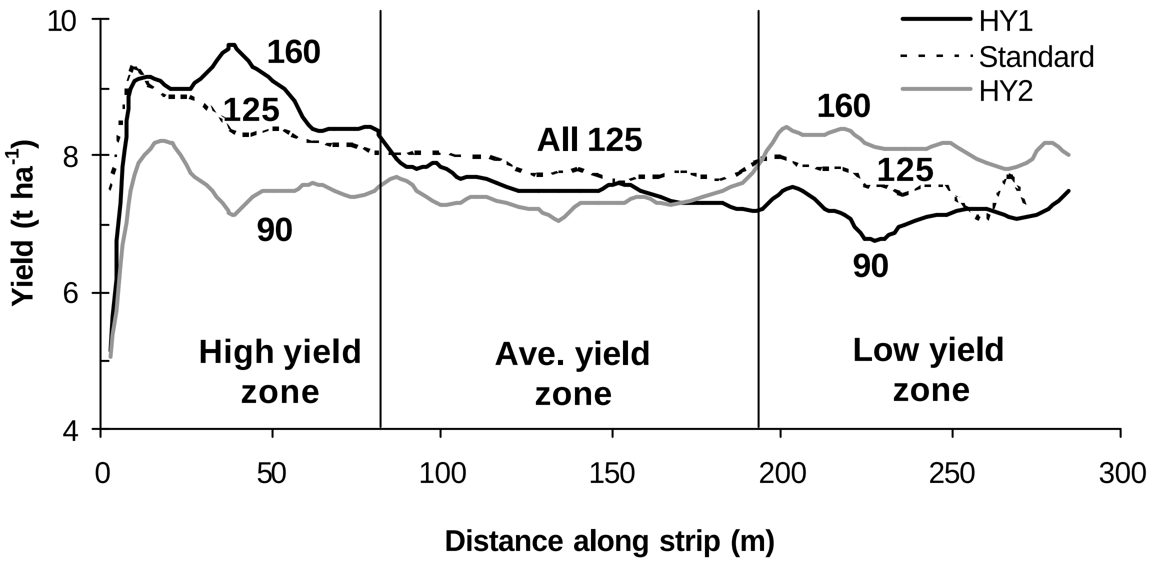


Figure 6. Combine-harvester yield of 'Historic Yield' treatments (HY1 & HY2) compared with a standard application along the treatment strips in Trent Field. Shaded areas are transition zones and are deleted from the analysis.

Table 3. Economic consequences (£ ha^{-1}) of 3 years of alternative nitrogen management scenarios for all fields in comparison to a standard application rate

Strategy	Trent Field	Twelve Acres	Far Sweetbrier	Mean
HY1	-5.41	-21.23	-7.80	-11.48
HY2	-12.56	-21.88	5.85*	-9.53*
SD1	4.98	-15.38	-13.00	-7.80
SD2	0.43	-15.17	33.58	6.28

*contains data from 1998/99 and 1999/00 only

Managing the crop using maps of the relative shoot density from NDVI data provided a positive benefit when more nitrogen was applied to the areas of low shoot density, and less to the high density areas (SD2), but the success of this depended on the actual shoot populations present which differed between seasons. In Trent Field in 1997/98, the lowest recorded population was 1300 on average; in 1999/00, even the highest shoot population did not exceed this level. Equally, although variation in shoot density can be observed, the range can be small (e.g. within 100 shoots m^{-2}), which from hindsight using the principle of canopy management would respond best to a uniform application of nitrogen.

Overall, the shoot density SD2 approach which uses a real-time assessment of the crop canopy structure to control the nitrogen requirement, appeared to offer the greatest potential for crop production. Nitrogen strategies based on historic yield maps (HY1 and HY2) showed no or very little benefit. Yield maps are, however, a valuable tool for:

i the replenishment of potassium and phosphorous removed by the previous crop, and

ii identifying the size of the zones needing particular attention from the impact of the other factors listed in Table 4. These were identified in this phase of the study and could be treated by targeted measures. Their economic impact can be significant and if present in fields it is recommended that they are corrected prior to the application of spatially variable fertiliser and other inputs.

Table 4. Other economic implications

Issue	**Implication**	**Cost or Benefit**
Water-logging	Economic penalty	Up to £195 ha^{-1}
pH	Economic advantage	Up to £7 ha^{-1}
Uneven fertiliser application	Economic penalty	Up to £65 ha^{-1}

Canopy management studies

The results from the pilot study in 1997/98 clearly showed that plant populations increased up to the highest seed rate, but shoot and ear populations peaked at 350 seeds m^{-2}. Quadrat samples taken from four transects across the seed rate strips revealed spatial variation in both populations and their response to seed rate. However, compensation through an increased number of grains per ear and thousand grain weight resulted in the highest yield and gross margin being obtained at the lowest seed rate.

In 1998/99 the experiment suffered water-logging, and due to poor growth the variable dose consisted simply of a higher total amount (245 kg N ha^{-1}) applied uniformly to the 'variable' strips. Despite good autumn establishment, sampling revealed low spring shoot populations and an increase in ear populations up to the highest seed rate. There were complicated interactions between transect position and population responses. Compensation within yield components as ear populations decreased was evident. Yield responses to seed rate and nitrogen dose were irregular, and varied with location.

The results presented in Table 5 are a comparison of both the yield and the economic performance of the recommended uniform field nitrogen application rate strips with those receiving the variable nitrogen application rate based on canopy size in Onion Field and Far Highlands in 1999/2000. Also shown are the mean of the variable nitrogen application rate and the uniform rate.

Table 5. Nitrogen application rates (kg N ha^{-1}), Yield (t ha^{-1}) and gross margin (£ ha^{-1}) comparisons between variable and uniform nitrogen application strategies

	Target Seed Rate (seeds m^{-2})											
	150			250			350			450		
	Plant population (plants m^{-2})											
ONION FIELD	100			143			177			200		
	N	**Yield**	**GM**	**N**	**Yield**	**GM**	**N**	**Yield**	**GM**	**N**	**Yield**	**GM**
Variable N	243	6.31	366	227	7.24	432	188	7.23	434	192	7.47	441
Uniform N	200	5.92	349	200	6.63	394	200	6.87	403	200	6.69	381
Difference	43	0.37	17	27	0.53	38	-12	0.48	31	-8	0.75	60
	Plant population (plants m^{-2})											
FAR HIGHLANDS	120			195			240			320		
	N	**Yield**	**GM**	**N**	**Yield**	**GM**	**N**	**Yield**	**GM**	**N**	**Yield**	**GM**
Uniform N	197	8.24	437	189	7.77	397	135	7.79	406	144	7.77	391
Standard N	200	7.94	417	200	7.85	398	200	8.11	404	200	7.93	381
Difference	-3	0.30	20	-11	-0.08	-1	-65	-0.32	2	-56	-0.16	10

These show that regardless of seed rate in Onion Field both the yield and the gross margins for the variable nitrogen strategy exceeded those for the uniform practice. The similar data from Far Highlands show yield benefits at the lowest seed rate only. The other 3 seed rates show a small reduction in yield, which was economically compensated for by lower nitrogen application rates.

The financial benefits of variable N management versus uniform N management are also presented in Figure 7. In seven of the eight comparisons the gross margin was in favour of variable N management.

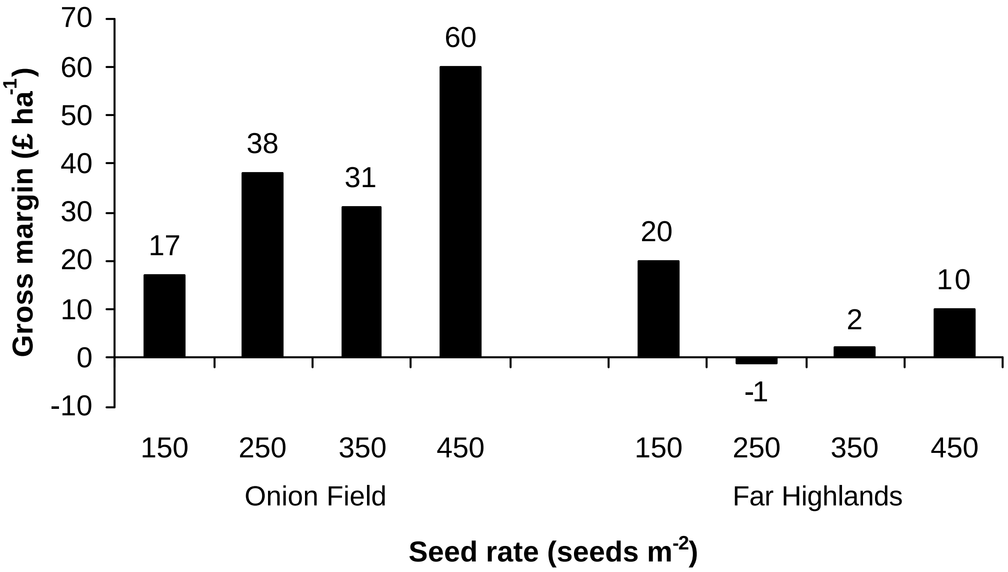


Figure 7. Gross Margins comparison between variable N and uniform N management.

The maximum advantage to variable N management was £60 ha^{-1} that was produced from a combination of higher yield (+11%) and a slightly lower total N input compared to the standard N approach.

Overall yield benefits were greatest where the mean application rate of the variable nitrogen strips was approximately that of the field standard. On average, for the two fields, the overall benefit of the variable nitrogen strategy was £22 ha^{-1}.

An analysis of the "responsive areas" to variable nitrogen in both the shoot density and canopy management studies indicate that between 12% and 52% of all fields responded positively depending upon field and season.

Economic Implications

An analysis of the capital and associated costs for alternative systems for yield mapping and spatial application of fertilisers and seeds in January 2001 enabled the annual costs per hectare to be assessed. These costs ranged from less than £5 ha^{-1} to £18 ha^{-1} for a single yield mapping and spatial control unit managing an area of 250 ha per year depending on the system chosen. The basic low cost system is associated with marginally less spatial accuracy in the production of yield maps and the control of application rate is effected via changes to the tractor forward speed implemented by the driver after receiving instructions from the control system. The more expensive system simultaneously equips both the combine for yield mapping and a tractor/sprayer for variable seed rate and fertiliser application. The actual costs per hectare vary inversely with the size of the area managed per unit.

These studies demonstrated that historic yield records are not a sound basis for determining variable nitrogen studies. A more promising approach was to use a "real-time" measure of crop growth. This would currently require the additional cost of collecting and calibrating remotely sensed data from aerial digital photography or tractor based radiometry. This has an estimated annual cost of £7 ha^{-1} for farm scale operations for cereal crop areas in excess of 1500 ha per flight for the former and £10 ha^{-1} for the latter for a 500 ha cereal crop area.

Assuming that the average financial benefit, from variable nitrogen management, of £22 ha^{-1} holds for other farms, together with the costs presented above, there is an economic benefit from precision farming when the annual area harvested per combine is greater than 80 ha^{-1} for the basic system costing £4,500, and 300 ha for the more sophisticated systems costing £16,000. This is the situation for N manipulation but variable application of other inputs, if successful, will reduce these nominated areas.

The relationships shown in Figure 8 extend this approach to other situations to enable estimates of the potential yield increase required in the proportion of the field likely to provide a positive response to variable management. The example shown illustrates that a farmer with an area of 250 ha, where 20% of the area is likely to respond positively to precision farming, must achieve a yield increase of 1.10 t ha^{-1} for that particular 20% to break even. If the potential yield increase is greater than 1.10 t ha^{-1}, economic benefits will follow; if less, then there is currently no economic benefit to be gained from precision farming for that field or enterprise. The effects of the relative size of the responsive proportion of the field is also illustrated.

The above estimates are based on improvements from nitrogen management alone; if this more than covers the costs, then other benefits will have an immediate financial return. Results of studies into the variable application of both herbicides (Rew et al, 1997 and Parry et al, 2001) and fungicides (Secher, 1997) have each shown benefits of up to £20 ha^{-1}.

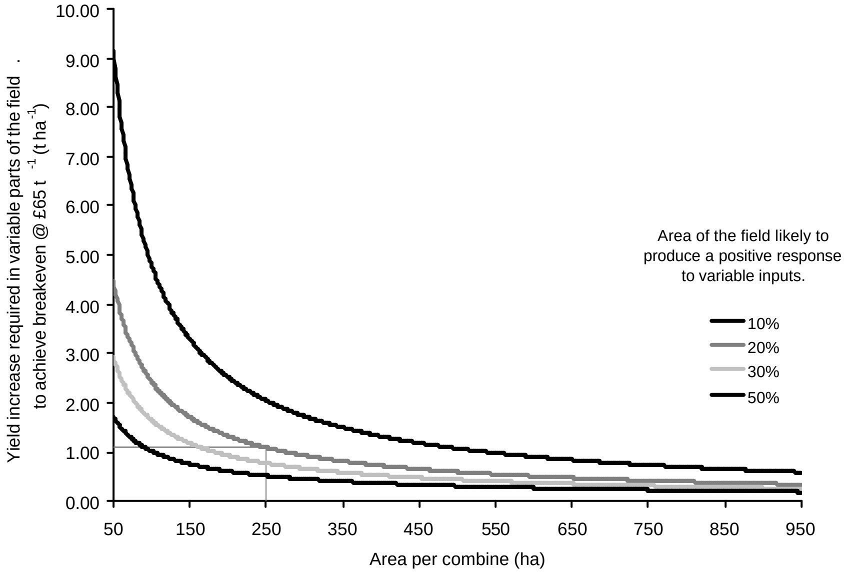


Figure 8. Yield increases required for a break even scenario for different proportions of the field likely to benefit from precision farming and the harvested area for a fully integrated precision farming equipment and software system costing £11,500.

Environmental Implications

Whilst this project did not specifically address environmental implications of nitrogen usage it is possible to draw some conclusions on the possible impact of precision farming decisions on the nitrogen balance in the environment.

Using the strip mean grain yields, average fertiliser N application rates, and grain and straw nitrogen contents measured in the quadrat samples, and assuming a straw yield equal to 65% of grain yield, it is possible to calculate the potential off-take of nitrogen in the variable treatment compared to the standards for each seed rate.

The plant populations in Onion Field were generally low and in the lowest seed rate (which produced only 100 plantsm^{-2}) both the uniform and variable nitrogen programmes had nitrogen off-takes which were significantly less than the amount applied, resulting in a surplus at the end of the season, see Figure 9.

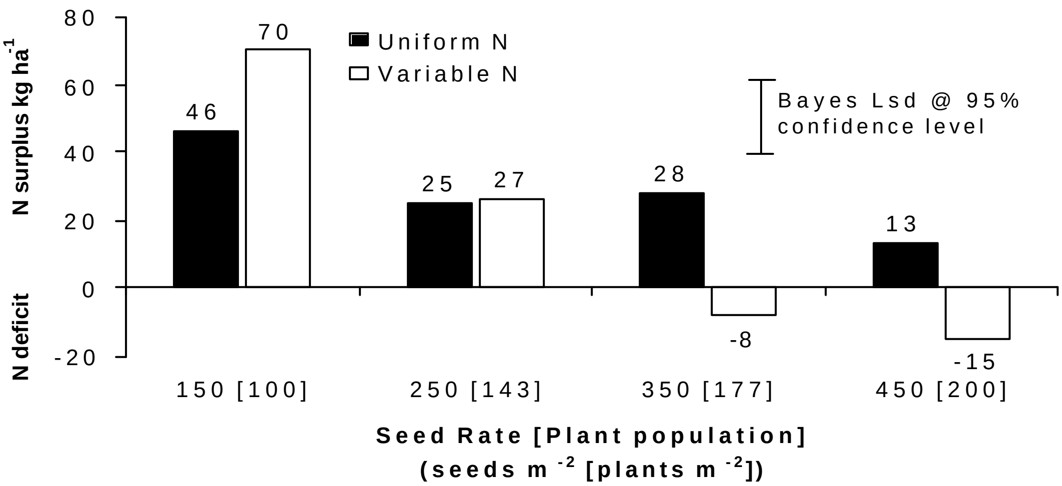


Figure 9. Surplus or deficit of applied nitrogen relative to off-take in grain and straw at Onion Field in 2000

However at the three higher plant populations the off-takes from the variable N applications were higher than applied N resulting in a net reduction in N balances. Averaged over the four seed rates, the N surplus for the variable treatments was 18.5 kg ha^{-1} compared to 28kg hl^{-1} for the uniform treatments. This represents a 34% reduction in the net amount added to the soil from the uniform application and this could have considerable longer-term environmental significance.

A similar analysis was conducted for Far Highlands 2000 and assuming similar grain and straw nitrogen contents as these were not individually sampled, the average saving from the variable N treatments compared to the uniform N treatments was 32.5 kg ha^{-1}.

Conclusions

i Yield maps are indispensable for targeting areas for investigation and treatment by precision farming practices and subsequent monitoring of results. They provide a valuable basis for estimating the replenishment levels of P and K fertilisers; however, they were not found to provide a useful basis for determining a variable nitrogen application strategy to optimise management in a particular season.

ii The possible extent and potential causes of yield variability can be determined using low capital cost yield mapping systems together with electro-magnetic induction techniques to assess variation in soil factors such as texture and water holding capacity. An objective methodology was developed to use these techniques to determine within-field management zones. Either individually or together, these systems provide a means for assessing the degree of variability within a field and provide a basis for targeting soil and crop sampling points, which is the most cost effective method for commercial use.

iii The spatial variation in canopy development within a field can be estimated using an ADP technique developed by Cranfield University for this project for “real-time” agronomic management. This technique can be extended from field scale to farm scale for crops of similar varieties and planting dates. The processing of the data from cameras mounted in light aircraft is sufficiently fast to enable application rate plans to be produced within a few hours of the aircraft landing. The technique can be used as a basis for determining the most appropriate application rate for nitrogen, and as a guide for herbicide and plant growth regulator application. It is feasible to adapt the system for use with tractor-based systems.

iv The application of nitrogen in a spatially variable manner can improve the efficiency of cereal production through managing variations in the crop canopy. Depending upon the field and the year, between 12% and 52% of the area of the fields under investigation responded positively to this approach. In 2000 seven out of eight treatment zones gave positive economic returns to spatially variable nitrogen with an average benefit of £22 ha^{-1}.

v Simple nitrogen balance calculations have shown that in addition to a modest increase in yield, the spatially variable application of nitrogen can have an overall effect on reducing the nitrogen surplus by approximately one third.

vi Common problems, such as water-logging and fertiliser application errors, can result in significant crop yield penalties. Precision farming can enable these problems to be identified, the lost revenue to be calculated and the resultant impact on the cost-benefit to be determined. This provides a basis from which informed management decisions can be taken. It is critical that these problems are corrected prior to the spatial application of fertilisers and other inputs.

vii At current prices, the benefits from spatially variable application of nitrogen outweigh the costs of the investment in precision farming systems for cereal farms greater than 75 ha if basic systems costing £4,500 are purchased, and greater than 200-300 ha for more sophisticated systems costing between £11,500 and £16,000.

viii Integrating the economic costs with the proportion of the farmed area that has benefit potential enables the break-even yield increase to be estimated. Typically a farmer with 250 ha of cereals where 20% of the farmed area could respond positively to spatially variable nitrogen would need to achieve a yield increase of 1.1 t ha^{-1} on that 20% to break even for a precision farming system costing £11,500. This figure reduces to 0.25 t ha^{-1} for a basic system.

ix The net effect of combining the benefits of spatially variable application of nitrogen (£22 ha^{-1}) with the benefits from both the spatial application of herbicides (up to £20 ha^{-1}) and fungicides (up to £20 ha^{-1}), found from other studies, should provide valuable returns from the adoption of precision farming concepts. However, this should not be considered as the simple addition of the maximum benefits quoted.

x These economic advantages linked to the environmental benefits should improve the longer term sustainability of cereal production.

References

1. HGCA. The Wheat Growth Guide. HGCA, London, 1998.
2. C.A.H. Hodge, R.G.O. Burton, W.M. Corbett, R. Evans, and R.S. Seale. Soils and their use in Eastern England. Soil Survey Bulletin No.15, Harpenden, 1984.
3. M.G. Jarvis, R.H. Allen, S.J. Fordham, J. Hazelden, A.J. Moffat, and R.G. Sturdy. Soils and their use in South East England. Soil Survey Bulletin No.13, Harpenden, 1984.

4. N.H. Perry, P.J.W. Lutman, P.C.H. Miller, H.C. Wheeler. A map based system for patch spraying weeds. (1) Weed mapping. Proceedings BCPC Crop Protection Conference – Brighton – Weeds, 2001. In preparation, 2001.
5. L.J. Rew, P.C.H. Miller, M.E.R. Paice. The importance of patch mapping resolution for sprayer control. Aspects of Applied Biology, 48, Optimising pesticide applications, pp49-55, 1997.
6. B.J.M. Secher. Site specific control of diseases in winter wheat. Aspects of Applied Biology, 48, Optimising pesticide applications, pp57-64, 1997.

ABSTRACTS OF PUBLISHED PAPERS

The objectives of the project have been reported in three main sections each of which contain a number of sub-sections written in the format of papers for publication in a special edition of the Precision Agriculture Journal (unless previously published) and to be used by the HGCA as the basis for a guide to precision farming for cereal crops.

Section 1: Estimation of Variation

This section considers techniques for mapping field and crop variation together with an analysis of the variation of soil and crop yield for 3 cereal harvests under conventional crop management. There are 6 papers and an appendix of yield map data, namely:

1. A review of the technologies for mapping within-field variability
2. Calibration methodology for mapping within-field crop variability using remote sensing
3. Soil factors and their influence on within-field crop variability I: Field observation of soil variation
4. Soil factors and their influence on within-field crop variability II: Spatial analysis and determination of management zones
5. Remedial correction of yield map data
6. Interpretation of trends from multiple yield maps

Appendix 1. Spatial and temporal trends in yield map data

Section 2: Crop Response to Variable Application of Nitrogen

This section considers the response of wheat and barley to variable application of nitrogen based upon historic yield map, tiller density and crop canopy information, by comparing the response of variable nitrogen in 10-12 m wide strips with an adjacent 10-12 m wide strip receiving a uniform application of the "standard" application rate for the field.

There are 3 papers, namely:

7. Developing strategies for spatial variable nitrogen application in cereals I: Winter Barley
8. Developing strategies for spatial variable nitrogen application in cereals II: Wheat
9. Real-time measures of canopy size as a basis for spatially varying nitrogen at different seed rates in winter wheat.

Section 3: Economics and Guidelines

This considers the economic implications of the results found in Section 2 together with a full cost analysis of alternative precision farming equipment systems. From these, the effect of both 'farm' size and the level of variability are integrated to determine the breakeven points for cost effective precision farming. Following this the major outcomes and guidelines are presented as the focal point in pages 33-43, which include clear step-by-step decision trees to enable the grower to decide to what extent Precision Farming techniques can be implemented, and the potential benefits that will accrue.

Section 1. Estimation of Variation

1. A review of the technologies for mapping within-field variability

Richard J. Godwin

Cranfield University at Silsoe, Silsoe, Bedford MK45 4DT, UK

Paul C.H. Miller

Silsoe Research Institute, Silsoe, Bedford MK45 4HT, UK

Techniques for mapping soil physical and chemical condition, topography and the weed status of fields are reviewed from a practical and economic perspective. The conclusions are that it is possible to target sample the soil physical and chemical status of fields and locate areas of high weed density following the use of inexpensive, non-invasive techniques (EMI, aerial digital photography (ADP) and radiometry). Semi-automated field reconnaissance systems on all terrain vehicles and combines also assist in locating the position of weed patches. P and K fertiliser can be replenished by using the "off-take" values determined from yield maps, whilst crop density in the spring period shows potential for the management of nitrogen fertiliser in cereal crops using ADP and could also be a benefit in the application of agrochemicals. Currently the most economically viable method to determine field topography is to use very simple surveying techniques, there is potential to automate this.

2. Calibration methodology for mapping within-field crop variability using remote sensing

Gavin. A. Wood, John C. Taylor and Richard J. Godwin

Cranfield University at Silsoe, Silsoe, Bedford MK45 4DT, UK

A successful method of mapping within-field crop variability of shoot populations in wheat (*Triticum aestivum*) and barley (*Hordeum vulgare* L.) is demonstrated. The approach is extended to include a measure of green area index (GAI). These crop parameters and airborne remote sensing measures of the normalised difference vegetation index (NDVI) are shown to be linearly correlated. Measurements were made at key agronomic growth stages up to the period of anthesis and correlated using statistical linear regression based on a series of field calibration sites. Spatial averaging improves the estimation of the regression parameters and is best achieved by sub-sampling at each calibration site using three $0.25m^2$ quadrats. Using the NDVI image to target the location of calibration sites, 8 sites are shown to be sufficient, but they must be representative of the range in NDVI present in the field, and have a representative spatial distribution. Sampling the NDVI range is achieved by stratifying the NDVI image and then randomly

selecting within each of the strata. Ensuring a good spatial distribution is determined by visual interpretation of the image. Furthermore, a block of adjacent fields with similar varieties and sowing dates can be successfully calibrated to provide multiple maps of within-field variability in each field using only 8 points per block representative of the NDVI range and constraining the sampling to 1 calibration site per field. Compared to using 30 or more calibration sites, restricting samples to 8 does not affect the estimation of the regression parameters as long as the criteria for selection outlined in this paper is adhered to. In repeated tests the technique provided regression results with an r^2 of 0.7 in over 85% of cases. At farm scale, the results indicate an 80-90% probability of producing a map of within crop field variability with an accuracy of 75-99%. This approach provides a rapid tool for providing accurate and valuable management information in near real-time to the grower for better management and for immediate adoption in precision farming practices, e.g. for determining variable rates of nitrogen, fungicide or plant growth regulators.

3. Soil factors and their influence on within-field crop variability I: field observation of soil variation

Richard Earl, John C. Taylor, Gavin A. Wood, Ian Bradley, Iain T. James, Toby Waine. James P. Welsh and Richard J. Godwin

Cranfield University at Silsoe, Silsoe, Bedford MK45 4DT, UK

Stuart M. Knight

Arable Research Centres, Shuttleworth Centre, Old Warden Park, Biggleswade, Bedfordshire SG18 9EA, UK.

A fundamental component of adopting the concept of precision farming in practice is the ability to measure spatial variation in soil factors and assess the influence of this on crop variability in order to apply appropriate management strategies. The aim of this study was to appraise potential methods for measuring spatial variability in soil type, nutrient status and physical properties in practical farming situations. Five fields that are representative of more than 30% of soils used for arable production in England and Wales were selected for use as case studies. Maps of soil type were generated from a conventional hand auger survey on a 100m grid and the excavation of targeted soil profile pits. These were compared with those refined using a mechanised soil coring device and scans of electromagnetic inductance (EMI) carried out while the soil could reasonably be considered to be at, or near, field capacity moisture content. In addition, soil sampling for nutrient analyses was conducted on a 50m grid to examine the spatial variation in nutrient status. Conventional methods for sampling soil were found to be appropriate for identifying soil types at specific locations within the field sites, however, they were time-consuming to perform which placed an economic and therefore a practical limitation on the sampling density possible. The resulting data were considered to be too sparse for demarcating soil type boundaries for use in the context of precision farming. The location of soil boundaries were refined by using the mechanised soil corer, however, the limitation of this was found to be the time required to analyse the soil cores produced. Maps of soil variation generated from EMI scans conducted at field capacity appear to reflect the underlying variation in soil type observed in maps generated using the mechanised soil corer. And, therefore, this approach has potential as a cost-effective, data-rich, surrogate for measures of soil variability. Results from analyses of soil samples for measurement of nutrient status indicated that whilst there was considerable variation in macro- and micro-nutrient levels in each field, with the exception of pH, these levels were above commonly accepted agronomic limits. Results did however demonstrate the potential for addressing variation in critical factors such as pH at specific locations, however, there is a need to develop protocols for targeting sampling in order to reduce costs.

4. Soil factors and their influence on within-field crop variability II: spatial analysis and determination of management zones

John C. Taylor, Gavin A. Wood, Richard Earl and Richard J. Godwin

Cranfield University at Silsoe, Silsoe, Bedford MK45 4DT, UK

Spatial variation of crop yields was examined in three trial cereal fields in England from 1994 through 1997. The fields were managed with uniform inputs but there were considerable differences in the spatial patterns and magnitudes of variation between fields and seasons. Up to 50% of the yield variation was within the tramline spacing distance (20 to 24m) and this appeared to relate to crop management practices rather than underlying soil factors. Longer-range variation generally increased up to field-scale but was not constant between seasons. Longer-range variation was more apparent in dry years and was attributable to soil variation. Soil series differences coincided with yield differences in dry years when the soil series differences could be expected to create large differences in soil-water relationships. Soil electrical conductivity, measured by electromagnetic induction (EMI) was investigated as a surrogate for detailed soil coring. Field zones created by EMI also coincided with yield differences and zones were similar to those delineated by soil series with expected differences in soil-water relationships. EMI observations were found to be a useful and cost-effective surrogate for representing soil variability in fields likely to create yield variations. Sub-division of fields into management zones using multivariate K means cluster analysis of historical yield and EMI observations formed an objective basis for targeting soil samples for nutrient analysis and development of site-specific application strategies. The appropriateness of site-specific management has to be assessed annually because the magnitude and pattern of variation changes from season to season.

5. Remedial correction of yield map data

Simon Blackmore[1] **and Mark Moore**[2]

AgroTechnology, The Royal Veterinary and Agricultural University, Denmark

[1]formerly at Cranfield University at Silsoe, Silsoe, Bedford MK45 4DT, UK

[2]AGCO Ltd, Banner Lane, Coventry, England.

Many yield maps exhibit systematic errors that attenuate the underlying yield variation. Two errors are dealt with in detail in this paper: those that occur when the harvester has a narrow finish to a land, and those that occur when the harvester is filling up at the start of a harvest run. The authors propose methods to correct or remove erroneous data by the use of an expert filter, or, alternatively, an interpolation technique called potential mapping.

6. The interpretation of trends from multiple yield maps

Simon Blackmore[1]

AgroTechnology, The Royal Veterinary and Agricultural University, Denmark, formerly at Cranfield university at Silsoe, Silsoe, Bedford MK45 4DT, UK

Yield data over 6 years (1993-1998) were investigated for spatial and temporal trends from a 7 ha field growing winter wheat and oil seed rape. The data were combined into two maps, which characterised the spatial and temporal variability recorded over those years. Techniques were developed to show the maps in either the single form for winter wheat, or multiple crops that included oil seed rape data. The two maps were then combined into single classified management map, which denoted three categories, each with different characteristics that can have an impact on the way the field is managed. These categories were: high yielding and stable, low yielding and stable, and unstable. The spatial and temporal trends in the single crop were more stable than those in the multiple crops. In percentage terms, with a single crop, the proportions of these classes were 55, 45 and 0% respectively. For the multiple crops, the proportions were 58, 39 and 3%, respectively. The economic significance of these area was assessed by the production of a gross margin map and further analysis showed that the categories returned 741, 691 and 644 £ ha^{-1}, respectively.

A1 Spatial and temporal trends in yield map data

Simon Blackmore[1]**, Spyridon Fountas**

AgroTechnology, The Royal Veterinary and Agricultural University, Denmark.

[1]formerly at Cranfield University at Silsoe, Silsoe, Bedford MK45 4DT, UK.

Mark Moore

AGCO Ltd, Banner Lane, Coventry, England.

Richard J. Godwin

Cranfield University at Silsoe, Silsoe, Bedford MK45 4DT, UK

As part of the research programme to develop precision farming management guidelines, started in 1995/96 on four sites in England, yield map data were recorded from 1995 onwards and their trends were used as an input to assist in the development of management strategies, namely applying nitrogen based upon long term, historic yield data. This short appendix gives the simplest analysis of yield showing the variation within the field (spatial), and between years (temporal). The instantaneous error of the grain flow meter is shown to be within 1%. The mean yield varied by only ±1 ton ha^{-1} over a six-year period. The average yield variation for four fields corresponded to a ± 25% variation about the mean yield.

Section 2. Crop Response to Variable Application of Nitrogen

7. Developing strategies for spatially variable nitrogen application in cereals I: Winter Barley

James P. Welsh, Gavin A. Wood, Richard J. Godwin, John C. Taylor, Richard Earl and Simon Blackmore.

Cranfield University at Silsoe, Silsoe, Bedford MK45 4DT, UK

Stuart M. Knight

Arable Research Centres, Shuttleworth Centre, Old Warden Park, Biggleswade, Bedfordshire SG18 9EA, UK.

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 kg N ha^{-1} 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.

8. Developing strategies for spatially variable nitrogen application in cereals II: Wheat

James P. Welsh, Gavin A. Wood, Richard J. Godwin, John C. Taylor, Richard Earl and Simon Blackmore.

Cranfield university at Silsoe, Silsoe, Bedford MK45 4DT, UK

Stuart M. Knight

Arable Research Centres, Shuttleworth Centre, Old Warden Park, Biggleswade, Bedfordshire SG18 9EA, UK.

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 examine 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.

9. Real-time measures of canopy size as a basis for spatially varying nitrogen applications to winter wheat sown at different seed rates.

Gavin A. Wood, James P. Welsh, Richard J. Godwin, John C. Taylor and Richard. Earl

Cranfield University at Silsoe, Silsoe, Bedford MK45 4DT, UK

Stuart M. Knight

Arable Research Centres, Shuttleworth Centre, Old Warden Park, Biggleswade, Bedfordshire SG18 9EA, UK.

Experiments at two sites growing winter wheat show that in order to manage a wheat canopy more effectively, the use of specific remote sensing techniques both to monitor crop canopy expansion, and to determine variable nitrogen applications at key timings is required. Variations in seed rate were used to achieve a range of initial crop structures, and treatments were compared to standard farm practice. In the first year, the effect of varying seed rate (250, 350 and 450 seeds m^{-2}) on crop structure, yield components and grain yield, was compared to the effects of underlying spatial variation. Plant populations increased up to the highest rate, but shoot and ear populations peaked at 350 seeds m^{-2}. Compensation through an increased number of grains per ear and thousand grain weight resulted in the highest yield and gross margin at the lowest seed rate. In later experiments the range of seed rates was extended to include 150 seeds m^{-2}, each sown in 24m wide strips split into 12m wide halves. One half received a standard nitrogen dose of 200 kg N ha^{-1}, the other a variable treatment based on near 'real-time' maps of crop growth. Both were split into three applications, targeted at mid-late tillering (early March), GS30-31 (mid April) and GS33 (mid May). At each timing, calibrated ADP was used to compare crop growth (shoot populations at tillering and canopy GAI at GS30-31 and GS33) with benchmarks from the HGCA wheat growth guide. Application rates were then varied below or above the planned amount where growth was above or below target respectively. In the first field, total nitrogen doses in the variable treatments ranged from 188-243 kg N ha^{-1}, which gave higher yields than the standards at all seed rates in the range 0.36-0.78 t ha^{-1} and gross margins of 17-60 £ ha^{-1}. In the second field, variable treatments ranged from 135-197 kg N ha^{-1} that, although resulted in lower yields of -0.32 to +0.30 t ha^{-1}, in three out of the four seed rates, produced higher gross margins than the standard ranging from -1 to +20 £ ha^{-1}. In both fields, the greatest benefits were obtained where the total amount of applied nitrogen was similar to the standard, but was applied variably rather than uniformly along the strips. Simple nitrogen balance calculations have shown that variable application of nitrogen can have an overall effect of reducing the nitrogen surplus by one third.

Section 2. Economics and Guidelines

10. An economic analysis of the potential for precision farming in UK cereal production

Richard J. Godwin, Terence E. Richards, Gavin A. Wood and James P. Welsh.

Cranfield university at Silsoe, Silsoe, Bedford MK45 4DT, UK

Stuart M. Knight

Arable Research Centres, Shuttleworth Centre, Old Warden Park, Biggleswade, Bedfordshire SG18 9EA, UK.

The results from alternative spatial nitrogen application studies are analysed in economic terms and compared to the costs of precision farming hardware, software and other services for cereal crops in the UK. At current prices the benefits of variable rate application of nitrogen exceed the returns from a uniform application by an average of £22 ha^{-1}. The cost of the precision farming systems range from £5 ha^{-1} to £18 ha^{-1} depending upon the system chosen for an area of 250 ha. The benefits outweigh the associated costs for cereal farms in excess of 80 ha for the lowest price system to 200 – 300 ha for the more sophisticated systems. The scale of benefits obtained depends upon the magnitude of the response to the treatment and the proportion of the field that will respond. To be cost effective, a farmed area of 250 ha of cereals, where 30% of the area will respond to variable treatment, requires an increase in crop yield in the responsive areas of between 0.25 t ha^{-1} and 1.00 t ha^{-1} (at £65 t^{-1}) for the basic and most expensive precision farming systems respectively.

MAJOR OUTCOMES AND PRACTICAL GUIDELINES FOR PRECISION FARMING FOR CEREALS

When this research project was proposed in 1996, one of the key driving forces was the concern that the technologies associated with precision farming were advancing faster than the understanding of the causes of yield variation within fields and the potential benefits of overcoming that variation.

At that time the techniques were available to accurately identify specific areas within a field and to precisely position equipment in specific areas of a field. However, the only agronomic tools that were available were yield maps. Whilst they were very useful they demonstrated 'effect' rather the 'cause' of variability. If the arable sector was going to capitalise on the potential benefits of the precision technology then it was vital that an understanding of the causes and extent of within-crop variability were obtained.

This project set out to explore the causes and extent of variability within fields, to develop techniques to measure variability during the course of the growing season and to develop methods of informing the arable grower of the potential benefits of precision farming. Two phases of the project were developed to explore the two primary issues:

1. What is the extent of the variability that exists within crops and can any causes for this variability be identified? This phase lasted for two years and focused in very great detail on four fields that represented major soil types in the UK.
2. Can within-field variability be monitored during the course of the growing season, rather than historically by the use of yield maps, to allow real-time agronomy to be implemented to optimise economic crop production? This phase lasted three years and monitored a total of six fields.

The main conclusions from the project are outlined below and they have been grouped into the primary topic areas. One of the key objectives during the course of the five year project was to release information and conclusions to enable the farming community to comment upon and benefit from the research findings of the project. This has led to the situation where some of the research findings have already found their way into regular usage and their initial origins in this project must not be overlooked.

The conclusions have been presented in the following topic areas:

?? the importance of variation in soil structure, texture and moisture holding capacity.

?? the role of yield maps.

?? the measurement and extent of within-crop variation using remote sensing techniques.

?? the management of within-crop variation.

?? the economic benefits of precision farming.

?? the environmental benefits of precision farming.

The importance of variation in soil structure, texture and moisture holding capacity

?? long term causes of yield variation can be attributed to soil and its associated water holding capacity.

?? historic yield maps, adapted to illustrate spatial trends, can be used to target specific areas of fields for investigation.

?? commercially viable soil survey techniques can provide valuable information on soil variability across fields and its potential impact upon yield.

?? electromagnetic induction techniques can further refine the delineation of soil types and water holding capacity variation within a field.

?? unless nutrient deficiencies are severe the current techniques of soil and tissue analysis do not provide useful information to assist in interpreting the causes of yield variation within a field.

?? the combination of yield maps and accurate soil mapping further improves the ability to target areas for intensive soil and crop sampling.

The role of yield maps

?? yield maps are valuable as a means of historically describing the yield variability existing in a field in any one season.

?? yield maps can identify specific areas within fields, particularly low yielding, that require attention.

?? yield maps, together with soil data, can be used to zone fields into potential management zones.

?? significant potential errors in yield mapping systems can be identified and corrected using expert filter systems.

?? by developing a spatial trend map it is possible to identify variation within a field over a number of seasons. Variability within a field has been shown to be less predictable when using several seasons of yield mapping. Fields should therefore be managed according to the current year's conditions rather than by the use of historic yield maps.

?? yield maps can accurately determine the cost of localised damage such as that arising from pests (rabbits), poor drainage, compaction or pH problems. They can also be used to measure the benefits of remedial actions.

?? yield maps verify the outcome of any spatially-applied precision farming inputs to enable cost /benefit analysis to be undertaken.

?? they can be used to determine the replenishment levels required of nutrients such as P and K by accurately measuring off-take levels.

The measurement and extent of within field crop variation using remote sensing techniques

?? the need to understand and control within field variability has been highlighted by the discovery of yield variation within one field ranging from 6 t ha^{-1} to over 14 t ha^{-1}, although a more typical range is 5 t ha^{-1} to 10 t ha^{-1}.

?? an aerial digital photography (ADP) technique has been developed to accurately measure within field crop variability during the course of the growing season.

?? the Cranfield University ADP technique, with the assistance of ground calibration, can determine within field variations in both shoot densities and GAI (canopy development).

?? herbicide and plant growth regulator applications can be varied as a result of the information produced through the use of the techniques.

?? the technique has been extended from field-scale to farm-scale for crops of similar varieties and planting dates.

?? the technique could be adapted for tractor-based systems as well as the currently operated light aircraft system.

The management of within-crop variation

?? studies on both wheat and barley indicate that historic yield maps did not provide a valuable basis for determining a variable nitrogen application strategy to optimise yield.

?? the extent of crop variability revealed by the Cranfield University ADP technique has allowed real-time agronomy input to be applied during the growing season.

?? during the course of the project between 12% and 52% of the area of fields responded positively to differential nitrogen applications identified by the Cranfield University ADP technique.

?? variable nitrogen management has been demonstrated to be cost-effective in the majority of circumstances where it was employed in this project.

?? variable nitrogen management presents the additional possibility of reducing total nitrogen usage in some circumstances.

The economic benefits of precision farming.

?? interpreting the information from the Cranfield University ADP technique and using real time agronomy (variable N management) produced an overall benefit of £22 ha^{-1} compared to a standard N management policy.

?? using historic yield maps as the basis for N application in a subsequent crop did not improve financial returns over those generated from standard N management.

- ?? current estimates of capital and associated costs for equipping a farm to be capable of adopting precision farming techniques range from £5 ha^{-1} to £18 ha^{-1} depending upon system chosen and farm size.
- ?? data collection and interpretation to enable real time agronomy to be conducted could be available from £7 ha^{-1} depending upon land area surveyed by aircraft or tractor mounted radiometry.
- ?? the potential benefits available from the correction of localised agronomy/management problems should not be overlooked. Benefits of up to £195 ha^{-1} from correcting water-logging and up to £65 ha^{-1} from correcting uneven nitrogen applications have been identified.
- ?? the total potential benefits from precision farming nitrogen (£22 ha^{-1}) herbicide (£20 ha^{-1}), fungicides (£20 ha^{-1}) are financially very attractive.
- ?? a typical farm, with 250 ha of cereal where 20% of the area could respond to variable spatial nitrogen application would only need a 1.1 t ha^{-1} yield increase in that 20% of land to create a break-even for a precision farming system costing £11,500.

The environmental benefits of precision farming

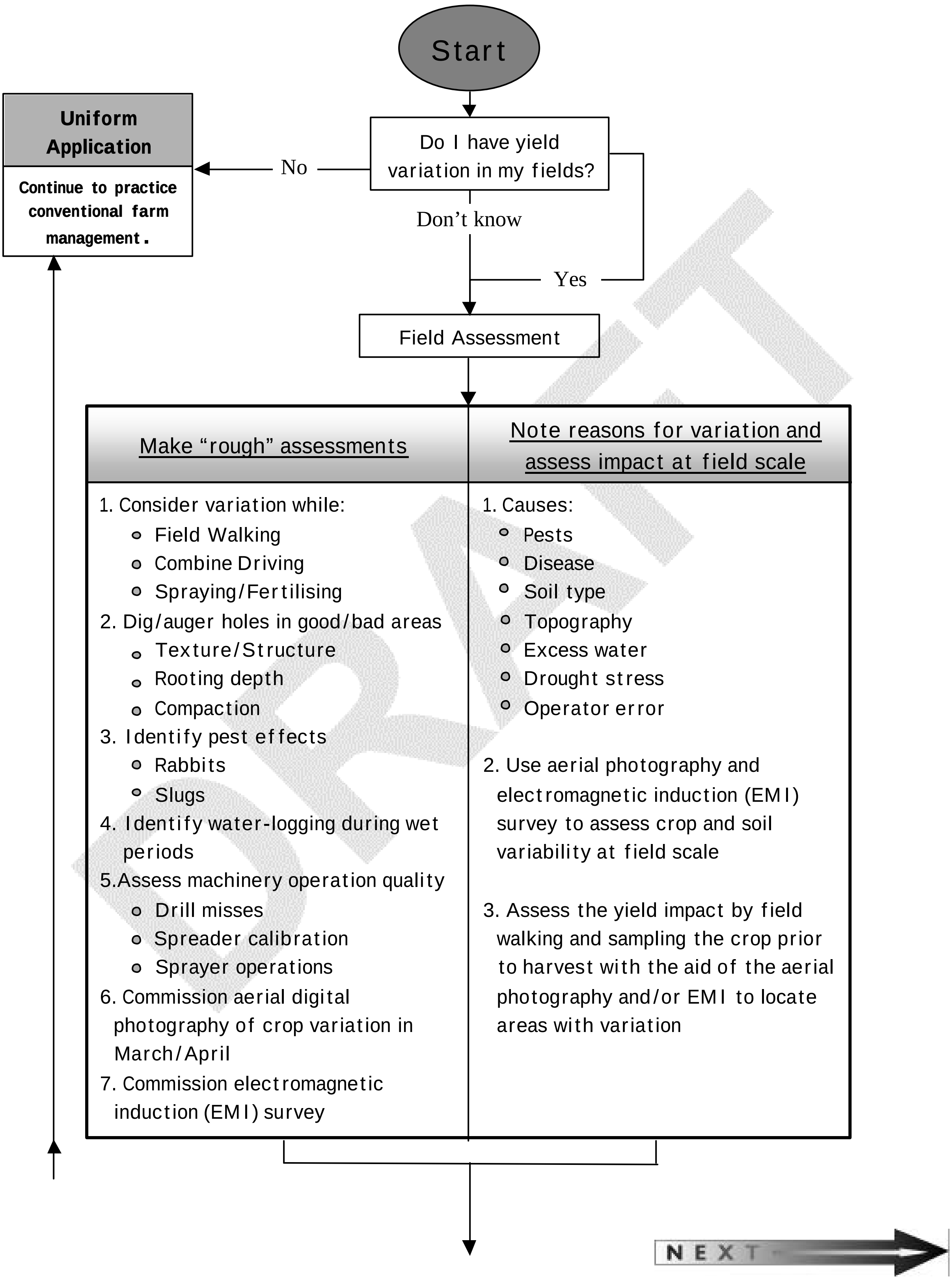
- ?? spatial applications of nitrogen, herbicides and pesticides are likely to result in lower overall applications in the majority of circumstances but in some cases higher levels of application will be justified.
- ?? whilst this project did not address the environmental implications of spatial applications it was clear that nitrogen rates were generally lower than with standard application procedures. One fully documented example produced a 34% net reduction in N added to the soil compared to standard application.

This project has clearly identified a range of opportunities for growers to adopt precision farming techniques. However, it is very clear that, before precision farming is adopted, routine agronomic and management practices must be optimised, otherwise they can seriously undermine any financial benefits from precision farming.

Entering precision farming is a step-wise procedure and part of the remit of this project was to develop guidelines for precision farming to enable the decision making process to be undertaken by the grower. The potential benefits of precision farming, up to £22 ha^{-1} from variable N application has been demonstrated in this project with the possible additive effect of variable application of other inputs, suggesting that many growers should be investigating the concept. The final part of the conclusion therefore brings together the key decision points and proposes a flow diagram to enable the grower to decide if their circumstances will benefit from the adoption of precision farming techniques.

Precision Farming Management Guideline Flowcharts

Guidelines for assessing the potential of Precision Farming for Cereal Crops



Uniform Application

Continue to practice conventional farm management.

Assess the total yield benefit from remediation

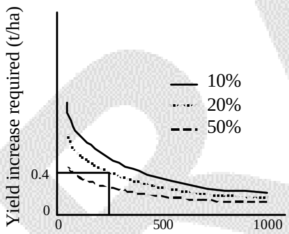
Assess total percentage of area that has potential for improvement

Decide if the potential yield improvement is sufficient to invest in specific Precision Farming systems.

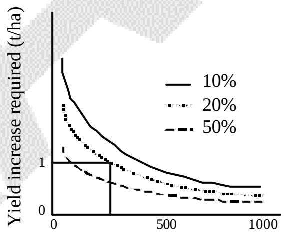
Use the charts over-leaf to determine your system requirement

Basic Entry Level Systems (£4500)	Fully Integrated Single Unit Systems (£11,000)	Multiple units for Combine and tractor (£16,000)

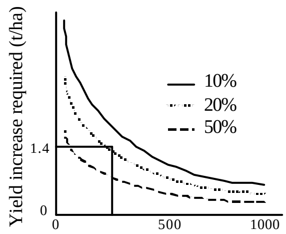
Percentage of field likely to produce a positive response



Area/Precision Farming system (ha)



Area/Precision Farming system (ha)



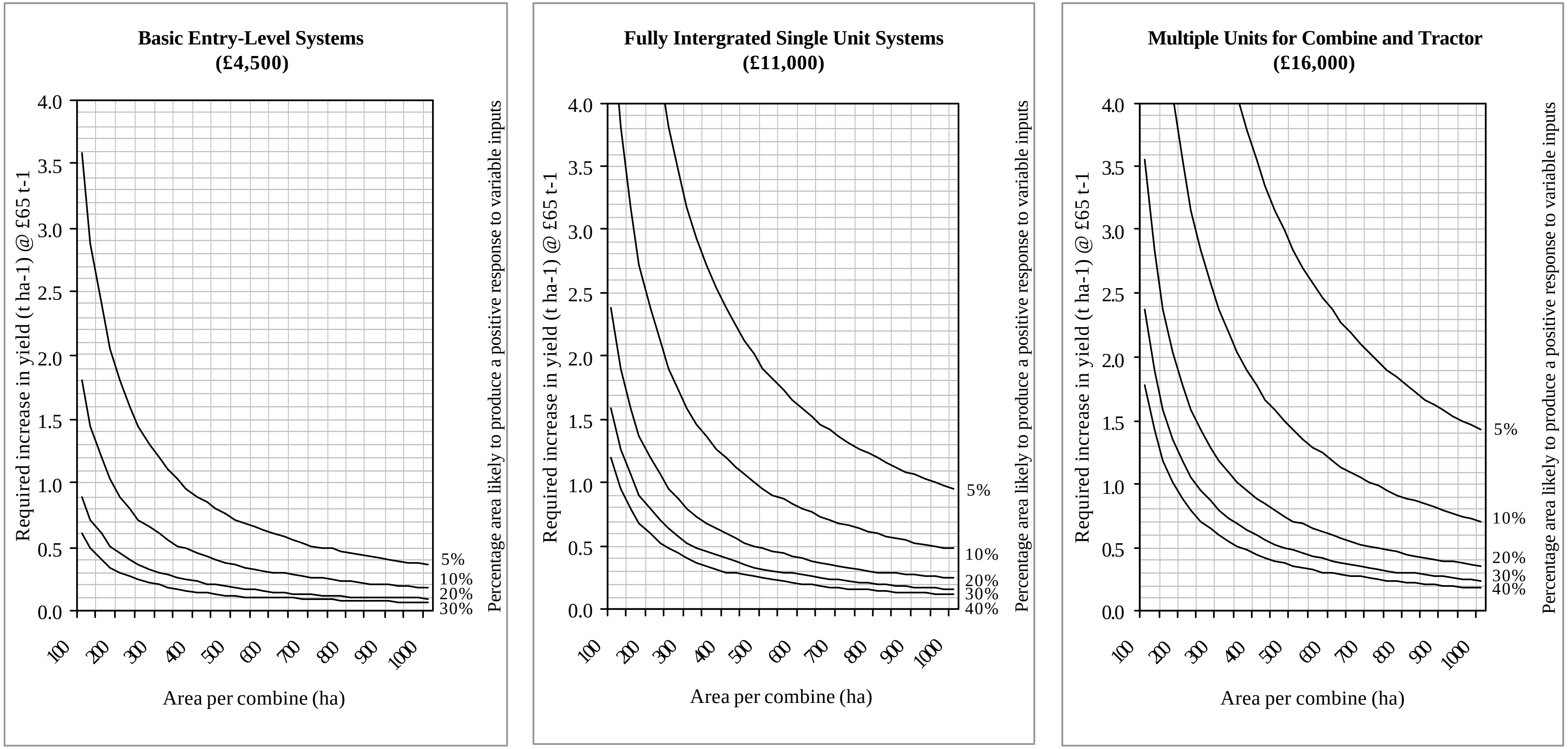
Area/Precision Farming system (ha)

Is Precision Farming economically viable for your farm?

No

Yes

NEXT



Farm-size or enterprise sensitivity analysis for three Precision Farming hardware systems, indicating the yield increase required to break even for different levels of field variability.

You have decided to adopt a precision farming system
but need advice on what to do next

Zone your field by sampling and mapping

How?

- Yield Mapping
- Soil Mapping
- Air Photo Interpretation

1. Yield Mapping - identify zones that typically yield high or low, or assess the effects of problems (rabbits, weeds, water-logging etc).

2. Soil mapping using
   EMI - Electro-Magnetic Induction at £14ha^{-1}
   Traditional soil survey at £25ha^{-1}

3. API - £15-20 for 5km^{-1} air photo: historical air photo's will help to identify any relative variations in crop growth, early senescence, pest and disease damage.

Create Management Zones

- Apply cluster analysis to yield, soil and photographic data using a service provider or farmer friendly software
- Decide number of management zones by moderating statistical results with practical considerations

Targeted Sampling
e.g. will cost $^{1}/_{3}$ -$^{1}/_{2}$ that of gridded sampling

1. Texture / Structure
2. Depth
3. Potential soil moisture
4. N + P + K
5. Micro-nutrients
6. pH
7. Pests and weeds
8. Diseases

Produce application maps

- Try to determine causes of variation
- Consider the number and size of management zones
- Are P + K levels uniform and correct?

NEXT

1. Correct any management problems

<u>Target "one off" infrastructural repair tasks</u>
e.g. Water logging - improve drainage
Rabbit damage - fencing

<u>Target "local limiting factors"</u>
e.g. Weeds - spatially variable herbicides
Compaction - subsoil affected zones

2. Prevent any management problems

<u>Human factors</u>
e.g. Improved operator training
(Avoid drill misses, better fertiliser & herbicide application)

<u>Machinery calibration</u>
e.g. Check sprayers and fertiliser spreaders for lateral uniformity

3. pH and Micro-nutrients

Targeted Soil Sampling

Boost areas below threshold levels

4. P& K Replenishment

- Assess P & K status by targeted soil sampling
- Use to calculate off-take
- Decide upon application strategy

Well above acceptable indices	Close to critical indices	Generally or locally below critical indices
No immediate action needed. Use yield maps to monitor off-take.	Replace in proportion to crop off-take.	Uniform or targeted application as required

Continue to monitor off-take using yield maps

Consider spatially variable N management using "Real Time" methods

NEXT

1. Autumn
Use a seed rate appropriate for the sowing date, aiming to produce a fertile ear population of 450 – 600 ears m^{-2}

2a December - February
Measure or estimate SMN in proposed management zones - determine the total nitrogen fertiliser requirement for optimum crop growth and yield.

2b Measure shoot density using ADP or other remote sensing techniques: GS23-29

2c Zone the field based on 2a and 2b

Below target Density	On - target density	Above Target Density
Increase first dose (and subtract from main dose)	Apply target dose	Reduce or omit first dose (and add to the main dose)
(If high SMN apply no fertiliser)	(If high SMN apply no fertiliser)	(This is essential if SMN is high)

First N application

Keep crop clean and free from pests and diseases

Continued on next page...

NEXT

3. March - April GS 31-32

Measure variation in green area index (GAI) prior to main nitrogen dose. Re-zone field compared to target shoot density/GAI value.

Below target	On - target	Above Target
Increase dose*	Apply target dose*	Reduce dose*
*unless the first dose was also increased. This would indicate more fundamental nitrogen availability problems.	* reduce, if first dose was an *increased* dose. * increase if the first dose was a *reduced dose*	*unless the first dose was a *reduced* dose, in which case, apply the standard dose.

Main N application

4. May GS37

Measure variation in green area index (GAI) prior to final nitrogen dose (usually 40kg N ha^{-1} for canopy survival). Re-zone field compared to final target shoot density/GAI.

Below target	On - target	Above Target
Increase dose*	Apply final target dose	Omit final target dose
*unless the main dose was also increased, in which case add the standard dose		

Final N application

Keep crop clean and free from pests and diseases