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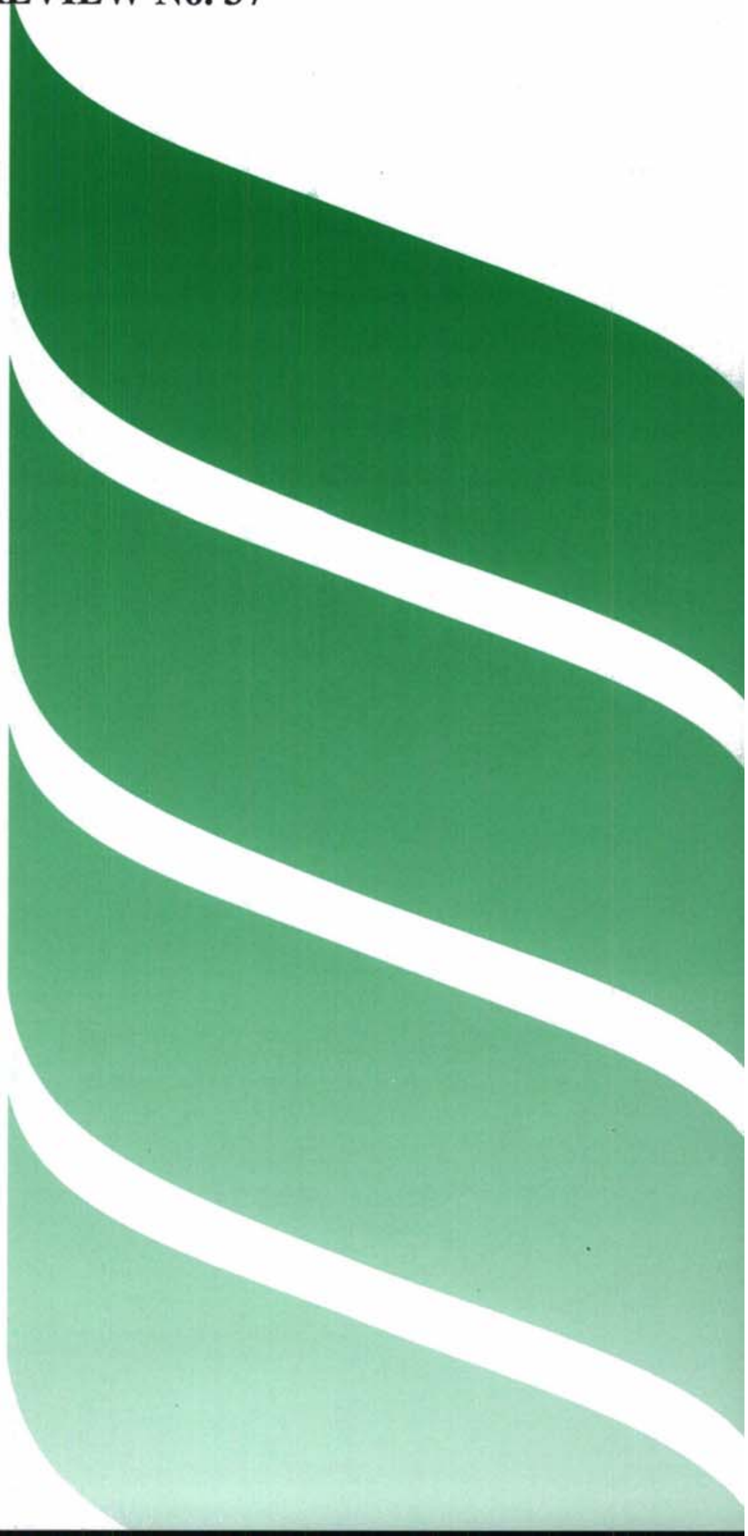
THE POTENTIAL OF PRECISION FARMING FROM AN AGRONOMIC PERSPECTIVE



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THE POTENTIAL OF PRECISION FARMING FROM AN AGRONOMIC PERSPECTIVE

by

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Contents

ABSTRACT

Precision Farming is the process of adjusting husbandry practices within a field according to varying conditions measured within the field. In this review, we explore the prospects for Precision Farming using the principles that underly conventional agronomy.

Many of the ingredients essential for Precision Farming already exist although some technologies are at an early stage of development. Current conventional agronomy depends upon the five underlying steps of 'locate, sense, decide, act and monitor'. To move towards Precision Farming, most of these steps would require a significant investment in automation. There are already technologies that can automate and improve most of the steps, but not the second: the major obstacle to the development of Precision Farming at present is the automation of 'sensing'.

The costs and techniques of sensing must provide parameters appropriate to the most important decisions with sufficient resolution to allow reliable definition of treatment zones. Satellite mounted sensors are unlikely to find a place in supporting Precision Farming in the short or medium term because their signals are too infrequent. A few low cost sensing techniques are known and these could be tractor-mounted but none has yet been developed to the extent that in-field variation in factors affecting agronomic decisions can be sensed with adequate timeliness, accuracy and precision.

Present position

In more detail, specific conclusions of this review are that :

1. The cost-effectiveness of Precision Farming is determined by :
   (a) the cost of defining zones,
   (b) the stability of zones through time,
   (c) the difference in treatment between zones in terms of cost, and
   (d) the responsiveness of the crop in terms of yield, quality and hence value, to changes in treatment.

   Additional environmental benefits from Precision Farming will accrue through reducing the extent of prophylactic or excess use of fertilisers and agro-chemicals on a sub-set of zones within fields.

   Cost-effective Precision Farming is most likely where prior knowledge indicates high heterogeneity and where treatment zones can be predicted, for example from soil type or field history. Headlands and amalgamation of fields with contrasting histories provide straightforward opportunities for zoning which may well prove cost-effective.

2. The cost of defining just four zones within a field is about 50 times that of assuming that the field is uniform. Thus zoning is most economic when the cost of sensing is minimal, particularly when the attribute in question can be taken as being stable through time.

   Soil related factors are likely to provide the main basis for Precision Farming because they tend to be stable through time, and influence crop performance. In

particular, the moisture available for crop growth may usefully be indicated by soil mapping. Organic matter maps are also likely to be useful for precision application of fertilisers, and occasionally for variable herbicide applications. Variation in soil pH can be mapped and used as a basis for variable lime application. However, comprehensive nutrient mapping is less likely to be economic with existing techniques of chemical analysis. Much of the variation in nutrients is at too fine a scale to be mapped economically, and spurious treatment of zones defined from inadequately precise data can lead to financial loss. No cheaper sensing technologies appear to be under development.

3. Agronomic decisions during crop growth tends to be influenced most by conditions at the time of treatment. Thus 'real time' sensing of crop attributes will be of most value in Precision Farming. Techniques for remote sensing of crop growth have been under development for several years, mainly through spectroradiometers mounted on aircraft or satellites; these can provide 'vegetation indices' and 'stress indices'. The main obstacles to immediate adoption of these techniquesare the infrequent coverage of data and its uncertain interpretation.

4. Current research shows the importance of crop characters such as shoot number and surface rooting for reducing lodging risk, and canopy size (measured as 'green area index') for controling nitrogen nutrition and fungicide rates. It is possible that, with further research, some of these characters could be inferred from spectroradiometry.

5. The low treatment thresholds and the mobility of most pests and diseases restrict the value of sensing any in-field variation in occurrence or severity. However, the crop's *tolerance* of pests and diseases is likely to prove relatively stable through a season and, if it can be detected, will probably justify variation in the use of pesticides and fungicides. It is possible that the symptoms of 'stress' that are detectable with spectroradiometry may be used to infer in-field differences in susceptibility to pests and diseases. However, considerable further research would be required to verify this.

6. When it comes to designing a complete system for Precision Farming, there are gaps in information and agronomic understanding which prevent full exploitation of the apparent potential. For example, there are still uncertainties in whether, and if so how, inputs should be modified according to yield potential; the association between yield and N requirement is in doubt.

7. The yield map gives information too late for treatments to be modified. Its value lies in identifying zones which are sufficiently stable to be of use in determining future practices. Maps of grain quality and nutrient content would significantly augment the value of yield maps in guiding marketing decisions and future agronomy. Interactions between soil differences and seasonal weather are large, so yield maps show considerable differences from season to season. Interpretation of such maps needs to follow a careful, informed analytical process. Guidance has yet to be developed.

Extensive and thorough field experimentation by crop scientists over many years has shown that yield variation arises as a result of a large and complex range of factors. It is highly improbable that simple explanations will be appropriate for much in-field yield variation. However, the capacity to sense yield variability within fields as opposed to between fields, where there are many confounding differences, such as rotation, provides an opportunity for the cereal industry to improve its understanding of soil-based effects on crop performance. This should support its decision-taking, whether through Precision Farming or through field-by-field agronomy.

It follows from these conclusions that further research and development on both immediate and longer-term issues is needed before the full potential of Precision Farming can be realised by the industry. Our suggestions for further research are that:

Future needs

1. In the short term, there is a need for greater information on **the extent of within-field variation**, especially that due to the less obvious causes. Where a field includes both sand and clay, significant yield variation is expected and current advice would already be to manage it as two units. However, more subtle within-field differences may have equivalent importance. Questions which should be addressed include :

   - How much variation exists in fields which would be treated uniformly under current advice?
   - How easy is it to predict fields with large in-field variability?
   - To what extent can persistent zones of variation be explained from available knowledge?
   - How much of the variation is due to easily remedied causes (e.g. compaction on headlands, acidity) and how much to inherent factors such as variation in the soil's 'water holding capacity'?

   These questions then need to be answered in economic terms to provide a basis for decisions by farmers who are considering investment in Precision Farming systems, and by those who are considering investment in further research or development.

2. In the longer term, the main research requirements are likely to be for the development of **improved systems for sensing**. This will require good collaboration between agronomists and engineers. Characteristics for which sensing techniques are most likely to bring benefit would appear to be :

   - soil nutrient status, and moisture content,
   - weed identity by image analysis,
   - crop canopy size, colour and moisture status, probably by spectroradiometry, and
   - grain protein content, perhaps by near infra-red reflectance.

3. In several of these cases there will be a need to **re-interpret existing agronomic practices** in such a way that husbandry decisions can be adjusted according to the most easily sensed information. For instance, there is little current guidance on how to alter husbandry according crop moisture status. If moisture status proves easy to sense, it is possible that adjustments to fertilisers, fungicides and aphicides would be justified. It has been demonstrated that droughted crops have a smaller

optimum amount of N than crops with ample moisture through irrigation, but it is not clear whether there are analogous effects where ample moisture is available through the retentive properties of heavy soils.

4. With the aid of yield mapping combines, it is possible to envisage simple but powerful experiments which would throw light on **interactions between soil variability and husbandry practices**, to the greater benefit of all forms of agronomy.

5. When fields are sub-divided into multiple units, the complexity of decision-making will be considerable, and farmers will need **information and decision support systems** to guide them and help them manage the information. Such systems will need to analyse and display spatial data (yield maps, soil maps, sensed information) and apply decision rules to guide the farmer towards action. Given the complexity and consequent uncertainties of some of the issues, the main purpose of such systems may be to visualise the main zones, present the variable information clearly, and suggest (rather than automatically dictate) responses. These systems will also need to turn the decisions into instructions for variable applications.

INTRODUCTION

As most commonly discussed, Precision Farming involves the use of high-resolution spatial information to place husbandry decisions at an appropriately accurate scale. Definitions of Precision Farming are many and varied. For the purpose of this review it is defined as the adjustment of husbandry practices within a field in relation to measured spatial variability.

Precision Farming has arisen mainly in response to advances in technology, rather than through advances in the fundamental sciences which support farming. These technological advances are of four main types :

- geo-referencing (to allow mapping of information and spatially accurate instructions for application of treatments),
- sensing and measuring (particularly yield-mapping combine harvesters),
- computing (to store and manipulate the geographical data), and
- application (through improved mechanisation and automation of cultivators, sprayers, spreaders and harvesters, e.g. allowing adjustments to concentrations and volumes of agrochemicals).

In particular, yield mapping combine harvesters, which give the farmer novel pictures of within-field yield variability, have caught the imagination of scientists and farmers alike. For this reason, Precision Farming has tended to relate to extensive agriculture and horticulture, and particularly to the cultivation of 'combinable' crops.

The advent of these technological advances now throws a challenge to cereal and oilseed agronomists: can their knowledge be applied to exploit fully the new opportunities that arise? Agronomists have been working for many years to understand and improve crop husbandry techniques on a field by field basis comprehensive guidance is now available on most important husbandry options for the important crops. Such guidance has evolved through an enormous and extensive investment in field experimentation, comparing effects of varying practices between plots within a field, and making careful interpretations, taking into account the extensive experience acquired by farmers of variation between fields. Thus, a premise for this review is that current agronomic knowledge should be sufficiently robust to provide a definition of both the potential and the limitations of Precision Farming.

This review attempts to make the necessary analysis for such a definition by assessing the way that husbandry decisions are currently taken and, in that context, assessing how the new techniques are likely to be most helpful. The review is restricted to a consideration of combinable crops, but sugar beet and potatoes are also undoubtedly appropriate candidates, and since Precision Farming of these crops is likely to be governed by similar considerations, it is hoped that the general principles which are developed will be more widely applicable. An inevitable outcome is an accompanying assessment of the limitations in agronomic knowledge that are highlighted by the new technologies, and an indication of the areas where further effort in research and development might be most beneficial.

The review starts by considering general issues concerning the husbandry process: decision-taking, automation, in-field variability and zoning, that govern an analysis of Precision Farming, and follows this with a topic by topic consideration of the way that the husbandry process might be developed in the light of these issues.

THE CROP HUSBANDRY PROCESS

The decision unit

Conventionally the farmer makes crop husbandry decisions for fields individually or, often, for groups of fields. For instance fields may be grouped into 'first wheats' and 'other wheats', or into 'crops of milling varieties' and 'crops of feed varieties'. Where fields are small and therefore numerous, field by field decision-taking can be difficult to achieve. Increasing mechanisation, increasing machine size and reductions in manpower have led to enlargement of arable fields in recent decades; average arable field size is now about 20 ha (derived from Burnhill *et al.*, 1996). However, there are concurrent processes of farm enlargement in North West Europe that keep the number of fields per farmer from decreasing, so that farm decision-taking on the basis of individual fields remains a challenge.

Conversely, the enlargement of arable fields has inevitably increased the probability that conditions within a field vary sufficiently to call for variation in inputs. In some cases field amalgamation has resulted in very different soil types being included within a single management unit (for example, Stafford *et al.,* 1996).

To an extent, these challenges are being met by employment of agronomic consultants who specialise in agronomic decision-taking. However, there are limits to the capacity of even specialists to make multiple decisions and it is clear that the concept of dividing fields into many small units would be impossible if the crop management or husbandry process could not be automated. In considering the scope for automation, it is necessary to develop a logic whereby fields can be sub-divided and these sub-divisions recognised; it is therefore necessary to identify the essential components of the husbandry process that must be applied to each unit.

The character of the husbandry process

In summary, crop management as a process is to :

(i) locate,
(ii) sense,
(iii) decide,
(iv) act, and
(v) monitor.

Location or 'positioning'has conventionally been achieved through the naming or numbering of fields. Sensing results in intelligence, decisions result from applying that intelligence through a set of rules, and action usually depends on machinery and physical resources. Lastly, monitoring provides further intelligence for re-evaluation of the decision, and may lead into a further decision cycle. Thus the process is repeated, sometimes only once but often several times during the life of one crop, because the imprecise character of agriculture commonly results in a requirement for corrective action.

Table 1. An overview of the main features of the crop and its environment which affect the decisions underlying cereal husbandry. These features should become targets for the sensing techniques needed to enable cost-effective Precision Farming.

Shading indicates the degree of influence.

Husbandry decision	*Factors affecting decisions*								
	Past yield	*Genotype*	*Soil type*	*Soil analysis*	*Weeds*	*Pests*	*Disease*	*Weather*	*Crop looks*
Crop	▒	NA	▒		▒	░	░	░	NA
Variety	░	NA					▒		NA
Cultivations			▓		▒			▓	NA
Fertilisers	▒	░	░	▓				▒	▒
Sowing		▒	▒					░	NA
Herbicides			▒		▓			▒	▒
Pesticides		░				▓		▒	▒
Fungicides		▒					▓	▒	▒
Growth regs		▒		░				▓	▒
Harvesting	░	░	░		▒			▓	▓

The introduction of Precision Farming must initially depend on using existing decision rules or 'recommendation systems' on units smaller than whole fields. The immediate prospects for Precision Farming will therefore depend on the requirements of existing recommendation systems, as shown in Table 1. The analysis presented in Table 1 is a summary of more detailed information that is presented later in this review. It showsthat most decisions have just one prime influence, but several modifying factors. Surprisingly few decisions are based on crop yield or performance in past seasons, even to a moderate degree. Decisions are primarily based on *current* observations. Despite the prominence that yield mapping has taken in the promotion of Precision Farming, the value of knowing the yield would appear to be in judging the success of *past* decisions, rather than in directly affecting *next* season's husbandry. Thus the main value of yield-mapping is to point out variation in factors such as soil type which will then have a more direct role in the application of existing recommendation systems.

Undoubtedly, in growing a crop, a wide range of intelligence is required, including attributes of weeds, pests and diseases, as well as the crop itself and the soil. Some of these attributes, particularly genotype and weather, can be taken as constant within a field, but most will vary, sometimes to a considerable extent. Thus they must be located and sensed automatically. There is therefore a need to consider the state of both location technology and sensor technology. Then individual decisions must be made and, assuming that these will be numerous, the decision-taking must be automated, probably using computers, and there is a need to consider the relevant computer technology. Then the decisions must be acted upon, usually by adjustments to application machinery such as cultivators, sprayers and spreaders. There is a need therefore to consider the automation of these adjustments. And finally the effects of these applications must be monitored, most probably using similar technology to those used for sensing, but most importantly including the measurement of yield and quality.

NEW TECHNOLOGY TO AUTOMATE AGRONOMY

Positioning

The most crucial technical advance in promoting Precision Farming has been the ability to record location within a field and reliably return to the same spot. Under conventional technology, demarcation of management areas would depend on simple devices such as hedgerow markers or counting tramline widths. These effectively limit the use of within-field zones to simple shapes, the same for all husbandry decisions. In practice, subdivision into more than two zones is rare with such conventional systems.

Global Positioning System (GPS) receivers, which use satellite signals to locate the observer have increased in precision and have decreased in cost such that they are now within the reach of commercial farming enterprises. Resolution depends on integration time, sophistication of the software and availability of a base station to allow correction for signal aberration. At present, real-time resolution of 2-3 m and post-processing resolution of 1-2 m is available and it seems likely that costs will continue to fall, whilst precision may increase further.

Yield-mapping combine harvesters use a GPS system for accurate positioning, and they have a system for continuous measurement of grain yield. In principle, therefore, a complete map of yield is obtained for a field. In practice some smoothing is essential so that the effective minimum zone size for interpretation of the data is of the order of 10-20m (Stafford *et al.,* 1996). There is a need for advances in data analysis to allow for variation in factors such as grain moisture, combine speed and cutter width, but the system can already demonstrate yield variation and total yields are reported to be accurate to within 5% or less (Massey Ferguson, pers. comm.).

Sensing

Sensing to provide geographically referenced data is not limited to crop yield measurement, although advances in sensing other factors which affect husbandry decisions have been less spectacular. Particular attention has been given to remote sensing (Danson and Plummer, 1995), a term used to mean earth observation from satellites or any form of automated non-invasive measurement from any distance above the crop.

Satellite imagery can be used to provide information for crop management (Curran, 1983). The value of such information does, however, need to be questioned, and in particular the interpretation and consequent management action. Satellite data are used routinely to monitor crop productivity on a regional scale for the management of processing and marketing for example (Demetriades-Shah, *et al,* and, 1990). Within individual fields, however, spatial and spectral resolution requirements are much more demanding. Vegetation indices are usually calculated: for example, the ratio of near-infrared (IR) and red (R) and the natural logarithm of that ratio (Danson and Plummer, 1995). By the use of appropriate vegetation indices satellite imagery can assess chlorophyll status or water status of crops, and inferences about disease levels, nutrition and soil-related problems can be made (Daughtry *et al.,* 1980; Ercoli *et al.,* 1993).

The difficulties with remote sensing from satellites relate to inadequate spatial and spectral resolution and the availability of images at times important for decision making. With current satellites, the availability of images of the UK is insufficient for the reliable supply to growers of crop images quickly and early enough to allow adjustments in crop management. The problem results largely from the low number of clear days. Cushnie (1988) found that less than 10% of SPOT-1 images of southern Britain had less than 10% cloud cover.

Despite the problems associated with satellite data for within-field crop sensing, these data may still have a useful role to play. Historical data can be used to identify areas of fields where the crop is under-performing, or is recognisably different to other areas. This could be invaluable in drawing attention to soil-related problems which are temporally stable such as acid patches and compaction. In geographical regions where cloud cover is less of a problem than in the UK, satellite data could be used to aid crop management within the current season: for example, nitrogen inputs could be varied relative to a map of chlorophyll status (Hinzman *et al,* 1986), and poor areas within crops could be inspected in time to take remedial action.

Perhaps the best prospect for remote sensing will be to develop uses of sensing technology nearer to the ground (Duggin and Cunia, 1983). This would have the benefit of overcoming most of the logistical limitations, such as frequency of data acquisition, spatial resolution and even spectral resolution since there would be more flexibility to use appropriate instrumentation. An example of this type of technology exploitation is in place in the USA, where customers of RESOURCE21, Inc. are supplied with weekly images of fields taken from aircraft by digital video cameras set up to record different specific wavebands (De Quattro, 1996). These images, which have a pixel size of 10 x 10 m, provide information about soil organic matter, soil moisture and vegetation density. Interestingly, RESOURCE21 are working towards the launch of satellite-mounted sensors which are expected to deliver information to farmers within a day of data acquisition. An alternative strategy might be to bring the sensors closer still to the crop, by mounting them on farm machinery. This would improve spatial resolution, and also make theoretically possible the real time spatial adjustment of inputs in response to data from sensors on the same machine. Such developments are technologically very demanding, requiring great speed in data processing and rapid response time for applicators; for most operations considerable research and development effort will be required by agronomists and technicians before this becomes a realistic scenario.

The technique of image analysis has several potential applications for crop management, an example being tilth quality, which might be sensed to through the size distribution of soil aggregates. Control systems on tractors are being developed, which will allow automatic control of power output, implement working depth and forward speed. These could be linked in real time to image analysis systems, providing automatic control of tilth quality to a predetermined standard and producing a uniform seedbed despite spatial variation in soil texture. Another use of image analysis which is under development is automatic guidance systems for farm machinery, allowing plant scale pest and disease control, and accurate inter-row mechanical weeding (Tillett *et al.,* 1995). The use of image analysis together with GPS as a tool to map weeds is not sufficiently well developed to be useful in the foreseeable future: the main difficulties are distinguishing monocotyledonous weeds from cereal crops, and identifying weeds at the seedling stage when control is often most effective.

Pests generally are a low priority for the development of spatially variable management options because (i) pest distribution within fields is temporally unstable, (ii) pesticides are relatively cheap, and (iii) sensing and analysis costs are high, prohibiting map production. If new sensing methods can be developed, these are likely to be most useful as research tools, but might lead to commercial applications in the longer term.

Automated disease sensing and mapping is also not a practical prospect in the foreseeable future, but research is necessary to take this area forward, particularly to define more closely what needs to be sensed. The condition of the subject of the disease, i.e. the crop, is a primary factor in determining the response to control of the disease and, as pressures to minimise fungicide use increase, the importance of this will be increasingly recognised in the future. Sensing of the crop may therefore become necessary, in particular, crop growth stage and canopy size, perhaps using remote sensing techniques. The development of future methods for disease sensing will be dependent on the resolution required. The purpose of assessing current disease is to aid prediction of future disease. It will be necessary to identify critical ranges of current disease which have a substantial effect on future disease severity; this is being addressed by current research (Paveley *et al.,* in preparation). Initial indications are that the values within these critical ranges are small (sometimes as low as 0.01% mean severity). New sensing methods must be quantitative within the critical range, rapid and meet the necessary economic criteria. Possible future sensing methods which need to be considered are: immunology based techniques (e.g. ELISA); nucleic acid based techniques (e.g. probes, polymerase chain reaction (PCR)); electronic noses (detection of volatile substances from fungal disease organisms in the field is a theoretical possibility, but the required sensitivity is challenging); spectral reflectance (possibilities exist for measuring the crop and the disease (Horler *et al.*, 1983), but detection limits need to be established for the latter); spore assessment based on within-crop air sampling may be useful for obligate pathogens like mildew and rusts.

Data processing

Processing the GPS signal and associated measurements requires complex software. Recent advances in computer power and software mean that appropriate systems are now available at modest cost. A Geographical Information System (GIS) can produce maps of measured variables using data from the GPS, it can interpolate to provide continuous estimates of the variable, it can integrate data from different sources (e.g. field boundary position with yield data and weed assessments) and it can facilitate interrogation and display of the data to aid understanding and interpretation. In principle it is now possible to set up a complete Decision Support System for precision farming. This would include a GIS system at the core, linked to data processing software to analyse the incoming measurement (e.g. yield and GPS data), a decision support system structure to interpret the data and propose treatments, and programmes to turn the resulting decisions into instructions for variable treatments using a GPS system. However, no such system has yet been developed.

Application

The use of new technology to map variables within fields is of no value unless crop husbandry can be adjusted. Existing technology would allow adjustment of most husbandry treatments for areas 12 to 24 m wide using tramlines, and this capability could be of some value, but finer scale resolution is often implicit in Precision Farming scenarios. Technology is available to allow the development of machines which can automatically adjust the application rates of agrochemicals by linking the machine controls to a cab computer with GPS. For example, current commercial services for the spatially variable adjustment of soil nutrients depend on specialised spreading machinery which independently meters the application of three individual fertilisers. In future it may be possible for the instructions for such variable applications to be transferred to the cab computer from a farm-tailored Decision Support System.

DEFINING ZONES TO MANAGE IN-FIELD VARIABILITY

Current practice

Although at present it is unusual for farmers to split fields, sometimes they perceive this to be worthwhile. Typical examples include variable application of lime as a result of topsoil sampling for pH; differential cultivation and possibly cropping to accommodate different soil types; and, more recently, introduction of rotational set-aside areas. Standard recommendations for soil sampling have for a long time included the advice that 'areas of land known to differ in some important respects (e.g. soil type, previous cropping, applications of manure, fertiliser or lime) should be sampled separately' (MAFF, 1994). However in practice management of single fields as several units is the exception rather than the rule. This is in part related to the cost of defining zones for differential treatment, relative to the benefit, and in part because farmers mostly lack the technical facilities which would be needed. Advocates of Precision Farming consider that recent advances in technology could make it the norm.

Yield variation

Yield maps give an effectively continuous representation of yield within a field. Analysis of the data requires care to avoid spurious output (for example due to variable cut width and speed), but the continuity of the data prevents most of the errors associated with interpolation.

It has been suggested that by collecting yield maps for several years, a consistent pattern emerges which can be used either directly in adjusting inputs, or to delineate zones for further investigation. Information to date from fields mapped for several years indicates that consistent patterns do indeed occur, and may account for up to 50% of the variance in yield in subsequent years (Froment *et al.,* 1995). Discounting such obvious features as headlands, the cause of consistent patterns is almost always identified as soil variation (Stafford *et al.,* 1996). Interestingly significant yield variation, attributable to soil variation, has been found even where the soil classification of the whole field would have fallen into the same category for deciding inputs. The causes of such yield variation must be understood before an appropriate response can be formulated. For example, late or poor establishment due to poor soil conditions, leads to inefficient use of nitrogen and therefore potentially as great a requirement for fertiliser as well established crops, despite a lower yield (Webb *et al.*, 1995). However, yield depression may be caused by sub-optimal nutrient supply, low pH, or other remediable factors, for which clearly action must be taken. The investigation of the causes of yield variation is, therefore, essential before decisions can be made.

Soil

Stafford *et al.,* (1996) report that for a field with a wide range of soils (clay to loamy sand), zones could be identified by mathematical analysis, and could be approximately related to zones delineated on the basis of soil survey. However, yields within this experiment were small, and the spatial pattern of yield varied temporally. Results were consistent with the view that yields were poorest on clay soils in wet years, when creating a good seedbed might have been difficult, and poorest on sandy soils in dry years, when drought would have limited yield. The soils of intermediate clay content gave the most consistently good yields.

Froment *et al.* (1995) found a tendency towards greater yields on a chalk soil where the soil depth was greatest. High yields were also correlated with greatest magnesium and clay content, and with lowest calcium carbonate content. All of these are in fact explicable on the basis of the increased depth of topsoil, and it was judged that the latter was most likely to be the true cause. Yield variation was not correlated with plant number, and it was concluded in this as in other studies that plant water supply was most likely to be the mechanism leading to yield variation. However little direct evidence for this conclusion exists, and it is not clear whether the main factor is soil water supply itself, or some interaction between soil and plant roots which affects the plant's ability to extract water from the soil.

Variability in yield has often been associated with soil type differences - for example sandy soils tend to have smaller potash contents but greater phosphate contents than clays, under the same management.

Sampling and statistical analysis

Reliable definition of zones within a field requires more samples than might at first appear. Most factors which could be measured (e.g. soil texture, soil nutrient content, pest infestation, plant population) vary both at a fine scale (within 1-20 m) and at a coarser scale (Beckett and Webster, 1971; Van Meirvenne and Hofman, 1989; Cussans *et al.,* 1996). It is the coarse scale variation which is of use in defining zones for differential treatment. This is because it is relatively simple to apply to within 12 m with current machinery but more complicated to achieve much finer precision. The cost of mapping to finer precision would often be prohibitive and precision of zone location is usually limited both by cost of equipment and by boundary stability (e.g. soil and weed seeds are moved by cultivations).

If we define 12m as our minimum unit for sampling, and find that samples from two adjacent units differ, it could be because there is a real (coarse-scale) trend across the field; or because of fine-scale variation within units. The overall mean of the two units may actually be similar. To be sure there is a real trend we need to be sure that the differences are not due simply to small-scale variation.

This problem is often approached using geo-statistical techniques. By taking a large number of samples it is possible to assess the distance over which there is spatial correlation between samples (the range parameter), the variability which persists even at the closest conceivable sampling distance (the nugget variance), and the variability at large distances where spatial correlation no longer applies (the sill variance). The best fit to the form of the distance relationship can also be determined. With this information (the semivariogram) it is possible to estimate values between sampling points, and to assess the precision of those estimates. Thus a continuous map can be produced from a series of point measurements. This technique is known as kriging.

Based on a review of such geo-statistical studies, Beckett and Webster (1971) stated “up to half the variance within a field may already be present within any square metre of it. Within-field variance often changes little with the size of the field." They report typical range parameters ranging from units to tens of meters for variables such as soil available P and K content and soil physical properties. Typical total coefficients of variation for topsoil available nutrients were around 30% at the finest scale considered (the nugget variance, which is at too fine a scale for zone definition). A further 15-30% was attributable to variation between zones within a field, so that the total coefficient of variation expected from single samples taken far apart within the field would be around 50%. The variance between field means, for fields of the same soil association, was given as adding a further 30-50%. This is to be expected since soil nutrient levels are affected by management, which will differ between fields more than within fields. The values quoted are given solely as a broad indication, since results vary greatly between fields and between studies. Where variability is not homogeneous, as is common in agricultural soils, the calculated range and other properties may themselves depend partly on the density of measurement. For example, if measurements are taken 40m apart (see e.g. Oliver and Webster, 1991), range parameters smaller than this cannot be defined.

Beckett and Webster (1971) also report significant variation in soil physical properties within a mapped soil unit. Thus clay or sand contents varied by 20% of their true value, and about half of this variation was at scales so fine that they could not be mapped. Similar results are reported by Dampney *et al.* (1997) Such variation is sufficient to affect factors such as ease of cultivation and soil available water capacity.

The reported range parameters for nitrate varies from less than 1 m to tens of meters (Beckettand Webster, 1971). The values would be expected to vary with direction of measurement due to the directionality of field operations, and this has indeed been reported (e.g. Van Meirvenne and Hofman, 1989). These authors also found that range parameters varied for nitrate within the same field, from 10 to 34 m, and the form of spatial dependence also varied, depending on date of measurement.

Geo-statistical techniques applied to such data have shown that between 100 and 200 measurements might be needed to accurately define the form of the variability itself, together with the relevant confidence limits (Webster and Oliver, 1992). The variogram so computed is then applicable strictly only to the field from which it was derived. The number of data items needed is far greater than the number of analyses normally undertaken for a field. For example, current advice is that for a crop management unit of up to 10 ha, of uniform history and soil type, 25 topsoil samples, taken in a representative pattern, should be bulked and a single analysis of the bulked sample should suffice for recommendations of P, K, Mg and lime inputs (MAFF, 1994). For nitrate, which is more expensive to sample, often only 10 samples are taken and bulked.

Furthermore the statistics embodied in the variogram are appropriate only to analysis of random variation. Webster and Oliver (1992) suggest that where the range of the variogram is small relative to the size of the field, as is common for many nutrients, standard grid sampling would give little information on this variation and a set of transects should be used, each with closely spaced samples to give information on fine-scale variation. This is undoubtedly correct if our aim is to understand variation, but not if our aim is to determine whether, within this particular field, there are zones greater than 20m square (say) which justify differential treatment.

Zones requiring separate treatment are often the result of non-random processes, at scales large relative to the size of the field. For example soil type, weed infestation, and nutrient differences resulting from differences in past cropping all vary in a clearly non-random manner. The aim of defining zones which justify separate treatment is quite distinct from the aim of defining the form of the random variability. Since the cost of the latter is so great, alternative approaches to the former need to be considered.

Rigorous analysis of within-field variability all too often indicates that the differences in sample values are not statistically significant. At the same time, commercial companies produce for paying clients nutrient maps for which a single measurement point may suffice as the sole representative of a neatly delineated zone. Maps produced in this way imply erroneously that each measurement perfectly represents the mean value for all points closest to that measurement. Perhaps the optimum use of the data lies between these extremes.

Economic issues

The cost of defining zones varies greatly, from the cost of visual inspection immediately prior to spot treatment for weeds, to approximately £50 per sample for measuring soil mineral nitrogen content to 90 cm. The cost of defining as few as four treatment zones within a field is likely to be at least 50 times the cost of an individual observation or analysis (see below). The cost assessment must also take into account the frequency with which the zone must be re-mapped. Soil type needs to be mapped only once. Soil nutrient content and pH would be relatively stable, except that the usual response to a map of variability would be to take steps to ensure that low areas of the field were treated to bring them up to the desirable level. Most pest and disease infestations must be assessed immediately prior to each potential treatment. Weed infestations are intermediate in stability.

Here we have concentrated on the numerical size of the variation in measured values. However of greater significance are the implications of that variation for treatment. In a survey of within-field variability it was found that in most cases over 90% of samples were within the range which would have the same fertiliser application recommendation as that based on the whole-field mean (Froment *et al.*, 1995). This survey did not differentiate fine-scale from coarse -scale variability, so that it almost certainly overestimated the proportion of a field which might lie within a definable zone whose mean nutrient content was sufficiently different from the field mean to result in different fertiliser recommendations. Thus the cost benefit of defining the zone must accrue from less than 10% of the sampled area, but must pay for sampling of the whole area, unless we can find methods of concentrating our efforts on the most promising locations.

The most cost-effective approach to in-field sampling will depend on the cost of sampling and the perceived chance that differential treatment is likely to be worthwhile. If that chance is seen as small, and the attribute to be assessed is relatively stable, a few samples might be taken initially and more detailed sampling undertaken only if the initial results suggest a large enough range. Since analysis is often more expensive than sampling, it is common to bulk prior to analysis several samples from an area of size similar to the minimum resolution of the zone. Reducing the variance on the individual sample increases the chances of recognising any real trends.

In many cases the most efficient sampling strategy will make use of prior knowledge to define sampling zones. Factors to consider include old field boundaries (indicating a difference in past cropping and fertiliser use), soil variation, and proximity to the field boundary. Division of the field into a number of tentative zones, each of which is sampled to produce as representative a result as possible (within practical and economic constraints), could result in a number of potential zones, which might on the basis of the data result in perhaps 2 or 3 amalgamated treatment zones. Such an approach is already recommended in current fertiliser advice (MAFF, 1994 and 1985). Given the knowledge available on within-field variability, costs of sampling, and benefits of differential treatment, it should be possible to define more explicitly approaches to sampling which are optimal for the different variables under consideration, and to test those approaches on commercial farms.

THE HUSBANDRY PROCESS : PRIORITIES FOR AUTOMATION

The preceding general description of principles governing application of current husbandry knowledge to sub-units of fields now enables a more detailed, topic by topic, analysis of each facet of the husbandry of a crop. These facets are taken in the approximate order in which they would be considered by the decision-taker throughout the growing season of a cereal crop, starting with fertilising and seedbed preparation and finishing with harvesting. In each case the intention is to identify, using existing technology, the most serious obstacles to full agronomic automation and hence the adoption of Precision Farming.

Lime, phosphate, potash and magnesium

For combinable crops, actual yield responses to applications of lime, phosphate, potash or magnesium fertilisers are rare and usually small. In most situations, these materials are applied for the purpose of long term maintenance of soil pH and nutrient status, so as to prevent a gradual decline into a deficiency state. In most cases, responses from the actual crop receiving the application are not to be expected.

Arnold and Shepherd, (1987) confirmed that soil analysis should be used to gauge likely response to fertiliser applications, and that yield responses are unlikely at Index 2 or above, but are possible at Index 1 and probable at Index 0. The MAFF Representative Soil Sampling Scheme provides survey data on the average nutrient status of arable fields in England and Wales. Table 2 shows that only a very small proportion of arable land is at Index 0 where yield responses might be expected.

As part of a MAFF review, Froment *et al.* (1995) studied the within-field variation of soil pH and P, K and Mg nutrients in 78 arable fields. This study confirmed that significant within-field variability does exist. On average, the proportion of samples falling outside of the mean Index value was calculated as:

47% of samples were outside of the mean P Index
31% of samples were outside of the mean K Index
37% of samples were outside of the mean Mg Index

Table 2. Percentage of samples within each MAFF Soil Index for arable fields in England and Wales (MAFF Representative Soil Sampling Survey)

	Soil Index					
	0	*1*	*2*	*3*	*4*	*5*
Phosphorus	4	14	31	37	11	4
Potassium	1	24	55	17	2	0
Magnesium	2	24	36	18	8	12

Although soil nutrient levels vary within fields, it may not be either economic or practically possible to map the changes precisely or to apply different fertiliser rates. It is an expensive process to determine within-field nutrient variability accurately using soil sampling and analysis, and there is considerable uncertainty concerning optimum sampling methods. A nutrient map of a field can only be constructed reliably if there is a density of sample data sufficient to allow reliable interpolation between the known points using geo-statistical techniques (kriging, etc.). Without sufficient sample density, interpolation cannot be carried out reliably since it is not possible to distinguish erratic short range variation from systematic spatial trends. Erratic short range variation will not generally be cost-effective to measure or manage, since Beckett and Webster (1971) reported that 50% of the variation in soil properties that occurs within 1 hectare often occurs within 1 square metre.

Webster and Oliver (1992) suggested that sampling at 40 metre intervals (over 6 samples per hectare) was necessary in order to map nutrient patterns reliably. This is considerably more intense than some current commercial systems based on 100 metre grids (1 sample per hectare). The economic implications of this are addressed in relation to phosphate in a later section of this report (see page 35, ***Cost-effectiveness of differential applications - a worked example***), where consideration is given to situations where phosphate is found to be above or below the optimum for crop performance.

Intelligent zoning of fields offers increased potential for addressing within-field variation in a cost-effective way. Sampling might be targeted to investigate specific 'zoned' field areas considered to be uniform with respect to factors such as old field boundaries, crop/yield performance, soil type, wetness, etc. Additional cost-effectiveness would be found if fields were also strategically targeted for more intensive sampling. Fields of known variation in soil type, cropping history or performance; fields with a history of organic manure applications or those that have received high fertiliser inputs are most likely to show cost-benefit. Targeted sampling in this way might detect areas of unusually low nutrient status at minimum cost.

Even where reliable nutrient maps are prepared, the modelling of P and K fertiliser application rates must be of an appropriate precision. Current recommendations for P and K are based on the philosophy of replacing nutrient offtake in crops in order to maintain a particular soil nutrient concentration. Variations in sub-soil nutrient supply and nutrient fixation are known but do not form part of recommendation systems. Crop nutrient offtakes are based on standard offtake values quantified in terms of kg/tonne of crop material (grain or straw), but it is known that a very large range of values exists in practice. For instance, Withers (1991) reported that nutrient offtake values in cereal straw ranged from <0.04 to >0.13% P and from <0.3 to >1.7% K. He also reported that soil nutrient concentration and weather influenced straw P and K concentrations. It is vital therefore, that any attempts to match fertiliser applications to mapped soil nutrient patterns must be accompanied by a commensurate precision in the model used to quantify the rate applied.

Cultivations and crop establishment

Cultivations undertaken between the harvest and re-sowing of arable fields used to grow combinable crops include subsoiling, ploughing, various surface operations including discing, harrowing and rolling, and the drilling operation itself. The choice of equipment and the combinations of cultivation practices are soil-specific, and their success in forming a seedbed in which drilled crops will readily germinate and establish is highly dependent on soil moisture content, since moisture so closely governs soil strength.

At the crudest level, the development of compaction, for example on headlands and in gateways, might give rise to subsoiling targeted in areas of particular need. In relation to the more haphazard in-field variation, prior to the creation of a seedbed, there is first a need to sense variation in cultivation requirements and then to alter either the action of the cultivator or the energy it applies. Attributes of the topsoil most closely related to cultivation requirements and also open to automated sensing are the aggregate size distribution and the moisture content. No such sensors are known to be under development. It is unlikely that the action of cultivation equipment could be changed easily within a field, but it is possible to envisage that the depth and energy input of the more versatile machinery might be changed in response to in-field differences. Machinery with this capability is not available yet. The main difficulty in furthering such developments may be that soil parameters change on a relatively fine spatial scale.

In the longer term, although the variation in soil properties is short-distance and temporally unstable, there seems every reason to believe that 'servo systems' could be devised for cultivators and drills just as strain gauge sensors have been developed to monitor the load on a beam section of a plough, and then communicate with the 'management centre' on a tractor, which in turn alters the engine settings. In the same way, a sensor of soil tilth or moisture, perhaps using precision radar imaging, might be linked directly to the speed or depth control of the machine, obviating the need for complex and problematic GPS and decision systems.

Extrapolating from cultivators to other husbandry operations, it might be possible to regard 'servo systems' as the ultimate mechanism for Precision Farming. They overcome many of the most serious obstacles to agronomic automation, particularly those of high spatial or temporal instability.

Seed rates are normally adjusted according to conditions for plant establishment. Seed rates used to establish combinable crops are normally set with a wide margin of error; the density of established plants normally exceeds the optimum over most of the field in order that parts of the field where there may be difficulties with establishment will be adequately populated. This results in considerable excess expenditure on seed and an overall increase in the risk of lodging, since dense stands have weaker root anchorage and so are more lodging-prone (Easson *et al.*, 1993). Within-field adjustment of seed rate therefore appears an attractive prospect. The parameters to be used as a basis for adjustment are likely to be the same as those that would dictate the requirements for seedbed cultivation, since both operations are directed at the same objective. One example area of improvement in the short term could be in stabilising seedbed consolidation using the control of a pressure roll on the seed drill (Billot, 1996). However, the ultimate objective of spatially controlled seed rates will not be achieved without further research and development to both define and sense optimum conditions for establishment.

Weed control and herbicides

There are many reasons for controlling weeds, in addition to their impact on yield. These include ease of harvest, prevention of contamination of the harvested crop and reducing weed populations in future crops, particularly where they may be difficult or expensive to control. Hence, the level of weed infestation at which herbicide application becomes economically desirable in a particular crop is often less than would be applicable according to the immediate competitiveness of the weed in question and depends on individual circumstances, particularly the crop rotation on the farm.

There have been many attempts to predict the impact of weed populations on yield of combinable crops. These have been based on either the numbers of weed and crop plants or the ground cover of weeds (Cousens, 1985; Kropff and Spitters, 1991). Current MAFF-funded research is showing that factors such as soil type and nitrogen nutrition can also affect the extent to which weeds reduce winter wheat yields (Cussans *et al.*, 1996).

While further research is required to define more precisely when herbicide application is justified, there are two major factors which prevent the practical adoption of such a 'threshold' approach. First and of particular relevance to this review, weed infestations are variable across the field. Secondly, major weed-control decisions are taken while the crop and weeds are small; it is inevitable that prediction of yield effects at such an early stage in weed and crop development will be imprecise, particularly if further weed germination may occur after decisions have to be made. It is to be hoped that risk analysis techniques will improve this aspect of decision making (Cussans *et al.*, 1996). Both of these factors have inhibited optimisation of herbicide application according to financial margins of the current and future crops.

Ideally, to address the in-field variability, weed-crop competition should be sensed in real time while the tractor is progressing through the crop. Then, rates of herbicides could be adjusted according to variations in weed infestations and crop competition. Further adjustment might also be possible according to the prevailing weather conditions. The technology for such real time detection is in its infancy. A development of image analysis allows for the detection of crop rows and of plants between crop rows, assumed to be weeds. However, insensitivity of the existing equipment prevents identification of individual small plants between rows, i.e. less than 5 cm in diameter (N. Tillet, Silsoe Research Institute, pers. comm.), whereas weeds are usually treated with herbicides prior to reaching this size, to minimise risk and to maximise margins over herbicide costs.

Another approach has been to map weeds, either through crop surveys (Rew *et al.*, 1996), or through 'marking' patches with GPS equipment as the tractor or combine progresses through the crop. Weed patches are relatively stable and surveys would only need to be repeated every four or five years (Wilson and Brain, 1991). Detailed surveys would take some time to complete and would require expenditure both in labour and in equipment to create the maps to control the sprayer. This will mean that patch spraying systems are likely to be restricted to the larger farmers and contractors. Set-aside offers an ideal opportunity to map weeds.

The 'marking' of weed patches from the combine during harvest by exploiting its GPS equipment (which is providing data for yield mapping) has proved a relatively accurate method of positioning. This has been possible for weeds that are unlikely to have been controlled during crop growth such as creeping thistle and common couch but it may also be of value in mapping weeds surviving earlier treatment, such as wild-oat. The seeds from these surviving plants could well produce areas of high infestation in the following year and additionally may mark the main focus of patches already present. This latter hypothesis remains to be confirmed. Maps of creeping thistle and common couch will be particularly useful where root crops share the rotation and where couch and thistles may be treated selectively when they are at or below crop canopy height.

Current LINK-funded research (Rew *et al.*, 1996) is exploring two broad approaches for patch spraying of weeds using digitised field maps: one where a rate of a herbicide is applied overall and additional herbicide is applied to the patches of high infestation of weeds; the other where only the patches of high infestation are treated. The best approach may depend on the weed species present and their distribution. In both cases, there is expected to be a need to treat a buffer area around patches of high infestation to ensure that the whole of the patch is treated and that its area does not increase. Initial research would suggest a 4m buffer is adequate to avoid this problem.

There are likely to be significant savings in herbicides through the adoption of successful precision application techniques. Current LINK-funded research suggests that savings in herbicide costs are likely to be in the order of £4.65-£12.60/ha for common couch and £5.40-£10.30/ha for black-grass and that the costs of a weed map based on a field survey could cost £0.65-£2.50/annum. This cost, coupled with those for the additional machinery and management suggests that the patch spraying of weeds will only become standard practice once there is automated (either tractor- or satellite-based) sensing of the spatial distribution of weeds and that the additional cost of the sprayer is shared with spatial application of other pesticides.

Thus, suggested research requirements relating to the precision application of herbicides might include :

- A clearer understanding of the dynamics of weed patches - the balance between movement and stasis for the weed species particularly appropriate for patch treatment (e.g. cleavers, black-grass, wild-oat) is not fully understood.
- Refinement on the prediction of the impact of weeds to individual crops.
- Real-time sensing of weed infestations and species at crop and weed stages when herbicides are applied to minimise risk and to optimise margins over herbicide costs.
- Decision Support System to optimise herbicide use according to weed growth stage and infestation level, the predicted effect of current range of weed infestations on current and future crops, crop competition and weather conditions.
- Development of practical methods of weed mapping.

Plant growth and plant growth regulators

Though lodging has been much less prevalent since the introduction of short-strawed varieties and plant growth regulators, there is still extensive loss of yield and deterioration in quality of cereal grain through lodging in some seasons. Lodging risks are currently mitigated by judicious choice of varieties, by careful scheduling of nitrogen applications and by use of several growth regulating chemicals. Recent research has shown that the causes of lodging in wheat are more diverse than is commonly appreciated, with root failure being at least as common as stem failure (Ennos, 1991; Pinthus, 1973). Lodging of barley which has less weight per shoot than wheat, weaker stem bases and more shoots (and thus roots) per plant, tends to be more through stem failure than root failure. The success of policies to minimise lodging will depend on the successful detection of its likely cause in each field or each part of a field.

It is rare for a field to lodge overall; on the other hand, there are years when most fields show some lodging. Within a field it is common for lodging to begin and to be most serious at the margins, specifically where the seed drill and/or fertiliser spreader have overlapped. There are also patterns of lodging which may be associated with valley bottoms or previous meadowland, where the soil is more fertile, and with hill tops where the crop is more exposed. Lodging is rare in plants adjacent to tramlines, where stems tend to be short and the soil is well consolidated. Although there is little published evidence which links lodging prevalence with different soil types, certain areas of differing soil types within a field are more or less prone to lodging than others. The reasons for these differences are often not identified and may be put down to higher inherent fertility; another possible cause in many cases could be poor soil strength which decreases root anchorage (Crook and Ennos, 1993) through low clay content or loose structure. In the growing crop, proneness to lodge is currently appreciated as being indicated by 'forward', 'dense' or 'lush' growth in the spring. Apart from the published 'standing power' of the variety under consideration, early sowing (Fielder, 1988), high seed rate (Easson *et al.*, 1993) and high levels of nitrogen fertilisation (Crook and Ennos, 1995) are all noted as increasing proneness to lodge. Nitrogen applications to lodging-prone crops may be delayed and reduced. Growth regulators are also commonly applied (Woolley, 1992, Garthwaite *et al.*, 1994); chlormequat is applied during early stem extension and shortens the lower internodes, whilst ethephon-containing products are applied during late stem extension to shorten the upper internodes and peduncle. The overall stem shortening achieved through the use of plant growth regulators can be increased by making repeated applications coincident with the extension of successive internodes.

The considerable intra-field variability in lodging suggests that there could well be advantages in equivalent variation in the husbandry of the crop within a field. However, no specific husbandry systems have been developed to achieve this and there appears to be no current research which might support this aim. The main obstacles are likely to be in detecting variation in lodging risk at a time when husbandry could be adjusted accordingly; the positioning equipment and sprayers developed for variable application of other agrochemicals would be equally suitable for variable application of growth regulators.

The prime benefits of varying lodging control measures within a field are likely to come through (a) reduced expenditure on the majority of the field where lodging is unlikely, (b) reduced lodging, hence increased yield and quality through increased control measures in the minority of the field where risks are greatest, and (c) earlier harvest and hence improved quality from the field as a whole when lodged margins would have otherwise delayed the harvest of the crop.

Since field margins are a relatively predictable focus for the initiation of lodging it is feasible that they could be selectively rolled to consolidate roots in the soil surface and given additional applications of growth regulators to shorten and stiffen cereal stems without any recourse to the more sophisticated approach to precision application of agrochemicals. Some straightforward tests of this would seem worthwhile. For the more extensive adoption of 'precision farming' with regard to lodging control it will first be necessary to automate the detection of dense, lush, forward and tall crops and loose soil in spring.

Avoiding overlaps of both seed (and fertiliser) through the use of intelligent drills (and spreaders) would significantly reduce the risk of lodging from the outset, removing what is probably the biggest cause of variability in lodging risk. Currently, seed drilling lends itself more to precise control than fertiliser spreading, although this may change if the use of boom spreaders becomes more common.

Nitrogen nutrition

For combinable crops yield responses to applied nitrogen are usually large and notoriously difficult to predict with any degree of precision (Sylvester-Bradley, 1993). Variation in the need of a crop for applied nitrogen can be regarded as arising from two sources, a) the demand for nitrogen by the crop at the expected level of production, and b) the ability of the soil to supply that nitrogen. From research on field to field variation (Goodlass *et al,*. 1996), it can be confidently inferred that both of these will vary within a given field.

Soil N supply - within field variability arises due to changes in:

1. losses of N through leaching or denitrification, both of which are affected by soil type interacting with climatic conditions and the extent of crop cover;
2. soil organic matter which may be associated with differences in soil type and is influenced by incorporation of crop residues and, where soils are incompletely leached, cumulative effects of previous nitrogen fertiliser applications;
3. soil microbial activity which relates to organic matter levels, but also to temperatures, to the amount and C:N ratio of crop debris, and to the presence of adequate air and water. The supply of air and water may be influenced by soil type and structure.

The net result of the above factors can be measured at any one time as the amount of mineral nitrogen in the soil to 90 cm depth (SMN). However this is a costly and time consuming measurement, and is at present only used on a field by field basis where high residues are suspected and hence where large potential savings (both economic and environmental) offset the cost of sampling and analysis. European work (Van Meirvenne and Hofman, 1989; Bahri and Berndtsson, 1996) and studies in the USA (Mohanty and Kanwar, 1994; Cahn *et al,*. 1994) have all indicated that soil N supply is spatially variable, whether measured as nitrate or soil organic matter. In the UK the preliminary results of detailed SMN sampling carried out by ADAS in spring 1997 (Dampney *et al.,* 1997) also indicate that soil nitrogen supply is spatially dependent. However, unless a means can be found of predicting soil N supply from other measurements, the cost of carrying out SMN sampling and analysis on a grid basis is prohibitively expensive (more than £6000 per field). Thus a practical way forward must depend on developing a means of predicting SMN at reduced cost.

Crop N requirement - within field variability arises due to changes in:

1. the efficiency with which the crop acquires soil and fertiliser N. Field by field research shows this to be affected by genotype (both species and variety), soil type (soils with more readily available water showing greater efficiencies) and date of crop establishment (late drillings show poorer efficiency). The presence of weeds, the degree of soil compaction and the extent to which rooting may be inhibited also appear to be influential.

2. the potential of the crop's growing conditions, often judged in retrospect through its yield. A multiplicity of factors affect crop growth and ultimate performance. Much of the in-field variation is likely to relate to the moisture holding capacity of the soil, but interacting strongly with seasonal rainfall and sunshine. For example, small yields can be expected on light soils in dry years and on heavy soils in wet years (Stafford *et al.*, 1996).

Inadequate N supply is unlikely to be a major cause of low-yields within arable fields, as considerable variation in N availability can occur with rather little effect on yield. This is because, for a crop receiving close to the economic optimum N input, the increase in yield resulting from an input of 100 kg/ha N is only about 1 t/ha. The yield difference between a crop receiving 100 and 200 kg/ha N as fertiliser (the latter being close to the expected optimum) is typically only about 10% for both cereals and oilseed rape (Lord and Vaughan, 1987; Sylvester-Bradley and Chambers, 1992; Chalmers, 1989). It is possible that analysis of harvested grain can provide a retrospective indication of whether N was a yield-limiting factor; where yield is limited by N supply, N content tends to be low, whereas where yield is limited by other factors, such as drought, N content tends to be high. Although this information may appear retrospective and therefore useless, on retentive soils it may be useful in predicting the residual amounts of nitrogen that may affect the succeeding crop.

Work in the United States (Fiez *et al.,* 1994) on different topographical locations within a field has shown little economic benefit from variable N applications, unless the N requirement is determined experimentally through N response trials in each individual location. Work on varying N application rates in the UK (based on SMN, soil type and yield) is just beginning[9]. Probably the most promising prospect in relation to N nutrition is in the application of the Canopy Management concept (Stokes *et al.*, in press) according to within field variation, since the size of the crop's leaf canopy has been shown to provide an index of its nitrogen status, and since it is easier to monitor the size of a leaf canopy using spectral reflectance (Curran, 1983) than any other way. The main concern here is whether it will be possible to make estimates of within field variation with equivalent precision; it may be that the technique would be mainly applicable where soil nitrogen supply could be confidently taken as small.

Disease control and fungicide use

Most of the cost of disease control in combinable crops relates to the use of fungicides active against foliar pathogens. Choice of fungicide is unlikely to be varied within a field; the main interest is in varying the rate of fungicide. Yield response curves have long been used to calculate economic optima for crop nutrients, but they are only now becoming widely used to help optimise fungicide inputs for disease control (Sylvester-Bradley *et al.*, 1995).

Experiments show that yield responses to increasing doses of fungicide diminish in a remarkably similar wat to the responses from application of nutrients. The economic optimum fungicide dose can be calculated as the point on the response curve beyond which the financial gain from the increased yield is less than the cost of the fungicide needed to obtain

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[9] Project funded by MAFF under its \link programme with , Massey Ferguson Ltd, Crowmarsh Battle Farms Ltd, and Yokefleet Farms Ltd. Research Collaborators: ADAS and Silsoe Research Institute.

the increase in yield. Adjusting fungicide applications spatially on an intra-field scale will only be worthwhile if there is substantial intra-field variation in optimum dose, and if that variation can be predicted at the time of the fungicide treatment decisions from spatial measurements available at reasonable cost.

Optimum dose is influenced by the *magnitude* of the response (Y_{res}) between the untreated yield (Y_{unt}) and the maximum yield (Y_{max}), and the *curvature* of the response between the Y_{unt} and Y_{max} points. *Magnitude* of response is controlled predominantly by disease severity and the sensitivity of the crop to that disease. *Curvature* is influenced predominantly by the innate activity of the fungicide(s) against the predominant pathogen(s) at a site (hence more active fungicides tend to have lower dose optima).

Disease effects

Final disease severity is a key determinant of Y_{res} and hence optimum dose. Host resistance and weather have a strong influence on disease severity (hence, optimum dose will tend to be low on more resistant cultivars and during seasons when the weather is not conducive to disease development) but, apart from local micro-climatic effects, is generally constant across a field. So host resistance and weather would remain key determinants of the need for treatment, but need not be considered in spatially adjusting the treatment.

Some diseases, such as yellow rust (*Puccinia striiformis*), develop initially from discrete foci which, although visually striking, occupy only a small proportion of the field area. Practical experience suggests that others, such as powdery mildew (*Erysiphe graminis*), sometimes exhibit gradients across fields. Theoretically, cost savings could be made by 'patch spraying', or adjusting the dose applied according to disease severity. However, the situation is not analogous to patch spraying of weeds, where a patch mapped in one season will not move substantially by the following season. Also, applying fungicides after an epidemic has developed is ineffective, so treatment decisions need to be based on indicators of future disease risk. One such indicator is the current level of disease in the crop, which acts as a source of inoculum for future epidemic development.

Regular mapping of disease by eye would be tedious and uneconomic. The development and operational costs of automated disease sensors might be justified to detect spatial variation of the main economic diseases of cereals. Their adaptation to allow spatial mapping might be justified for those diseases which express significant intra-field variation. To be of value, the sensitivity of detection would need to allow quantification of disease within the range of severities where variation in current inoculum influences future disease severity (between zero and 0.1% leaf area affected for yellow rust (Paveley *et al.*, in preparation)), rather than in the range where inoculum is no longer limiting epidemic development. Epidemiological theory suggests that similarly sensitive detection would be required to guide fungicide applications to control other foliar diseases capable of high rates of epidemic growth. Hence, the levels of disease that might be detected by remote sensing techniques would probably be too high, and would only serve to indicate that a fungicide should have been applied some time ago. Machine mounted sensors based on immunoassay (Dewey, 1996) or nucleic acid technology (Beck *et al.*, 1996) could achieve suitable levels of sensitivity, and might sample airborne spores within or above the crop canopy (Schmechal *et al.*, 1996). Widespread uptake would be required to reduce the unit cost of such complex technology to an acceptable level.

Crop effects

The effect of a given amount of disease on yield has been shown to vary substantially depending on the physiological state of the crop, and in particular, on the amount of green leaf area in the crop canopy (Bryson *et al.*, 1995). Data quantifying spatial variation in canopy size are rare. In a 1994 experiment described by Bryson *et al.* (1995), in which yellow rust was used as a model disease and replicated plots of peak GAI 4.2 and 6.6 were created by manipulating available nitrogen, substantial effects on epidemic development were found. Calculations using the Beer's Law analogy, assuming a constant conversion efficiency of intercepted solar radiation post-anthesis to grain dry matter, indicated that the contributions of leaf layers to grain yield were also markedly affected. Where yellow rust was excluded by fungicide treatment, the contributions to yield of the upper leaves were greater in the GAI 6.6 canopy. The contributions of the lower leaves were relatively unaffected by canopy size. The growth rate of the epidemic on the larger canopy was approximately double that on the small, and the combination of increased disease development and increased contribution, caused the calculated yield response to control of disease on the flag leaf to be approximately 2 t/ha higher. Returning to the effect of changes in Y_{res} on optimum dose; the larger response to disease control should indicate an increased optimum fungicide input; at least for flag leaf sprays around GS 39.

Conclusions

Research to determine the relationships between variation in crop and disease, and variation in optimal fungicide inputs at an inter-field scale, should provide a logical basis for progression to the intra-field scale. There is some evidence that intra-field variation in the state of the crop and the state of disease epidemics could cause intra-field variation in the optimum fungicide input. Quantification of the potential benefits from spatial adjustment of treatments is hampered by shortage of objective data on the extent of the variation in representative wheat crops. One exception is yield, where substantial data sets are now being accumulated. However, the poor relationships between past yield variation and yield variation in the current crop, and yield potential and yield response, limit the value of yield maps as tools to optimise disease control inputs.

Significant spatial variation in disease severity is apparent for yellow rust and mildew. To be fully effective, fungicides have to be applied early in an epidemic. Hence, disease detection systems will only be of value as decision aids if they are able to differentiate between the low levels of disease which determine future epidemic progress. The development of automated disease detection systems can probably be justified on economic grounds to improve the efficiency of measurement of inter-field variation. Further development to allow intra-field disease mapping may be justified for some diseases.

There is limited evidence for intra-field variation in the physiological state of wheat crops. The extent of such variation is not well quantified but, if common, may have significant effects on both the rate of epidemic development and the effect of disease on yield. Variation in canopy size may prove amenable to automated monitoring (Hinzman *et al.*, 1986) and has implications for a number of crop protection and nutritional inputs, so monitoring costs might be effectively shared across potential savings in a range of input costs. However, care will be required in converting such information into treatment decisions. It seems likely that variation observed in the rate of epidemic development in canopies of different size is due to differences in nitrogen uptake. Pathogen species are known to respond differently to the nutritional state of the host so theoretically, differences in canopy size could indicate opposite changes in the optimal fungicide input for different diseases. A neater solution might be to spatially adjust nitrogen inputs to ensure uniformly optimal canopy size, improving nutritional efficiency and removing the need to adjust fungicide inputs spatially to cope with the variation.

In general, while the research and technology is being put in place to gather and interpret intra-field data, there is much that can be done to improve disease management decisions at an inter-field scale.

Pest management

The apparent lack of progress on the implications of managing pests according to their actual within-field distribution has been principally because the distribution of many important foliar pests is highly dynamic both spatially and temporally, and is influenced by a number of biotic and abiotic variables which may be difficult to control or quantify. These include the effects of field boundary type and weather, the influence of natural enemies, the impact of previous pesticide applications (e.g. Duffield and Aebischer, 1994; Duffield *et al.*, 1996), patterns of immigration and emigration (including re-invasion after pesticide applications, e.g. Longley and Izquierdo, 1994 and the relationship between crop physiology and pest phenology. Given these constraints, the sampling problems inherent in making practical decisions on within-field pest management of mobile foliar pests are enormous, and have until recently acted as an effective 'bottleneck' not just to commercial interest in within-field pest management, but also on research which is essential to underpin any commercial uptake. This situation is now rapidly changing through a greater use of geo-statistical techniques for interpreting within-field pest distributions (e.g. Weisz *et al.*, 1995, Parker and Turner, 1996), the development of new techniques for dealing with spatial pattern such as SADIE (Perry, 1995), and the increasing availability and use of GPS-linked data loggers which make collecting large quantities of spatially-reference data a more viable proposition (e.g. Parker and Turner, 1996) at least on a research level.

Given the considerable difficulties in dealing with mobile foliar pests, it is not surprising that the main interest in within-field pest management currently lies with soil-dwelling pests such as cyst nematodes which tend to have more temporally and spatially static distributions (e.g. Francl, 1986; Webster and Boag, 1992). The ability to define where 'patches' of nematodes may be, and then to modify pesticide application strategies accordingly (e.g. Haydock and Evans, 1995) is an attractive one from a commercial point of view. However, for serious pests such as potato cyst nematodes (*Globodera rotochiensis* and *G. pallida*) the longer term-consequences of population management may be serious if patch applications lead to rapid increases in the pest population from very low or undetected levels in untreated areas of the field.

It will be apparent from the above discussion that the lack of suitable sampling methodologies remains the major stumbling block to the wider uptake of a within-field approach to pest management. This situation is now being addressed by a number of research projects in the U.K. (e.g. Collier *et al.*, 1996; Parker *et al.*, 1997), which will provide important data on the statistical definition of spatial and temporal change in pest distributions. However, the primary aim of such studies is to provide guidance on how *and where* to sample for pests to make decisions on a whole-field basis. Thus such work is in effect building on the extensive work done over many years to develop fixed-precision or sequential sampling schemes used to identify pest thresholds on a whole-field basis for a wide range of crop/pest situations (reviewed by Perry, 1994). If within-field pest management is to become a commercial proposition, then two critical issues need to be addressed. These are:

1. How to identify *actual* pest distributions in terms of spatial incidence *and* infestation level within individual fields. While this might be possible by direct observation on a research basis, the time involved in doing this is far in excess of what commercial crop advisers are prepared to spend. Thus the development of techniques for rapidly remotely-sensing pest distributions (using sensors mounted on platforms ranging from tractors to satellites) in sufficient time to enable action to be taken is essential. This is a very challenging objective as current remote-sensing techniques used in entomology (Riley, 1989) are not suitable for within-crop monitoring. The practical difficulties are considerable as major arable pests in the U.K. generally need to be controlled before they reach a level when overt damage symptoms (whether through direct damage or virus transmission) appear on the crop. Unless highly novel solutions can be developed, distinguishing between symptoms of poor crop health caused by pests and those caused by other crop protection of agronomy problems will be very difficult. Development of appropriate techniques will require the integration of expertise in sensor technology with skills in research on within-field pest distribution, coupled with a clearly-defined commercial need for such an approach.

2. Positive economic benefits must be demonstrated. This requires work to be done on investigating the likely economic impact of spatially-selective insecticide application by linking pest distributions to pest yield loss models (which may include variables such as crop growth stage and soil type) to produce yield loss maps which can then be compared with yield maps from the same field. This should help identify those pest/crop situations where within-field management is most likely to be appropriate and cost-effective.

It is important that research continues to develop in the two key areas outlined above, as measuring, interpreting and managing spatial, temporal and predictive variation lies at the heart of precision farming (Blackmore, 1996). It is vital that a practical focus is maintained, and it is likely that what will emerge is an increasing appreciation of the need to make decisions using information derived at the appropriate spatial scale - i.e. within-field management will be appropriate for some pests but not others. It is also possible that some of the methodologies developed to do research on within-field pest distributions will prove useful in evaluating new approaches to pest management such as the use of novel semiochemicals to manipulate pest and natural enemy complexes on a whole-field scale.

Harvesting

Combine harvesters fitted with yield monitoring equipment have been the most important 'sensor' in the development of the precision farming concept. However, there is limited information on the robustness of the data from both manufacturers of yield mapping combines or monitoring system manufacturers. There are differences in the principles of monitoring yield with the different manufacturers (Murphy *et al.*, 1994), such as yield monitoring based on mass flow or volume. Whilst it is generally acknowledged that yield monitors based on mass flow are more 'accurate' they have not been subject to independent evaluation in the laboratory or field which would allow system comparisons in terms of specification or tolerance. There is no independent assessment of system repeatability, reliability or confidence limits and this will become of increasing importance as a greater number of older combines, with yield mapping capability, are used on farms. Operators would appear to have to develop their own seasonal checks or calibration methods.

Further concerns have been expressed concerning lack of moisture correction and the requirement for monitoring of actual combine cutting widths. These problems are likely to be overcome with increasing system developments. In field use there has been no information on the reliability over time due to combining on sloping terrain or from foreign matter (weeds or accumulated dirt) on performance.

Accepting the accuracy limits within yield mapping systems, the yield map has nevertheless highlighted and quantified within-field variations in yield and in limited experimental studies, grain quality (Mulla *et al.,* 1992). Yield map information provided by the combine harvester is too late for agronomic treatments to be modified, but its value lies in identifying zones which are sufficiently stable to be of use in determining future agronomic practices, identifying under performing areas of fields which warrant further specific investigation or quantifying yield loss from known causes. The cost of yield mapping technology is falling and is relatively cheap. It is accepted that interactions between soil differences and seasonal weather patterns are large, so yield maps can show considerable differences from season to season for a field (Birrell *et al.*, 1993, Clarke *et al.*, 1996).

Interpretation of yield maps is the subject of current research (Stafford *et al.*, 1996; Lark *et al.* 1997) and needs to follow a careful, informed analytical process. There are considerable opportunities for further exploitation of yield mapping data through the development of practical guidelines on improved data validation, selection or rejection of data for utilisation in cross seasonal comparisons and integration with data from within-crop monitoring or soil and terrain mapping.

The scale of resolution and confidence limits associated with yield maps are ill defined, but they will undoubtedly improve with developments in positioning systems and computer software for the interpretation of data from yield monitors. The basic threshing processes during combining however, when the grain is threshed, sieved and cleaned are unlikely to change. This operation inevitably requires some grain re-cycling which will have a 'smearing' effect on the yield monitor output and mapped yield data. The grain volumes being re-cycled are affected by crop status and combine settings i.e. they are field specific.

The most important use of historical yield mapping information is as a component in the decision making process on nutrient inputs. Current nitrogen fertiliser recommendation systems for winter cereals in the UK adjust the nitrogen rate for expected yield, but there are uncertainties in whether and if so how, inputs should be modified according to yield potential. It should also be emphasised that advice on fertiliser use for most N recommendations systems is based upon empirical information from replicated plot experiments laid out in uniform areas within fields.

The harvesting operation provides further opportunities for data collection using additional sensors. The most likely development is in the use of moisture meters allowing yield adjustment to standard moisture content in fields. Within field variation in the moisture content of cereals is small, with the exception of headland areas, however there can be significant differences in the crop maturity in crops such as oilseed rape. For the grower, sensors capable of assessing aspects of grain quality, such as grain N content have potentially important implications in both the barley malting and wheat milling sectors, yet the difficulties in acting upon such information, to provide distinct grain 'streams' from field to store, should not be underestimated. Studies in Belgium have indicated that grain protein content can be assessed by direct measurement of ears using near infrared spectrometry (Dardenne *et al.*, 1996) and if such an approach could be developed for practical field scale application there could be significant economic benefits.

Another use of yield map information would be to assess the outcome of variable within field agronomic treatments and evaluate their economic and environmental consequences. Interpretation of the effects of variable application treatments in one season following several seasons where uniform treatments had been applied is a feasible option. However, developing this concept over several seasons, where the effects of variable application are compounded, will require clear strategies in terms of defining management units or zones within fields, and in setting yield goals and crop management plans for each zone.

Developing the husbandry process

It must be concluded from the fore-going sections that current agronomic 'recommendations' are a compromise between the scientific knowledge of what affects yield, and the practicalities of knowing these factors in time to respond to them at realistic cost. Some decisions can be taken well in advance of the relevant action because they depend on factors which are known well in advance. These include the choice of crops and which varieties to grow, seed rates, fertiliser and lime input, and herbicides to treat persistent weeds. Other decisions, particularly those on choice and timing of fungicides and pesticides, must be made during the growing season on the basis of infestation, weather and crop growth. There is thus a wide diversity of dynamics affecting husbandry decisions and proper recognition of the relevant conditions is crucial in analysing the problems of automation and devising solutions in each case. The new technologies must be exploited and developed according to the intelligence, the rules and the machinery essential to each of these facets of husbandry.

Thus although we might be able to achieve more precise adjustment of fertiliser inputs by frequent monitoring of soil supply and crop nitrogen uptake, the cost of such monitoring is the main obstacle to automation. Furthermore, responses to crop management depend on subsequent uncertainties. For example, the implication from irrigation studies on sands is that irrigation increases yield but also increases optimum nitrogen input (Shepherd, pers. comm.); it is likely that any attempt at precision with be partially thwarted by unpredictable changes in subsequent growing conditions. Thus, there is a need not only for careful analysis of cost-effectiveness of precision farming techniques in the light of existing agronomic knowledge, but there is a case for some empirical economic studies to confirm the theoretical predictions.

THE BENEFITS FROM AUTOMATION

Although a comprehensive analysis of the costs and benefits of automating crop husbandry is beyond the scope of this review, a crude assessment of its commercial potential is necessary in order to draw conclusions from the rather qualitative analysis provided in the preceding sections. What follows is therefore a worked example, to show the economic principles governing the economic value of adopting precision farming techniques and the approach to cost-benefit analysis that is considered appropriate, and then a semi-quantitative overview of the other main facets of husbandry. We suggest that there is scope for further more careful cost-benefit analyses before significant investments are made in the automation of crop husbandry.

Cost-effectiveness of differential applications - a worked example

We have chosen the management of phosphate applications for cereals as the best case for a worked example. Quantitative data are available for both the variability and the response to this input; given equivalent data, calculations for other inputs ought to be possible in the same way as those for phosphate.

The majority of arable fields in the UK have soil phosphate levels within a range at which yield responses to fresh fertiliser are small - typically about 15-40 mg/l P_2O_5 by Olsen extraction (Froment *et al.*, 1995; MAFF 1986). At current costs, topsoil analysis of a 20 ha field of single samples taken at 40 m intervals would require about 125 samples, and cost about £1600 including costs of sampling. This density of sampling has been suggested as adequate for development of accurate understanding of spatial variability (Webster and Oliver, 1992). Sampling every 50 m and bulking 4 samples to give a result for every ha would cost about £300. The analysis would cover P, K, Mg and pH.

This outlay would have to be recovered by savings in fertiliser or, in exceptional cases, by increases in yield. The latter case would be unusual for long-term arable fields. Phosphate fertiliser at present costs about £0.21 per kg (Nix, 1995). The recommendations for cereal crops are to apply sufficient to replace offtake at P Index 1, 2 or 3, (ranging from 40 to 80 kg/ha P_2O_5) and to build up reserves at P Index 0 by applying about twice this (MAFF, 1994). The typical cost of phosphate fertiliser for a field with average yields of 8 t/ha, at average soil P content, would be £12.60 per ha. At greater P levels, the recommendation is to omit P fertiliser. After a few years re-analysis would be required to test the effect of continued depletion on soil P Index.

Potential benefits from zoning might arise from avoidance of yield loss, if part of the field had extremely small phosphate content (less than 10 mg/l P). This is unusual in arable fields, but if it occurred might reduce yields by 1-2 t/ha until corrected. Thus a benefit of perhaps £150 per ha per year would accrue for an additional expenditure of about £12/ha, in the affected area, as a result of mapping. The gains might continue for about 10 years, after which time soil reserves would be approaching the level of diminishing response. This situation is highly profitable, but unusual, since very few sampled arable fields have such small phosphate levels.

The more common benefit would arise from a discovery that part of the field had unusually high phosphate content (in excess of 45 mg/l P). This zone would not require fertiliser for some years. Since the crop removes approximately 60 kg/ha P_2O_5 per year, and it takes about 30 kg/ha P_2O_5 to change the analytical result by 1 mg/l P, it would be expected to take more than 7 years for the analysis of the high-phosphate area to drop to 45 mg/l P. If the high-phosphate zone covers half the field, the total saving in fertiliser input would be 4200 kg P_2O_5 worth about £900. The saving would not pay for sampling at 20 m intervals, but would pay for sampling in 1 ha units. Again, such a saving would be the exception, so that sub-sampling will only be cost-effective if the fields are first selected on the basis of prior knowledge - such as a history of animal manure application, or an unusually high value from a whole-field nutrient analysis.

This preliminary analysis suggests there are potential gains from subdividing fields for phosphate application. How common are those gains likely to be? Each time a field is mapped, the response is to adjust fertiliser inputs to remove the observed variability. The implication is that for any field, large savings accruing from a phosphate map are likely to occur no more than once in a working lifetime, assuming sensible fertiliser policies are followed subsequently. The finding of Froment *et al.* (1995) that over 90% of samples from within fields would have received the same fertiliser advice as the mean value, suggests that no more than about 5% of field areas are likely to fall into zones which require differential advice. The other 5% of variation detected is likely to occur at too fine a scale to be mapped usefully.

On this basis a comprehensive mapping policy could only be justified if the unit area gains found when zones could be delineated were at least 20 times the unit area cost of mapping. This is clearly not the case even where yield benefits are expected. Strategic selection of fields for sampling will be essential. For phosphate, the main cause of variable levels will be past management - levels may be exceptionally low on land recently brought into cultivation, and exceptionally high after a history of large applications of manures, especially poultry manures, or of vegetable and potato cropping. If it is known that one area of the field grew vegetables for 10 years while the other was under an arable rotation, the obvious cost-effective approach is to divide the field into these zones prior to sampling, and take a representative sample from each zone. Greater confidence in the results might be obtained by subdividing each main zone into 2 or 3, and taking a sample from each subzone. The cost of such an approach would be £25 to £100 depending on whether the farmer did his own sampling, and how many samples were taken.

Since the case for field mapping of phosphate even at a modest scale - one bulked sample per ha - is rather weak, it is clear that sampling at sufficient density for use of standard geo-statistical techniques will be uneconomic for all nutrients with present methods. The requirement is for a robust technique to identify when a result, which would imply a difference in treatment, is actually indicative of a true spatial trend, and when it is simply an odd value caused by fine scale variation.

Table 3. Characteristics of measurements affecting ease of making agronomic decisions on subdivided fields. Costs of measurement or assessment are estimated assuming 50 sampling or assessment points within a 20 ha field. Effects on costs of inputs are derived for a winter wheat crop, assuming the field is treated as two halves with relatively extreme values, compared with treatment as a whole using the greater of the two treatment costs. The final column is an attempt to indicate the risk to yield of failure to allow for major variation in the item within a field. (*** indicates considerable risk, for example from herbicide damage; - indicates negligible risk). The scaling is subjective only.

Measurement	*Stability*	*Measurement cost (£)*	*Actions or inputs affected*	*Potential effect on cost of action (£)*	*Risk of yield penalty if no adjustment*
Soil type	Stable		Cultivations	little effect	**
			N	75 - 225	*
			K	90	-
			Herbicide	0-150 / application	***
Topsoil organic matter	Stable	250	N	0-150	**
			Herbicide	0-150 / application	***
Topsoil P, K, Mg (and pH)	Stable - until fertiliser input	600 for all	Fertiliser (and lime)	125 (P), 105 (K)	*
Topsoil pH	Slowly declining - until lime applied	100	Lime		**
Topsoil available N	Sample autumn or early spring - variable over time and affected by fertiliser	perhaps 800	N	150	*
Typical yield	Use mean of several years	Small (once equipment is purchased)	N for Winter Wheat, Oilseed rape	150	-
Actual yields	(Sum since last input of P, K)		P, K	40 (P), 25 (K)	-
Weed patches	Variable - some persist between years	50	Herbicide	100-300 / application	**
Insect pests	Usually days	50 / application[α]	Pesticide	25-125 / application	**
Potato Cyst Nematode	Persists year to year		Nematocide		***
Foliar disease	Usually days	50 / application[α]	Fungicide	30-250 / application	***
Take-all	Some carry-over year to year	250	N timing and rate, Fungicide in future		*

[α] At present precision of assessment and speed of spread are such that few advisers would advocate part-field treatment.

Cost-effectiveness of differential applications - other husbandry factors

Table 3 shows the attributes which contribute to the main agronomic decisions, the typical cost of analysis for 50 points, the decisions which are affected by that factor, and an estimate of the value of splitting a field, in terms of the potential for saving on input costs or the avoidance of risk of yield loss. For this purpose it has been assumed that the field in question does indeed vary substantially in the item considered, for example from a sandy loam to a clay, or from having serious weed infestation to having none, and that this variation is sufficiently well-marked for subdivision of the field to be practicable. These assumptions will be true of only a minority of fields for a given decision item, so that the quoted benefit must be viewed as optimistic.

It can be seen that soil type (including soil organic matter) stands out as a factor which might be used to subdivide fields, both because it is stable, and because it affects so many decisions. Soil pH and weed location are useful because of their relatively low cost of definition. These are two areas where Precision Farming is currently applied. It is common for lime merchants to test pH at several locations in a field and, if significant differences are found, to apply differential lime dressings. Patch spraying of certain relatively persistent grass weeds is common practice, and is supported by active research. (e.g. Rew and Cussans, 1995). Few other variables show promise under current technology and recommendations systems. Although mapping certain pest or disease infestations may be relatively inexpensive, at present there is little enthusiasm for adopting within-field variation in treatment. The reasons given are that current assessment systems cannot detect extremely low infection or infestation levels, so that treatment of identified areas only could result in residual foci which would rapidly spread across the field.

Implications of Precision Farming for recommendation systems

Current management advice depends on information generated by soil analysis, counting of pests, assessment of disease and weeds and plant sampling. The advantages of non-invasive sensing are obvious - but the main disadvantage for farmers is that the rules for responding to the information have not been developed in many cases.

The implications of image analysis for weed detection or tilth assessment are relatively clear and the responses are being worked out in current research. For weeds, the main problem at present, once sensing methods are adequate, is the implications of spraying only a small, highly infested patch for spread of the weed in subsequent years. In these cases the sensing technique is closely linked to the variable of interest.

Sensors for pests or diseases, and nutrient status are not so easy to envisage. By the time symptoms are seen in the plant, it may be too late for effective preventive action. However, sensors can readily be envisaged which would be able to quantify plant cover, plant growth, greenness, and possibly plant or soil surface water status. Unfortunately current research is only just revealing how to respond to these results and it may be some time before this reaches a sufficient level of reliability for use within fields.

The general value of yield maps has been discussed. A specific use of them is to modify phosphate and potash inputs to allow for variable offtake. The saving would not justify purchase of a yield mapping combine harvester, but might well justify the marginal effort of calculating and carrying out the variable application. The permanence of a soil map, and the number of operations affected by soil type, mean that where soils do vary a map is almost certainly worthwhile. Whether it needs to be surveyed professionally is more difficult to determine.

Considering all husbandry factors the general conclusion would appear to be that mapping should be undertaken only if there is good prior cause to suspect variation sufficient to result in differences in recommendation. Even then, there is great economic value in knowing where the zones are likely to be, and obtaining for analysis relatively few, representative samples from these zones.

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