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REVIEW PAPER

Precision Farming of Cereal Crops: a Review of a Six Year Experiment to develop Management Guidelines

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This paper summarises the results of a 6-yr study, involving five principal fields in England covering 13 soil types, which represent approximately 30% of the soils on which arable crops are grown. The aim of the project was to determine guidelines to maximise profitability and minimise environmental impact of cereal production using precision farming. The study focused on the interaction between soil/water variability and nitrogen applications. The earlier work concentrated on identifying the in-field variability and the development of a 'real-time' sensing technique, while the later work compared spatially controlled inputs with uniform agronomic practice. A number of techniques were used to decide upon the variable application strategy. These included yield variability from historic yield maps, variability in shoot density in the spring, and variability in the subsequent development of the canopy; the latter two enabling the development of the concept of 'real-time' agronomic management.

In uniformly managed fields, there were considerable differences in the spatial patterns and magnitudes of yield variation between fields and seasons, which linked to soil variation and annual differences in rainfall and earlier field operations. Electromagnetic induction (EMI) was found to be a suitable surrogate for detailed soil coring and cluster analysis of EMI and yield data provided an objective method to subdivide fields into management zones for targeted sampling of soil nutrients and pH; and for estimating replenishment levels of P and K fertilisers. Considerable reductions in the cost of soil sampling were possible with this approach.

Yield maps, however, were not a useful basis for determining a variable nitrogen application strategy. It was shown that the spatial variation in canopy development with a field can be effectively determined using aerial digital photography for 'real-time' management. This technique can improve the efficiency of cereal production through managing variations in the crop canopy and gave an average economic return of £22 ha^{-1} while reducing the nitrogen surplus by approximately one-third.

Benefits from spatially variable application of nitrogen outweigh costs of the investment in precision farming systems for cereal farms greater than 75 ha for systems costing £4500. This area increases in size in proportion to the capital cost. 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 farm with 250 ha of cereals where 20% of the 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. These economic advantages linked to the environmental benefits should improve the longer term sustainability of cereal production. Common problems, such as water-logging and fertiliser application errors should be corrected prior to the spatial application of fertilisers and other inputs. From the overall results a set of practical guidelines has been incorporated in a single decision support tool to help farmers.

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1. Introduction

Precison 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;
(ii) the risk of environmental pollution from agrochemicals applied at levels greater than optimal can be reduced; and
(iii) greater assurance from precise targeting and recording of field applications to improve traceability.

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

This paper provides a review of a 6-yr study to develop 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; and
(iv) collaborating with farmers to ensure that research findings are appropriate for adoption.

The emphasis of this work was the development of practical 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 this approach to farming in recent years. The main catalyst for this was the advent of affordable differential global positioning systems which 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.

2. Approach

A summary of factors that could influence the yield of crops in a given location developed by Earl *et al.* (1996) 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 inputs costs without an adverse effect upon crop yield.

The duration of the study extended over six cropping seasons and included the harvests in 1995–2000. 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

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 diseaes

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 wheat
Twelve Acres	Hatherop, Gloucestershire	Sherborne/Moreton/Didmarton	Continuous winter wheat
Supplementary fields			
Short Lane	Gamlingay, Cambridgeshire	Wickham/Ludford/Maplestead	Continuous winter barley
Short Wood	Gamlingay, Cambridgeshire	Hanslope/Denchworth	Winter wheat
Far Highlands	Old Warden, Bedfordshire	Wickham/Evesham	Winter wheat

*After Jarvis *et al.* (1984) and Hodge *et al.* (1984).

been in cereals for several years prior to the experimental work.

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 to the 'key' fields in the harvest seasons of 1995–1997. Yield maps for these seasons provided an indication of crop yield variation both in space and time. Since the 1997–1998 cropping season effects of variable inputs were studied on all fields shown in Table 2 with the exception of the pilot study in Short Lane which started in 1996–1997.

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.

3. Inherent variability

3.1. *Crop yield*

Typical variations in crop yield are presented in *Fig. 1*, which shows that there is some similarity over the 3-yr period. The spatial trend map (average yield), after Blackmore (2000), for the period shows that, on average, the yield range for this particular field is in excess of $\pm 20\%$ 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 developed by Blackmore and Moore (1999) to compensate for field operational artefacts 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. In uniformly managed fields, there were considerable differences in the spatial patterns and magnitudes of yield variation between fields and seasons, which linked to soil variation and annual differences in rainfall and earlier field operations.

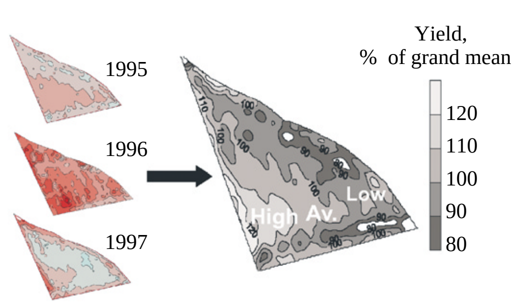


Fig. 1. Spatial trend (average yield) map for yield at Trent Field, 1995–1997

Further analysis of the data over a 6-yr period by Blackmore *et al.* (2003) shows that there is compensation in the spatial distribution of crop yield such that the spatial variability of the cumulative yield reduces with time.

3.2. *Soil types*

The fields were initially surveyed at a commercial detail level of approximately 1 auger hole ha^{-1} to provide an overview of soil textural and profile variation. These were complemented by 'targeted' profile pit descriptions as given in Earl *et al.* (2003). 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 (Wood *et al.*, 2003a) captured in May 1996; and
(iii) soil maps based upon auger sampling at a 100 m grid spacing.

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

Further studies with both 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 between soil textures as shown in *Fig. 2*, where the higher levels of conductivity indicate higher moisture content soils which if conducted at field capacity would indicate a greater clay content (Waine, 1999), as shown in Godwin and Miller (2003). Thus electromagnetic induction observations correlate well with assessments of soil series where these are differentiated by the soil texture and water holding properties.

Objective techniques, using cluster analysis, have been developed which enable potential management zones to be determined using historic yield and EMI data (Taylor *et al.*, 2003). Differences in soil nutrient levels have been identified between the management zones and, hence, form a basis for targeted sampling of soil nutrient status to reduce the cost of field sampling.

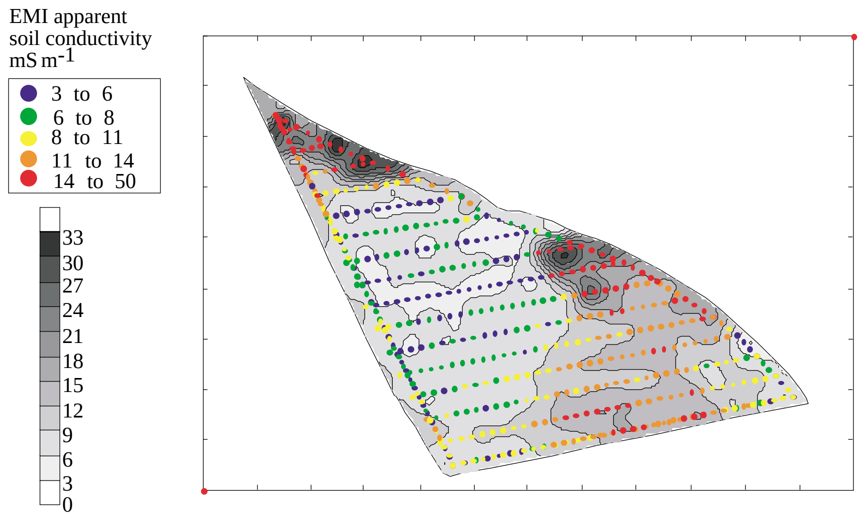


Fig. 2. Electro Magnetic induction (EMI) conductivity Trent Field 2 February 1999

3.3. *Soil fertility and crop nutrition*

Detailed analyses of macro- and micro-nutrients in both soil water extract 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 analysis by Earl *et al.* (2003) showed that the levels were above the commonly accepted agronomic limits.

3.4. *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 infrared (NIR) filters as described in Wood *et al.* (2003a). Field images obtained form aerial digital photography (ADP) from a height of 1000 m give a pixel resolution of 0·5 m by 0·5 m. Normalised difference vegetation index (NDVI) values were estimated from the following equation:

$$I_{NDV} = (\lambda_{NIR} - \lambda_R)/(\lambda_{NIR} + \lambda_R) \quad (1)$$

where: I_{NDV} is the normalised difference vegetation index; and λ_R and λ_{NIR} are the red and near infrared spectral wavebands. The resulting images, such as *Fig. 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,

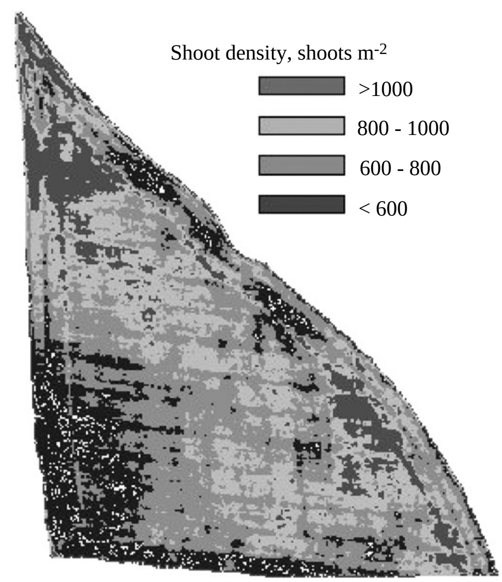


Fig. 3. Normalised difference vegetation index (NDVI) image of Trent Field

when calibrated against detailed agronomic measurements at targeted locations, were used in near 'real-time' to estimate crop condition and potential nutritional requirements as described in Wood *et al.* (2003b). Extension of this principle to farm scale operations results in effective calibration between the crop indicators and NDVI using eight sampling points, Wood *et al.* (2003a). The cost of extending this technique to commercial practice has been estimated by Godwin *et al.* (2003) at £7 ha^{-1} for 3 flights yr^{-1}, during the January to April period, for areas of 1500 ha per flight. It has been possible using this system to also identify areas in need of spatially variable application of herbicides and plant growth regulators.

3.5. *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. There was variation in the availability of plant nutrients, potassium, phosphorus and the micro-nutrients in the study fields, however, in agronomic terms, were not limiting. The stable patterns in the yield maps observed in the early years of the work, changed with time to reduce the variation in cumulative yield, (Blackmore *et al.*, 2003). The aerial digital photography (ADP) system specified for this project allowed variations in crop yield components to be mapped in near 'real time'.

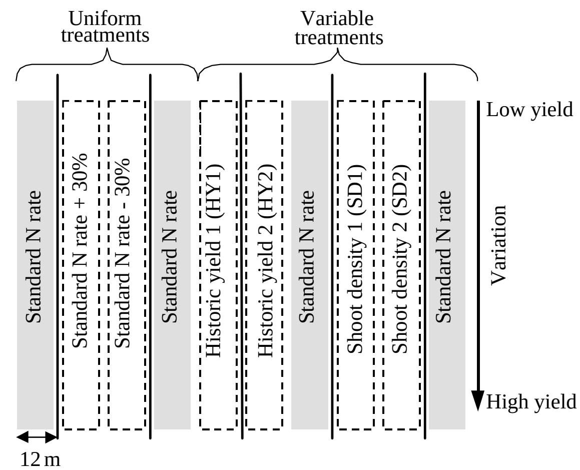


Fig. 4. Plan of field experiments

4. Variable application of nitrogen

4.1. *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.

Pilot studies by James and Godwin (2003) in Short Lane, investigated the use of a series of long treatment strips, which ran through the main areas of variation within each field. This was developed into the proposed final design by Welsh *et al.* (2003a, 2003b), comprised a series of long strips, which ran through the main areas of variation within each field, an examples of which is presented in *Fig. 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% as given in Moore (1998).

4.2. *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.

4.3. *Historic yield and shoot density studies*

These treatment strips were established to test the following strategies in the same fields as 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: and
(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 *Fig. 2*; and
(ii) shoot density data, estimated from NDVI data, as shown in *Fig. 4*, (after Wood *et al.*, 2003a).

Using this approach, experimental strips (*Fig. 5*) 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.

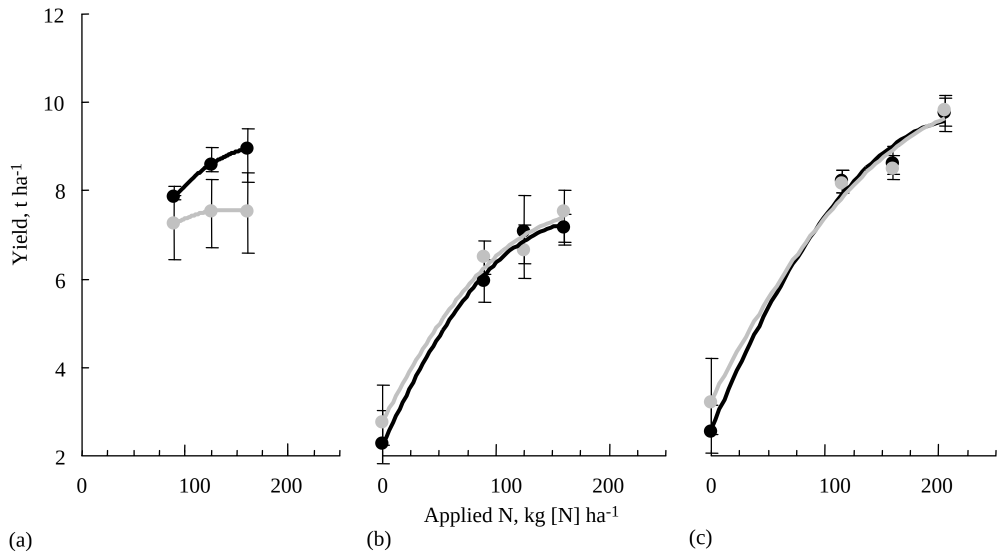


Fig. 5. Yield response to applied N in the Andover and Panholes soil series zones in (a) 1997/98, (b) 1998/99 and (c) 1999/00; error bars denote the yield range about the mean: ●, Andover; ●, Panholes

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 were not possible.

4.4. *Crop canopy management studies*

The methodology for these studies, described by Wood *et al.* (2003b), was developed over 3 yr 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, along which one received a standard field rate of nitrogen fertiliser (200 kg [N] ha^{-1}), and the other a variable amount dependent upon crop growth. Observations were made in near 'real time' using the aerial digital photographic technique and crop canopy measurements described in Wood *et al.* (2003a). 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, growth stages GS30-31 and GS33) compared with benchmarks from the Wheat Growth Guide, HGCA (1998). 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.

5. Results

5.1. *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 *Fig. 5* for the 3 yr of the experiment from the data presented by Welsh *et al.* (2003a). 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 similar for both soil types, resulting in common yield response curves. This observation was also made by James and Godwin (2003) in Short Lane, where the optimum application rate from the winter barley yield response curves of the contrasting clay loam and sandy loam soils was the same in each of the three seasons studied, despite significant variations in annual rainfall.

As reported by Welsh *et al.* (2003b) 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.

5.2. *Historic yield and shoot density studies*

An example of the yield distribution along the variable treatment yield strips is presented in *Fig. 6* (after Welsh *et al.*, 2003a) 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.

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. This occurred because there was little variation along the strip with a low shoot density, 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 (Welsh *et al.*, 2003a, 2003b). 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.

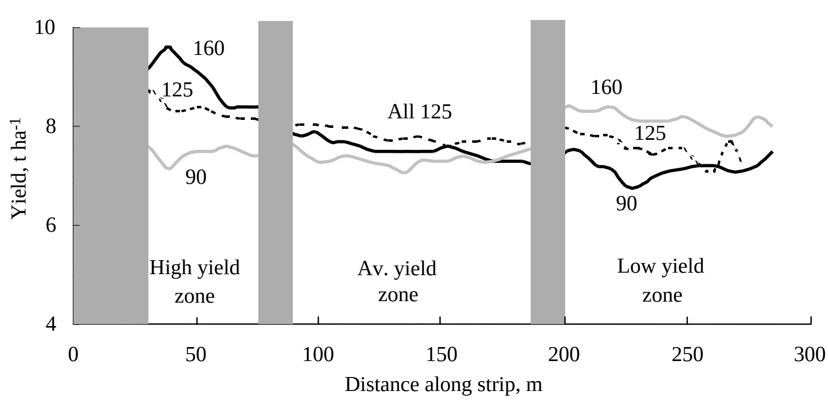


Fig. 6. Combine harvester yield of 'historic yield' treatments (HY1 & HY2) compared with a standard application along the treatment strips in Trent Field; shaded areas are transition zones and are deleted from the analysis: ——, HY1; – – –, standard; ——, HY2; fertiliser application rates in kg [N] ha^{-1}

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

Strategy	*Relative economic consequences, £ ha^{-1}*			
	Trent Field	*Twelve Acres*	*Far Sweetbrier*	*Mean*
Historic yield 1 (HY1)	−5·41	−21·23	−7·80	−11·48
Historic yield 2 (HY2)	−12·56	−21·88	5·85*	−9·53*
Shoot density 1 (SD1)	4·98	−15·38	−13·00	−7·80
Shoot density 2 (SD2)	0·43	−15·17	33·58	6·28

*Contains data from 1998/99 and 1999/00 only.

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}

The zones needing particular attention were identified in this phase of the study and could be treated by targeted measures. Their economic impact can be significant (Godwin *et al.*, 2003) and if present in fields it is recommended that they are corrected prior to the application of spatially variable fertiliser and other inputs.

5.3. *Canopy management studies*

The results from the pilot study by Wood *et al.* (2003b) 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.

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 three 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 *Fig. 7*. In seven of the eight comparisons the gross margin was in favour of variable 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 as described by Wood *et al.* (2003b) 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 and depending upon field and season.

Table 5
Nitrogen application rates in kg [N] ha^{-1}, yield in t ha^{-1} and gross margin (GM) in £ ha^{-1} comparisons between variable and uniform nitrogen application strategies

Onion Field	Target seed rate, seeds m^{-2}											
	150			250			350			450		
	Plant population, plants m^{-2}											
	100			143			177			200		
	N, kg ha^{-1}	*Yield t ha^{-1}*	*GM, £ ha^{-1}*	*N, kg ha^{-1}*	*Yield, t ha^{-1}*	*GM, £ ha^{-1}*	*N, kg ha^{-1}*	*Yield, t ha^{-1}*	*GM, £ ha^{-1}*	*N, kg ha^{-1}*	*Yield, £ ha^{-1}*	*GM, £ ha^{-1}*
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
Far Highlands	Plant population, plants m^{-2}											
	120			195			240			320		
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

6. 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 by Godwin *et al.* (2003) enabled the annual costs per hectare to be assessed. These costs ranged from less than £5 to £18 ha^{-1} for a single yield mapping and spatial control unit managing an area of 250 ha per yr^{-1} 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 £4500, 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 *Fig. 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.

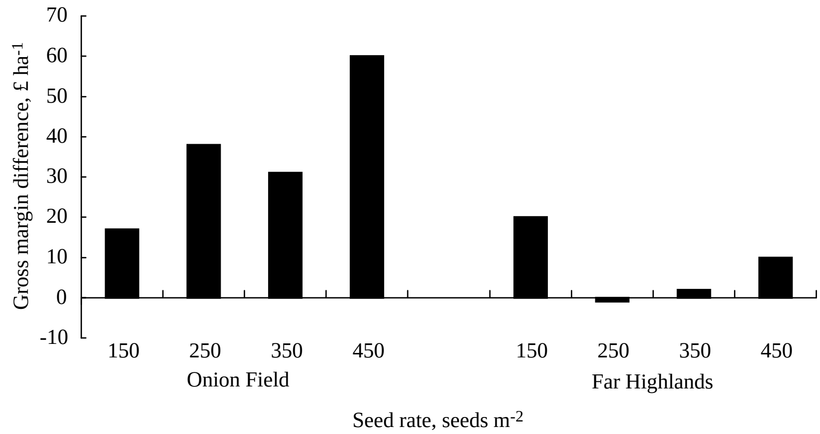


Fig. 7. Difference in gross margins in £ ha^{-1} between variable N and uniform N, i.e. variable N has uniform N

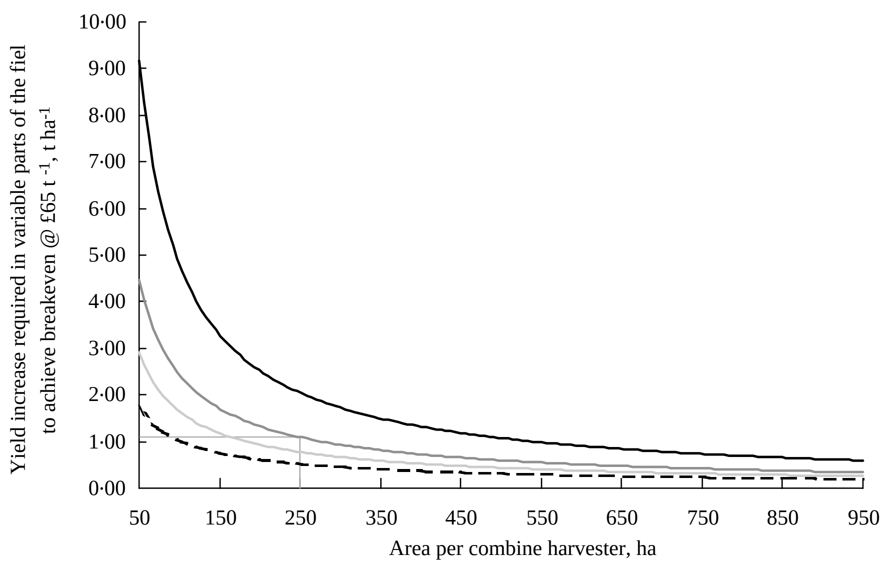


Fig. 8. Yield increases required for a break even scenario for different proportions of the field likely to benefit from precision farming and the harvested area for a fully integrated precision farming equipment and software system costing £11 500; area of the field likely to produce a positive response to variable inputs: ——, 10%; ——20%; ——30%; - - -50%

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; Perry *et al.*, 2001) and fungicides (Secher, 1997) have each shown benefits of up to £20 ha^{-1}.

7. Environmental implications

Whilst this project did not specifically address environmental implications of nitrogen usage patterns, 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, Wood *et al.* (2003b) calculated 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 plants m^{-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 *Fig. 9*.

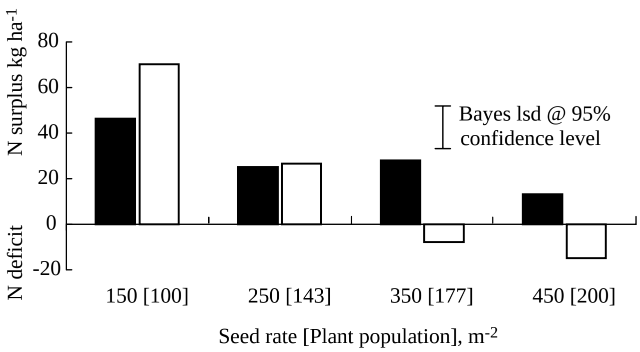
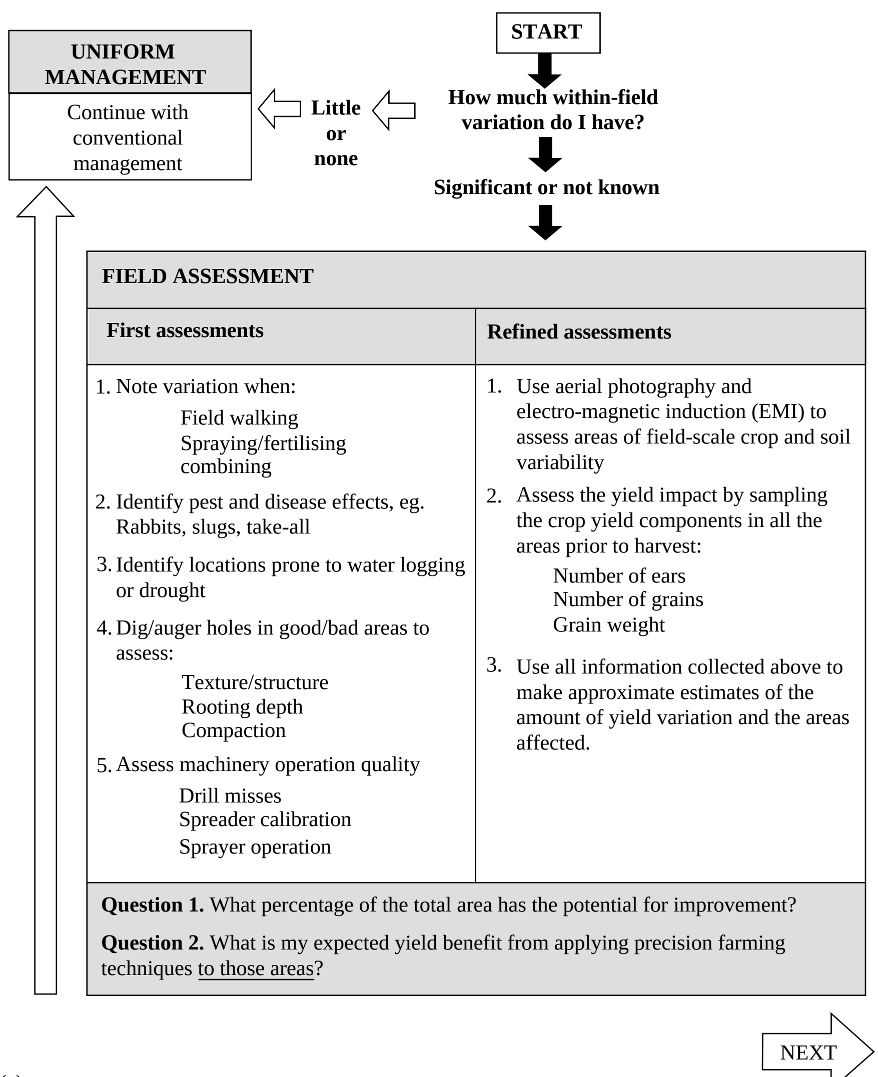


Fig. 9. Surplus or deficit of applied nitrogen relative to offtake in grain and straw at Onion Field in 2000: ■, uniform N; □, variable N

However at the three higher plant populations, the off-takes from the variable N appliations 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 [N] ha^{-1} compared to 28 kg [N] ha^{-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 significances.

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 [N] ha^{-1}.



(a)

Fig. 10. (a) Stage 1 of the practical guidelines: initial investigations of within-field variation, (b) Stage 2 of the practical guidelines: is precision farming economically viable? (c) Stage 3 of the practical guidelines: understanding the causes of variability and identifying management zones. (d) Stage 4 of the practical guidelines: addressing fundamental management practices prior to variable application, and strategies for managing nutrients. (e) Stage 5 of the practical guidelines: real-time management of variable nitrogen fertiliser for optimising economic yield

UNIFORM MANGAGEMENT

Continue with conventional management

LEVEL OF YIELD INCREASE, t ha					

System (investment)	**% area responding**	**Cereal area** 250 ha	500 ha	750 ha	1000 ha
Basic unit (£ 4500)	5%	1.44	0.72	0.48	0.36
	10%	0.72	0.36	0.24	0.18
	20%	0.36	0.18	0.12	0.09
	30%	0.24	0.12	0.08	0.06
Single integrated unit (£ 11000)	5%	3.81	1.91	1.27	0.95
	10%	1.91	0.95	0.64	0.48
	20%	0.95	0.48	0.32	0.24
	30%	0.64	0.32	0.21	0.16
Multiple units for combine and tractor (£ 16000)	5%	5.68	2.84	1.89	1.42
	10%	2.84	1.42	0.95	0.71
	20%	1.42	0.71	0.47	0.35
	30%	0.95	0.47	0.32	0.24

e.g. taking the basic entry-level system - if your farmed area is **750 ha**, of which **10%** is expected to respond to variabe inputs, the level of yield increase on those areas in order to break even must be at least **0.24 t ha^{-1}**

shaded areas: sustainable improvements of this magnitude were not generated during the project

Is Precision Farming economically viable on your farm?

No

Yes

NEXT

(b)

Fig. 10 (continued).

8. Practical guidelines

The results of the project have been integrated into a simple-to-follow flow chart, shown in *Fig. 10*, to guide the grower through the respective elements of precision farming. The flow chart addresses the questions and choices facing the grower at various stages of the decision–making process, including determining whether precision farming would be viable on their farm, to identifying management zones for soil nutrient management, to detailed crop monitoring for varying fertilizer nitrogen. These have been made available and distributed to all UK levy paying cereal growers (HGCA, 2002).

9. Conclusions

(i) Yield maps are indispensable for targeting areas for investigation and treatment by precision farming practices and subsequent monitoring of

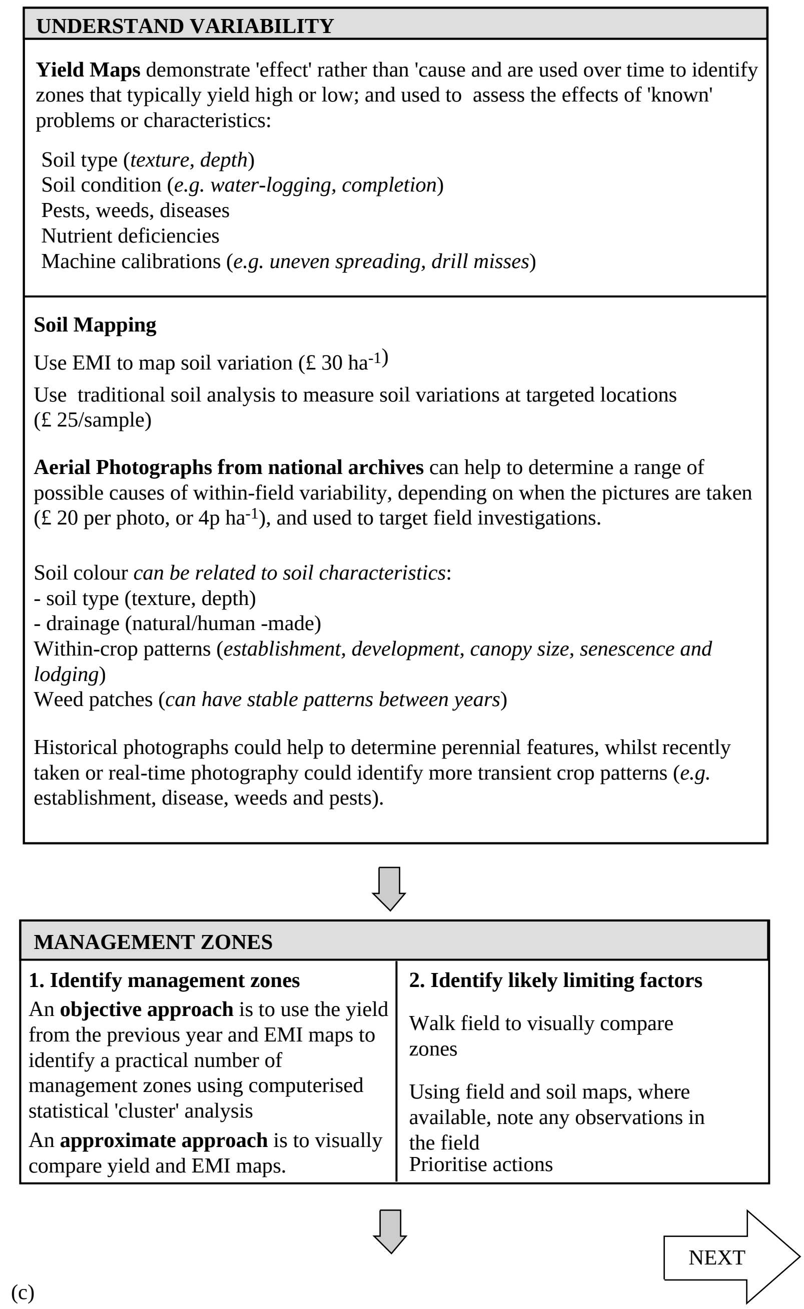


Fig. 10 (continued).

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. This was particularly illustrated in the study of Short Lane, where despite significant differences in yield between two contrasting soil types, the optimum nitrogen application rate was the same, despite significant differences in annual rainfall.

(ii) The spatial variability evident in the yield maps of the fields studied was inconsistent from one year to the next, hence the variation in the spatial distribution of the cumulative yield reduced with time.

(iii) The possible extent and potential causes of yield variability can be determined using low capital cost yield mapping systems together with electromagnetic induction techniques to assess variation in soil factors such as texture and water holding capacity. A methodology using cluster analysis

MANAGEMENT ISSUES

One-off infrastructural tasks, *e.g.* water–logging–improve drainage; rabbit damage–fence crops.

Local limiting factors, *e.g.* weeds–apply herbicides spatially; compaction–loosen affected zones

Machinery factors, *e.g.* poor distribution of sprays and fertilisers–calibrate sprayers and spreaders, check for uniformity.

Human factors, *e.g.* drill misses, poor fertiliser placement–improve operator training

NUTRIENT MANAGEMENT

PHOSPHATE AND POTASH

1. Monitor P & K status using targeted soil sampling and repeat every 3-4 yr

2. Calculate annual off-take using yield maps and determine application strategy

Well above critical index	Close to critical index	Generally, or locally below critical index
Do nothing	Apply according to offtake	Apply according to offtake, plus an additional amount

pH AND MICRO-NUTRIENTS

Use t**argeted soil sampling to quantify deficiencies**–replenish levels in areas below recommended critical levels.

NEXT

(d)

Fig. 10 (continued).

was developed to use these techniques to determine within-field management zones. Both individually and together these systems provide an objective means for assessing the degree of variability within a field and provide a basis for targeting a reduced number of soil and crop sampling points, which is essential to reduce costs for commercial application.

(iv) 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 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.

(v) 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}.

(vi) 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.

(vii) Common problems, such as water-logging and fertiliser application errors, can result in significant

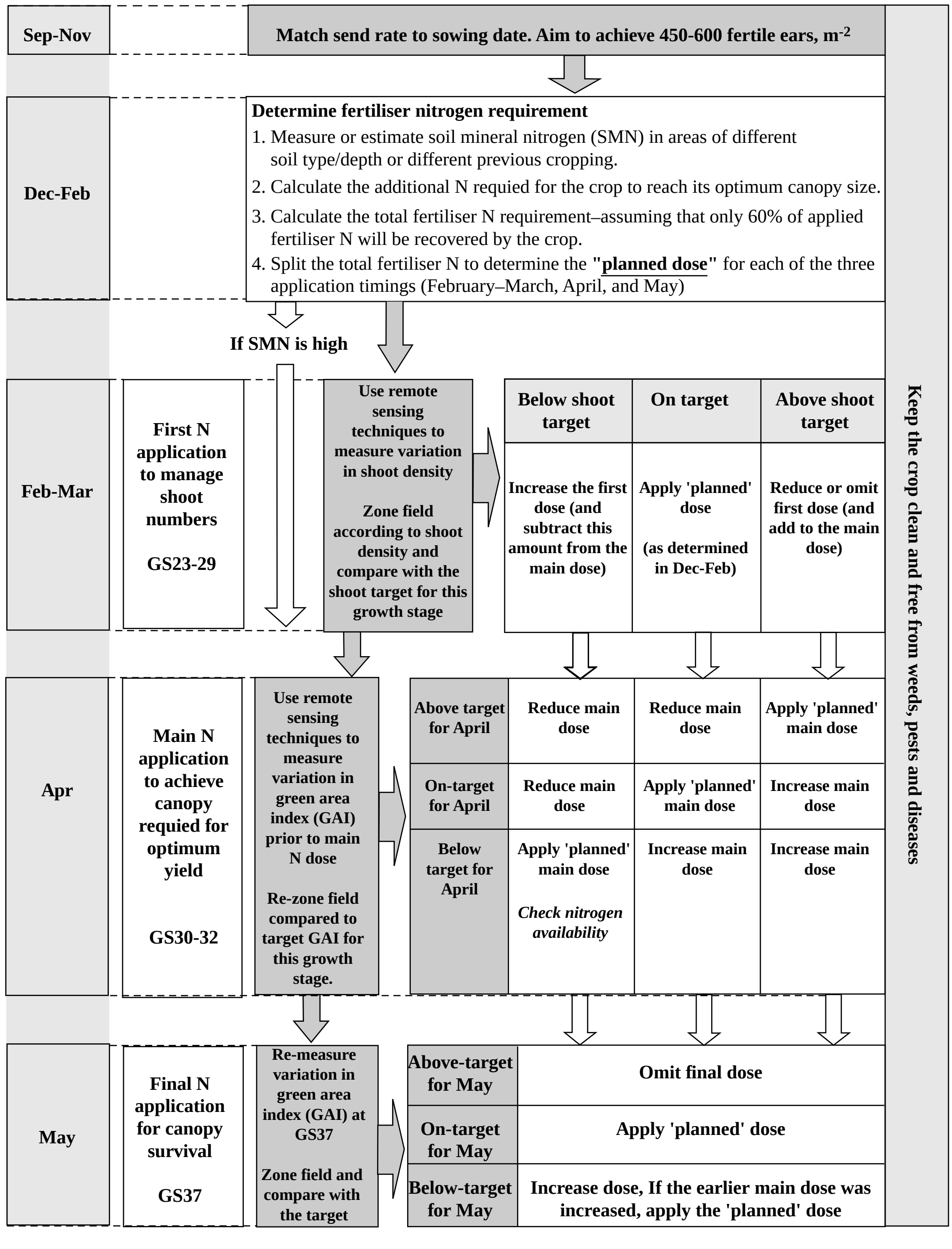


Fig. 10 (continued).

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.

(viii) 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 £4500 are purchased, and greater than 200–300 ha for more sophisticated systems costing between £11 500 and £16 000.

(ix) 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 £ 11500. This figure reduces to 0.25 t ha^{-1} for a basic system.

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) 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.

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

The results of the above have been incorporated into a simple decision support tool in the form of a flow chart, to help farmers with practical decisions.

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