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An up-to-date cost/benefit analysis of precision farming techniques to guide growers of cereals and oilseeds

by

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Abstract

Precision farming techniques have a potentially important role in addressing the conflicting demands and constraints on combinable crop production. Economic benefits may result from higher yields, saved inputs or faster work rates, and depend on farm size, cropping and the amount of soil, crop or yield variation as well as crop values and input prices. Practical and environmental benefits may also be obtained as a result of decreased operator dependence and reduced input wastage respectively. The price, replacement value and lifespan of the equipment needed have a significant impact on annual cost. GPS guidance systems have been a significant development, offering good prospects of achieving a benefit over cost of at least £2/ha on a 500ha farm. Pass-to-pass accuracies of +/-10cm or less, and adding auto-section sprayer boom control, enable savings from reduced input overlaps to be maximised. Determining the extent of variability in soils, growth or yield is essential to decide the best strategy for managing inputs. Mapping soil texture using electrical conductivity, remote sensing of crop canopies and yield mapping can provide useful information and could cost as little as £1-2/ha each for a 500ha farm.

Variable rate application of P & K fertilisers can be based on nutrient offtake and targeted sampling derived from yield maps, or soil nutrient maps obtained by grid sampling, at a total cost of £6-7/ha. This could protect yield worth an average of £5/ha and save fertiliser worth £3/ha or more on a 500ha farm with 250ha treated variably. Variable rate N fertiliser is only justified in fields with large variation in crop canopy. For a 500ha farm with 250ha of wheat and oilseed rape treated variably, estimated benefits are £9.50/ha at a total cost of £5/ha for a satellite-based service or up to £8/ha for a vehicle-mounted system. The case for agrochemicals is weaker. An economic benefit from variable rate PGRs is unlikely unless their costs increase or their use is restricted. There are significant practical barriers to the patch spraying of herbicides, but variable treatment of 250ha of cereals on a 500ha farm could give savings of up to £9/ha at a cost of about £7/ha.

As the equipment and services involved could be used in multiple techniques, the benefit over cost of the whole system should be considered. Potential net benefits of around £6, £10 and £19/ha were calculated overall for farms of 300, 500 and 750ha respectively. Guidance was one of the main contributors to the benefits, and for many growers this would represent the lowest risk entry into precision farming.

Summary

Introduction

Precision farming technologies and techniques have a potentially important role to play in helping growers to address the conflicting demands and constraints that they face within current combinable crop production systems. However, the economic benefits that might be obtained by individual growers from the many options open to them depend on their farm size, cropping and the amount of variation that is present on their farms, as well as crop values and input prices. The analysis in this report is based on a 500ha farm growing:

- 125ha of feed wheat (yielding 8.0 t/ha at £100/t)
- 125ha of breadmaking wheat (yielding 8.0 t/ha at £120/t)
- 125ha of oilseed rape (yielding 3.5 t/ha at £240/t)
- 62.5ha of spring barley (yielding 6.5 t/ha at £130/t)
- 62.5ha of field beans (yielding 3.25 t/ha at £120/t).

The costs of fertilisers, pesticides or other inputs are based on expected prices in 2009.

The numbers of fields on the farm (as a percentage of the total) that are assumed to have significant variation are:

- 50% with variation in soil texture (mainly medium, some light and some heavy soil)
- 50% with variation in harvest yield (within-field variation of 10% or more above or below the field average)
- 67% with variation in crop structure (within-field variation in canopy GAI at the start of grain fill of 20% or more above or below the average for the field)
- 80% of fields with variation in their weed populations (fields are considered to have patchy weeds if a given species occupies less than 67% of the field).

The major financial investment from adopting precision farming methods is usually the purchase of the equipment, although the annual cost of bought-in mapping services can be higher. The extent to which that equipment comes as standard on the specification of machine normally being purchased, the period over which it is depreciated and its value at replacement can all have a significant influence on the annual cost per hectare of the technique that is being considered. For this analysis, straight-line depreciation of 17% per year has been assumed, with a replacement value after 5 years of 15%, and capital

interest of 6% charged on the mean value. However, to achieve success also requires a reasonable investment in time, for training, analysing data and setting-up equipment, as well as a willingness to have faith in the technology.

Economic benefits may be derived from a combination of increased yields, saved inputs, faster work rates and possibly improved timeliness. The array of other potential benefits though may itself provide a compelling argument for the use of some techniques. Most growers gain satisfaction from a 'job well done', and precision farming enables the accuracy of operations and applications to be improved (or maintained for longer or at higher work rates) whilst reducing operator fatigue. Matching input use to local crop need, or reducing treatment overlaps, are not only sources of financial saving but also help to minimise exposure and wastage in the environment, the benefits of which may be hard to quantify but nevertheless invaluable in addressing government policy objectives.

Machine Control

The introduction and commercialisation of guidance systems (using Differential GPS) for agricultural vehicles has been one of the most significant developments in precision farming within the current decade. In addition to its potential economic advantages, guidance offers a range of other practical and environmental benefits. Equipping two vehicles with an entry-level manual-steer system achieving a pass-to-pass accuracy of +/-40cm is likely to cost around £1.25/ha per year on a 500ha farm, but deliver potential savings of £2.50/ha from reduced overlaps (mainly during cultivations). This option is likely to be the most cost-effective for farms of about 300ha or less.

At least half of the potential savings from guidance systems come from saved spray and fertiliser inputs. To obtain these, tramline (and therefore drill) overlaps must be reduced to less than those achieved with conventional marker systems. This is only likely with medium-high accuracy guidance systems achieving pass-to-pass accuracies of +/-10cm or less, which would require a paid-for DGPS correction signal and either assisted or auto steering. The typical cost of equipping two vehicles with such a system on a 500ha farm is likely to be about £12/ha per year, but could deliver savings of around £14/ha.

An RTK-based system achieving a pass-to-pass accuracy of +/-2cm would cost considerably more, at around £20/ha per year for a 500ha farm (including auto-steer on three

vehicles). Potential savings would also increase to around £22/ha. This option is unlikely to be cost-effective on less than 500ha of combinable crops, and is probably best suited to very large farms or those growing higher value / cost crops. The high accuracy of location and steering that is possible with an RTK system also facilitates the adoption of controlled traffic farming (CTF). Potential benefits of CTF include better soil structure, improved water infiltration rates and lower draught requirements, leading to higher yields with reduced cultivation costs. There may be some additional expense in ensuring that matched equipment is purchased, and in maintaining the permanent tramlines. Data from two sites suggests that yield increases of 2-5% over trafficked non-inversion cultivation systems are feasible on most soil types in the short term. This could increase winter wheat returns by £16-40/ha. RTK might also have a value where the intention is to use strip tillage, to enable accurate matching of cultivated strips and drill rows.

Adding auto-section boom control to a sprayer could further reduce overlaps (on headlands and at field edges), for an annual cost of less than £1/ha on 500ha. This would typically be recouped by a reduction in the total quantity of pesticides used of only 0.5-1.0%.

Assessment of Variation

Determining the extent (and causes) of variability in soil parameters, crop growth or yield is essential in order to decide the best strategy for managing inputs or treatments. The factors that vary within a field are no different to those that vary between fields, and a rough assessment of variation is possible without investment in precision farming through routine inspection of crops and problem areas, existing farm maps and aerial photos, or free satellite images (from previous years) available on the internet. These can be used to indicate the need for more detailed investigation.

Differences in crop requirement or performance across a field will often reflect changes in soil properties. Mapping variation in the apparent electrical conductivity (ECa) of the soil can be used to define more accurately the boundaries between different soil textures, provided that the soils are mapped at field capacity, and soil pits are dug or cores taken to verify the differences in soil properties. ECa mapping is offered as a commercial service which, if spread over 10-15 years, would equate to cost of about £1-1.50/ha.

Mapping crop yield produces rapid and data-intensive information about variation that could be economically important. Data must though be analysed correctly, and trends that are stable over a number of years identified, in order for the information to be most useful. The likely cost of yield mapping on a 500ha farm would be around £3/ha per year, but less than £2/ha where the same equipment is shared with other tasks. Variability related to site or soil features will often be evident within a field as differences in size or colour of a growing crop. Remote sensing technologies that measure spectral reflectance form the basis of several commercially-available options for quantifying such variation. Systems differ in terms of area scanned, the wavelengths used, spatial resolution and the way that the impact of cloud or varying light levels is accounted for. The main decision for growers is the choice between an annual bought-in (satellite-based) service whereby all of the data collection, analysis and interpretation is done by the service provider and made available to the grower within a few days (near real time); or a vehicle-mounted sensor system owned (or rented) and operated by the grower, with data available instantly for on-the-go adjustment of crop inputs in real time.

The major cost difference is the initial investment and the greater impact of farm size or usage area for owned equipment compared to a bought-in service. The cost of obtaining crop canopy maps using a satellite-based service would typically be about £2/ha for a 500ha farm. This does not include the cost of the application maps for N or other inputs, which would be necessary in order to vary inputs. Using the Yara N-Sensor as an example, obtaining similar information from a purchased vehicle-mounted system is likely to cost around £6.50/ha per year on 500ha (less as farm size increases), but any additional expense associated with translating the canopy information into a variable rate of N or other input should be less.

Managing Limitations to Crop Performance

Having established that significant variation exists, an appropriate response must then be determined. It might be possible to improve average performance within a field, by not cropping problem areas or through targeted remedial treatments. Alternatively the variation could be managed through better targeting of inputs, which could be as simple as manually-triggered adjustments in one or two areas of a field. In addition to variability within a field in one season, there will be season-to-season differences. Strategies that are based only on the former and that ignore seasonal interactions are risky and could

exacerbate the range in performance achieved. It must also be recognised that in most cases precision farming helps a grower to decide where to do something, not what to do. The actual techniques used are therefore only as reliable as the agronomic rules and interpretation that go with them.

Mapping the crop canopy or yield enables losses caused by waterlogging, rabbit damage or uneven N fertiliser application to be quantified and targeted. It can also be determined from yield maps whether or not remedial actions are likely to be worthwhile, and their subsequent impact can then be monitored. Compaction can be linked to variation in growth or yield, or mapped directly using a commercial service that involves measurement of penetrometer resistance at different depths within a field on a grid basis. The soil profile must be inspected and soil moisture taken into account to ensure that data is properly interpreted. The cost for this service is about £12/ha, but should only be required every 3 or 4 years. Reducing by half the amount of subsoiling required on 100ha each year, or improving yield by 5% on 50ha each year, would typically be sufficient to cover the annual costs incurred.

Crop Establishment

Reducing the potential variation in crop structure should ideally start at establishment, by compensating for the impact of variable seedbed quality caused by differences in topsoil texture. Varying seed rates based on maps derived from ECa mapping provides a means of achieving this. Where fields have distinct areas with different soil types, seed rates can be adjusted manually. The cost of adding a variable seed rate controller to a seed drill (already fitted with electrically-operated seed rate adjustment), and producing seed rate maps from ECa maps, is likely to be around £1.50/ha per year. Assuming that only 50% of fields have sufficiently large soil variation to justify variable seed rates, average savings in seed costs alone on a 500ha farm might only be around £1/ha. However if a 1% yield loss could be prevented on heavier patches that might otherwise end up with sub-optimal plant populations, benefits should be sufficient to recoup the costs of the variable seed rate capability and a share of the ECa mapping cost. Preventing a 1% yield loss also on lighter soil patches that might otherwise lodge due to excessive plant populations could give benefits sufficient to cover the full cost of ECa mapping.

Nutrient Management

There are two main approaches to determining variation in requirement for phosphate (P), potash (K) and magnesium (Mg) fertilisers within a field. Yield maps can be used to identify areas of consistently low or high yield where differences in offtake may have resulted in above or below target soil nutrient indices respectively. An intensive targeted sampling approach within these areas can then be used to confirm this, and application maps produced based on replacement of crop offtake and also the need to raise or lower indices, taking into account any soil texture variation. Alternatively, the whole field can be sampled on a grid basis by a commercial service provider, allowing application maps to be produced based on soil indices. In both cases, sampling itself would only take place about once every four years, although applications would be varied on an annual basis.

Due to the relatively high cost of soil sampling and analysis, it is not cost-effective to obtain more than one (bulk) sample per hectare, which means that when grid sampling interpolation is necessary for areas of the field in between. This can be a source of error, especially where there are unusual patterns in the distribution of nutrient indices within the field. Where yield maps show consistent and discrete high and low yielding areas within a field, and the previous field history is well known, targeted sampling might be a more cost-effective approach. Where such information is not available to target sampling, an unbiased grid survey may be a more useful starting point.

A commercially-provided grid sampling service is likely to cost about £5.50/ha per year over the four year life of the information. A strategy based on targeted sampling is likely to cost nearer £4.00/ha on a 500ha farm, or £2.50/ha if only half the fields have sufficient yield variation to justify variable treatment. A variable rate spreader controller is likely to cost no more than £0.75/ha per year, assuming that the expense can be shared with variable N application. Savings in P & K fertiliser may be small, unless the farm has a history of over-applying nutrients in excess of offtake. There will be some savings in low yielding areas, and by restoring indices to target levels in higher offtake areas this should ensure no loss of yield potential. If 50% of fields on 500ha are treated variably, averaged over the whole farm saved yield could be worth £5/ha and P & K fertiliser savings could amount to £3/ha or more (where average soil indices are currently above target). This would give a potential net benefit equivalent to about £2/ha over the whole farm.

For spatially-variable application of nitrogen (N) fertiliser to be justified, the optimum N dose for a crop must vary significantly within a field. Evidence suggests that this does occur, but the impact of seasonal variation in N response will often be greater and annual application strategies must account for this. Canopy size and colour, mapped by remote sensing of reflectance, provide the best means of determining the interaction between spatial and seasonal impacts on N supply and crop requirement, and this forms the basis of most commercially-available systems for determining variable N applications. The most appropriate response for crop areas with above or below average canopy size may vary according to growth stage or other factors, but typically the objective is to increase growth in areas that are below target early in the season and hold-back growth in areas that are above target. Later the strategy may be reversed to avoid over-fertilising areas of low yield potential or under-fertilising areas of higher potential. A re-analysis of previous HGCA-funded research suggests that for winter wheat only where crop canopies in May vary by more than about 20% above or below target, which may equate to earlier plant or shoot populations varying by more than about 40% above or below target, is variable N application likely to be justified. It can be estimated that no more than half of all wheat fields (perhaps a larger proportion of oilseed rape fields) are likely to benefit.

In addition to the expense of satellite-derived canopy maps indicated earlier, the annual cost of generating N fertiliser application maps can be estimated at £1.50/ha per map (£4.50/ha per year for wheat or £3.00/ha for other crops). With the canopy mapping and a share of the cost of the variable rate spreader controller, the total cost for this approach is likely to be around £6.50/ha for a 500ha farm. Assuming 250ha of wheat and oilseed rape are treated variably (and require treatment maps), the costs (averaged over the whole farm) would be £4.75/ha. The only additional costs for a vehicle-mounted system like the N-Sensor would be in setting up the system to translate the crop canopy information into a variable N dose, which can be estimated at about £0.50/ha per application (£1.50/ha per year for wheat or £1.00/ha for other crops). With a share of the spreader controller costs, the total for this approach is likely to be around £8.25/ha for a 500ha farm, or if used on 250ha of wheat and oilseed rape then £7.50/ha (averaged over the whole farm).

Potential benefits can be estimated at an average 2% yield increase, from re-distribution within a field of the same total quantity of N fertiliser, or alternatively a 10% reduction in the total quantity of N applied to a field to maintain the same average yield. The potential

improvement in margin over N cost would then be around £15-20/ha. For a 500ha farm with 250ha of crops that are treated variably, this would equate to an average benefit over the whole farm of £9.50/ha, giving a net benefit of £4.75/ha with the satellite-based approach or £2.00/ha with the vehicle-mounted system. Increasing the area farmed to 750ha would reduce the costs of the vehicle-mounted system in particular and increase the net benefits for the two approaches to around £5.25/ha and £4.25/ha respectively.

Crop Protection

Crop structure in spring can be a useful indicator of lodging risk. Maps obtained using remote sensing could provide an indication of how risk varies within a field, if properly calibrated and correctly interpreted. These could be used to produce variable application maps for Plant Growth Regulators. As the potential penalties caused by lodging vastly outweigh the likely savings in PGR costs, a treatment strategy based on varying the dose applied would be more appropriate than a spray / no-spray strategy, except perhaps for late-season applications. In addition to a share of the costs of the canopy sensing and patch spraying capability, described later, the only expense would be in producing the variable rate PGR maps. The total cost on 500ha can be estimated at £3.75/ha per year (averaged over the whole farm), assuming 167ha of wheat treated variably. Savings in PGR cost alone are unlikely to reach this even on a much larger area. Assuming that 5% yield loss could be prevented in areas where the canopy size is excessive, the benefits would just about cover the cost of variable rate treatment. In practice, variable application rather than a robust uniform treatment is only likely to be adopted if PGR use becomes restricted or if the costs of the PGRs themselves increase significantly

The evidence for variable rate application of fungicides in response to predicted differences in disease development or fungicide requirement is conflicting and relatively weak. Based on our current capabilities and understanding, the conclusion must be that there is unlikely to be an economic benefit from varying fungicide application to combinable crops in the foreseeable future.

The principles for variable rate application of herbicides are well established, although some debate remains on the stability of weed patches. This affects the most appropriate mapping frequency and potentially the most suitable treatment strategy (including the

size of the safety margin around the patches), all of which have an impact on the cost. Investment in the patch spraying capability and associated expenses can be estimated at £4.00/ha per year for a 500ha farm. A strategy based on mapping weeds every two years at a cost of £6/ha would make the total cost £7.00/ha per year. Assuming 80% of the farm's cereal area (250ha) has patchy black-grass, cleavers and wild oats, savings on specific post-emergence herbicides can be estimated at about £9.00/ha, with a potential benefit over cost of £2.00/ha. If only 50% of the cereal area had patchy weeds, variable rate herbicides would not be cost-effective unless the patch spraying equipment expense could be shared with variable rate PGR application. Increasing reliance on pre-emergence herbicides, a tendency for most growers to adopt a zero-tolerance strategy for managing the weed species for which patch spraying has been evaluated, and difficulties involved in weed mapping are however significant barriers to uptake of this technique.

Traceability and Record Keeping

Precision farming techniques offer the potential to contribute to the generation and maintenance of records of most farming operations. There is a legal requirement to keep records of the application of crop protection chemicals (pesticides) and some fertilisers. Such records need to contain information relating, for example, to the date and time of an application, the crop to which the application has been made, the materials applied (both dose and relevant ingredients), the weather conditions at the time of the application and the justification for the treatment. Application systems with a precision farming capability are able to start the creation of such records automatically including in situations where spatially variable applications have been made. To date however, no commercially viable method of detecting what is loaded into a sprayer tank or fertiliser spreader hopper has been established although a number of research concepts have been identified. Data relating to the materials that have been applied must therefore be entered manually with existing systems.

The cost/benefit of using automated record generation units depends on allocating a value to having accurate records. Some authors have suggested that there would be a time saving associated with part automated record generation while others consider the sole benefit to be in the quality and timeliness of the records produced. In this study, it was concluded that there could be some labour time savings associated with the generation of records having a higher level of accuracy when using precision farming

techniques compared with wholly manual methods. No added value has been allocated to records that would be more accurate and reliable. For a typical 500ha arable farm, the labour saving from generation of pesticide application records with precision farming systems but manual entry of products applied was estimated to average £0.27/ha with shared equipment costs of £0.21/ha. This approach therefore gives marginally positive cost/benefits without giving a higher value to more accurate and reliable records. Increasing the farm area increases the benefit. For fertiliser application records, the farm area needs to be at more than 700ha to give a positive cost/benefit ratio.

In addition to records of crop inputs, precision farming approaches will also enable records of other field operations, such as cultivations, to be obtained with greater accuracy and less time than with comparable manual systems. Yield mapping with a correctly calibrated and operated system can generate records relevant to monitoring the output from a defined field area as well as the marketing of farm outputs.

Whole Farm Systems

Many precision farming techniques involve the use of equipment or services that are common to two or more tasks. In some cases the economic benefits from an individual task may be small, and it may not be cost-effective in its own right. However by covering part of the cost of components used in other more cost-effective tasks, the profitability of the overall system may still be improved. An objective of this project was to produce an interactive cost/benefit calculator tool that could be used by a grower to obtain an indication of the individual techniques and overall system that might produce a benefit over cost on their farm, taking into account their cropping, input/output costs and estimated variation. Likely costs and potential benefits were calculated for three example systems for farms of 300, 500 and 750ha. All were based on the same cropping split (50% winter wheat, 25% oilseed rape, 12.5% spring barley and 12.5% field beans).

The 300ha farm system comprised a lightbar-based low accuracy level guidance system, the use of satellite-derived crop canopy maps to vary N application rates, and variable application of P & K based on a grid sampling service. Overall system benefits were calculated to be £20.00/ha, for a cost of £14.25/ha, giving a net benefit of £5.75/ha.

The 500ha farm system comprised a medium-high accuracy guidance system based on a paid-for DGPS signal with part auto / part assisted steering, auto-section sprayer boom control, yield mapping to quantify yield variation, improve farm records and to target low yielding areas (caused by compaction), the use of satellite-derived canopy maps to vary N application rates and variable application of P & K based on a grid sampling service. Overall system benefits were calculated to be £36.25/ha, for a cost of £26.50/ha, giving a net benefit of £9.75/ha.

The 750ha farm system comprised a high accuracy guidance system based on an RTK signal with auto steering on all main vehicles, auto-section sprayer boom control, yield mapping to quantify yield variation, improve farm records and to target low yielding areas (caused by compaction), ECa mapping of soil texture to guide the use of variable seed rates, the use of an owned vehicle-mounted sensor system to vary N and PGR applications, variable application of P & K based on a grid sampling approach, weed mapping / patch spraying of herbicides and improved recording of spray and fertiliser applications. Overall system benefits were calculated to be £55.00/ha, for a cost of £36.00/ha, giving a net benefit of £19.00/ha.

Increasing farm size was associated with an increase in the number of techniques that could potentially be cost-effective and a larger overall benefit over cost for the system. The level of sophistication justified, and the scope to use owned equipment rather than a bought-in service, also tended to increase with farm size. However, timeliness is crucial for many operations and any delays introduced due to precision farming being adopted could easily result in their advantages being negated in the short term. In all three of the example systems above, variable N application and guidance together contribute about 80% of the net benefits. However, as the contribution from variable N application depends heavily on the amount of canopy variation present, for many growers guidance will give the highest probability of an economic benefit over cost and is likely therefore to represent their lowest risk entry point into precision farming.

Research Review and Consultation

1.0 Introduction

1.1 Background

Growers of cereals and oilseeds have to contend with many conflicting demands and constraints on their production systems. Investment in often scarce and expensive inputs has to be made against a background of volatile grain prices. There is a strong incentive to maximise yield to meet demand for both food and fuel crops, but this has to be reconciled with the need to reduce diffuse pollution, protect water quality and minimise greenhouse gas emissions. Finally the impacts of pesticide resistance and the revocation of product approvals mean that alternative solutions may be needed for some common agronomic problems.

To maximise efficiency, improvements to the productivity of the land must be achieved using management that is matched as locally and closely as possible to the properties of the soil, crop and its immediate environment. With the area of land per farm manager, farm operator or agronomist steadily rising, this must also be accomplished with minimal increase in amount of time taken or burden of record keeping, and against a background of the burgeoning requirement for verifiable and automatic traceability.

Over the last two decades there has been significant investment in research and development in the area of 'precision' or 'site specific' farming, both scientifically and commercially. Until recently, low grain prices and high costs of technology have provided little incentive for many growers or agronomists to consider the opportunities and capabilities that now exist. However, the combination of circumstances highlighted means that the time is potentially now right for the promise offered by precision farming to be explored and exploited more widely.

The realisation of this has resulted in an upsurge in interest in precision farming techniques, and the benefits that they might offer to farm businesses. This change to a more favourable environment for precision farming is not restricted to the UK. A recent survey in the USA (Akridge & Whipker, 2008) revealed that, amongst 275 retail crop input dealers who responded, the most commonly used precision technologies are now

GPS guidance systems (72.8%, with 36.8% using autosteer), satellite/aerial imagery (28.3%) and soil ECa mapping (9.2%). When asked what precision agriculture might look like in the future, 24.1% of respondents indicated an increased use of variable-rate fertiliser application, 22.8% suggested more data analysis and handling, 21.4% variable rate seeding, 15.2% variable rate chemical application and 14.5% indicated an increased use of autosteer/automation. Technology issues felt to be a barrier to growth included equipment changing too quickly and increased cost (62.2%), incompatibility across equipment (44.9%), equipment too complicated for operators (32.9%), data collection not accurate enough (14.9%) and application technologies not accurate enough (13.1%).

Further uptake of precision farming techniques has the potential to benefit UK agriculture either through increased output or reduced costs. Previous research and analyses have tended to focus on the average financial gain that might be associated with particular techniques, rather than assessing the likelihood of a benefit for an individual grower. There is a need to provide growers with information and tools to help them determine which techniques are likely to be of most benefit to them (economically or practically) or the environment on their farm, and to help them avoid investment in techniques that are unsuited to their situation and unlikely to deliver the benefits that they might expect. This involves a requirement to link the type and level of investment that is likely to be appropriate with the particular characteristics of the farm and its cropping, and the extent of on-farm or within-field variation that is necessary to justify it.

It is however also important to acknowledge that 'good practice' is a driver for many crop husbandry decisions on farm, not just the ratio of costs and benefits. In some cases benefits can be considered in terms of increasing the value of an asset such as the land (for example improving the soil nutrient status or securing a greater proportion of its yield potential), and this might not always translate to an immediate benefit over cost for an individual crop. Better farm management and crop assurance (improved food quality and lower pesticide residues) are other potential outcomes that may not have a direct or instant impact on annual profitability, but may be important in the longer term. Environmental benefits (less leaching and diffuse pollution, increased biodiversity) in particular may be difficult to put an economic value on for an individual farm, unless they are linked to the avoidance of financial penalties, but may be of considerable significance for the Industry as a whole.

1.2 Aims and Objectives

The overall aim of this review is to produce an up-to-date analysis of the benefits and costs of precision farming techniques, to guide decision-making by individual growers of cereals and oilseeds. Specific objectives are to:

- Evaluate the practical, economic and environmental benefits that can potentially be achieved through the adoption of current precision farming techniques.
- Assess the likely impact, on the incentive to adopt precision farming techniques, of:
 - changes in input prices and crop values
 - the need to reduce diffuse pollution and greenhouse gas emissions
 - the underlying or inherent level of variation associated with key inputs/outputs.
- Review the costs of investment associated with a range of precision farming capabilities.
- Use the information generated above to produce a simple 'dynamic' chart or tool that can be used by individual growers under changing circumstances to assess their likelihood of obtaining a benefit from the techniques available to them.

1.3 Approaches

HGCA have funded a series of relevant research projects over the last 10 years (listed in Appendix C). Some of these documents contained an analysis of the potential costs and benefits of particular precision farming techniques. However most had not been updated to account for recent agronomic developments, commercial availability of equipment and services, or current costs. This review included a re-examination of the assumptions and conclusions from those previous studies and from other work in the UK and elsewhere. In addition to analysing past research and current capabilities and costs, the review process involved consultation with key influencers (commercial service-providers, equipment manufacturers, researchers and established practitioners of precision farming), and a meeting of stakeholders (facilitated by the Precision Farming Alliance). The main outputs of the project are this report and an interactive spreadsheet-based cost/benefit calculator tool.

2.0 General Considerations

2.1 Costs

Soil or crop information obtained using precision farming technologies, and the ability to carry out spatially-variable management within fields, has the potential to enhance crop and farm performance through improved decision making. However the potential benefits have to be offset against the likely costs of acquiring and exploiting the information. In some situations, this may require a reduction in 'variable' (input) costs to be balanced against an increase in 'fixed' (equipment) costs (Bryson *et al.*, 2000).

Development of guidance (positioning and steering) systems for farm machinery has meant that investment in technology can bring about a reduction in some costs that might be classed as 'fixed'. Nevertheless the largest financial outlay in precision farming will invariably be the equipment itself, even though in terms of annual costs bought-in mapping services can be greater. This will often be purchased separately, or as an optional extra when buying key items of machinery for the farm, but in some cases may come as standard on machines of a certain size or specification. If the farm is large enough to warrant investment in machinery at that level, the extra cost incurred in order to be able to utilise the precision farming capability may be quite small (as well as there being more area to spread the cost over). A good example would be autosteer, which may come as standard on high horsepower tractors or on top-of-the-range combines, and only require activation and the addition of a controller to make it operational.

In addition to its purchase price and finance costs, the period over which equipment is depreciated (and its value at replacement) has a significant impact on its annual cost. Electronic devices may have a shorter lifespan than the machinery they are used in. Even though equipment may still be well within its normal working life, replacement may be necessary sooner than planned to upgrade the system, as additional capabilities are added to the farm. Having a clear (but flexible) strategy that takes all of this into account is therefore essential. For all equipment there is likely to be an element of cost involved in annual upkeep, whether this is servicing and maintenance or simply checking and calibrating. This may be limited with equipment that consists mainly of a box of electronics. There may also be annual subscription or software costs associated with some functions.

The use of precision farming equipment may in some instances allow the use of less skilled labour to carry out certain some tasks, but that labour will still require training in how to use the technology appropriately. Even with well-trained operators, there will be time needed to ensure that the equipment is set up properly for each operation or each field, and 'down-time' (especially in the first year) through signal loss and compatibility or communication problems. It is difficult to quantify how much time might be lost in this way, and it should become less as the technology improves further, but it should not be ignored as without careful consideration it could prove to be expensive in the long run.

2.2 Benefits

Improved margin over cost or profit are of course an important (and for many) essential outcome if investment is to be made in precision farming technologies. However, it is important from the outset to acknowledge that there are many other benefits, some of which cannot easily be expressed in terms of a monetary value.

Precision farming undoubtedly has environmental benefits. The principle underlying all of the available techniques is 'doing only what is needed and where it needs to be done'. Often this will mean that improved profitability and reduced negative environmental impacts are achieved simultaneously by avoiding overlaps (and therefore waste) or by matching input doses to local needs (Pierce & Nowak, 1999). As the direct costs of environmental impacts relating to agricultural inputs are often not borne by the grower, other than through financial penalties for specific instances, it is difficult to put a value on reducing these impacts. Indirectly though there may be a cost to growers through usage restrictions (dose, timing or areas that cannot be treated) which could be quantified in terms of lost yield potential or margin. Both indirectly through less wastage of nitrogen fertilisers, and directly through reduced machine passes and therefore fuel use, there will be reductions in greenhouse gas emissions per hectare of land or per tonne of crop output, and increasingly in future this may have a value measurable in carbon credits.

Practical benefits, in particular from guidance, may include time saved or the ability to achieve more within the working day. This will have an immediate economic benefit through a reduction in labour costs, but potentially a bigger impact through improved timeliness, leading to increased yields and/or lower optimum doses of pesticides. The closer that the farm machinery is being operated to its maximum daily or seasonal

capacity, the greater the potential benefit. Mistakes resulting from human error should be reduced, with a quantifiable saving in potentially lost output, and greater operator flexibility may result from enabling less experienced operators to undertake more difficult tasks, or skilled operators to achieve even higher standards of work, with a resulting reduction in management cost. The benefit to an individual grower may therefore depend on who is operating the machines on their farm. Both operators and managers alike are likely to benefit from having the satisfaction of a 'job well done'.

It should not be assumed that the advantages offered by precision farming for record keeping, traceability and crop assurance will necessarily result in reduced time taken for these tasks. A more realistic outcome might be improved quality of the records, for the same investment in time. The value of this may be realised through the avoidance of penalties through for example cross-compliance, and also the securing of preferential contracts or a price premium for crops grown on the farm.

2.3 Cost-Effectiveness

Pawlak (2003) conducted a simulation study which indicated that the field-level cost/benefits of adopting precision farming techniques improve as the price of the equipment declines, the size of fields increases, the annual use of precision-equipped machines increases, the amount of input savings rises, yields increase and the economic value assigned to environmental improvement increases.

A key factor in determining the potential benefit from precision farming techniques on an individual farm, especially variable inputs, is the level of inherent within-field variability. Often this will be related to variation in soil type, depth or water availability, but it could also be due to variation in organic matter or stone content, or topography (slope/aspect). There may also be induced variability within a field, resulting from previous management differences. This could be where fields have been amalgamated over time, have been split and then recombined, or have been strip-cropped. It may also apply where manures have been applied to fields unevenly (or they have been stocked with animals).

Farm size and geography will impact on the viability of most techniques, but especially those that require a significant investment in equipment when a large-enough farm size inevitably makes it easier to justify the cost. Even if the farm is relatively large, if it is

spread over a number of blocks that are separated by quite a distance, or by large obstructions (woods, buildings), or there are large differences in altitude between blocks, this may for example limit the practicality of techniques that use a shared resource. Input costs and output prices for crops being grown are important for most techniques, with high costs and high prices representing the conditions under which the benefits may be greatest from precision farming (and low costs and prices likely to show least benefit). Similarly on soil types where inputs need to be high, but so are potential yields, benefits are likely to be greatest. On soils where yield expectations and input requirements are relatively low, benefits might be less.

In understanding and overcoming limitations to yield within a field, precision farming can help at a number of stages in the yield-determination process (Figure 1). Achieving a benefit from better knowledge of crop or soil conditions for example may not necessitate precision farming technologies, but can be made easier through the use of them.

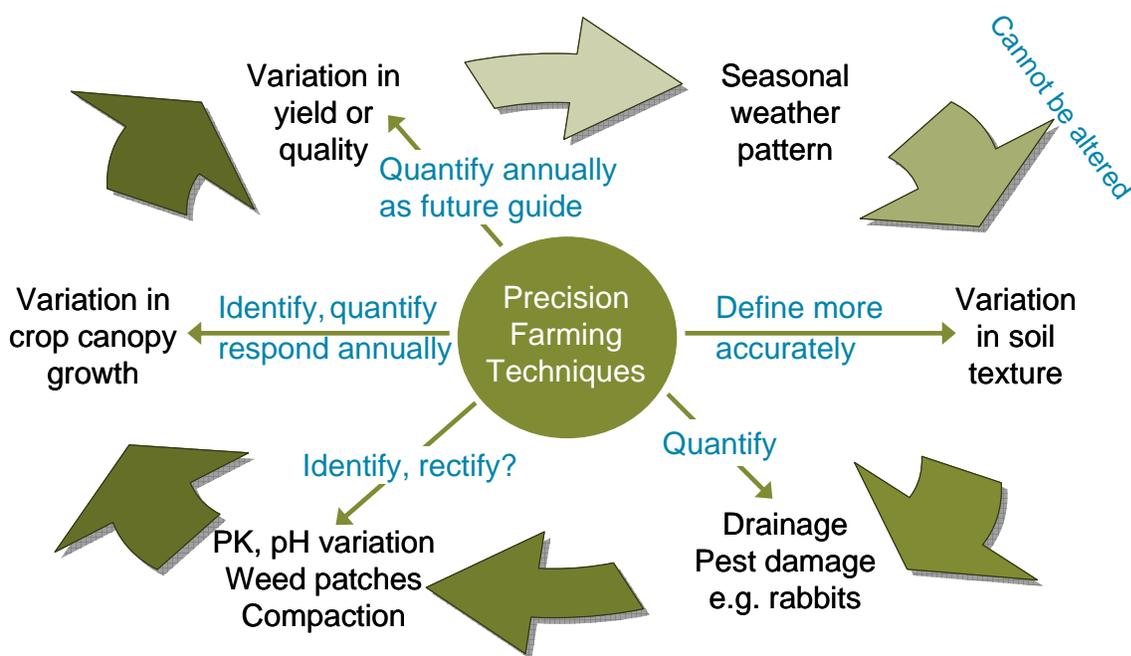


Figure 1. The role of precision farming techniques in the yield determination process

In situations where fields are relatively uniform, the emphasis when seeking to improve performance using precision farming techniques is likely to relate to matching applied treatments to:

- the condition of the crop or soil in the field as a whole *e.g.* average crop size or yield

- weather conditions at the time of treatment
- field areas by, for example, minimising overlaps and over/under treated areas
- the nature of field boundaries to account for effects at or beyond the boundary (in particular to reduce non-target contamination and adverse environmental impacts).

2.4 Suitability and Success

The suitability of precision farming techniques to a particular farm doesn't depend only on their potential cost-effectiveness. Success may also be influenced by the farming system. A simple approach to management based on treating every hectare of each crop the same and with a comprehensive programme may be less easy to adapt than where a field, variety and sowing date specific approach is already being taken. This may in turn be linked to management priorities on the farm, for example accepting a slightly lower margin per hectare but farming as large an area as possible, or maximising margins from a limited area being farmed. Where the farm operators have an aptitude for computers and electronics, it may be easier to introduce the technologies involved than where the operators do not, although training will also be necessary. Inevitably mind-set will be important, and successful adoption will require managers and operators to have adequate faith in technology, and its reliability. Access to rapid, knowledgeable backup and support from machinery dealers, service providers and software suppliers will also be essential. Finally attitude to risk may have an important influence.

2.5 Risk Management

The main risks to agricultural production have been identified as adverse weather, pests, disease, human error and misuse of new technologies (Anon, 2008). While precision farming may help to reduce the risk of human error, there is an increased risk of misuse of new technologies. Reducing uncertainty in expected yields is a desirable objective for most farm managers, and over time, improvements in technology and production practices have helped decrease agronomic risks and achieve this objective. However, as observed by Whelan & McBratney (2000), yield variation from year to year is often larger than within-field spatial variability, and the risk of inappropriate actions is increased if differential treatments are based solely on spatial variability. There is a need for example to consider how site and season interact *e.g.* soil texture variability and seasonal rainfall to identify if and when trends are likely to change. Whelan & McBratney (2000) argued that conventional uniform management at a field scale is a more risk averse strategy.

3.0 Specific Assumptions

Unless otherwise stated, the cost and benefit calculations reported within this analysis are based on the following assumptions:

- 500ha combinable crop farm, growing 125ha of winter feed wheat, 125ha of winter breadmaking wheat, 125ha winter oilseed rape, 62.5ha of spring malting barley and 62.5ha of field beans.
- Yields, crop prices, input levels and input costs are based largely on values used for 2009 gross margin calculations by TAG Consulting (unpublished), and/or relevant standard figures. Key values used are given in Table I in Appendix A.
- Equipment costs assume straight-line depreciation of 17% per year, with replacement value after 5 years of 15%, and capital interest of 6% charged on the mean value.
- Costs include an allowance of £250-500 for training in the use of hardware/software (where appropriate), spread over 5 years, and also an allowance for annual servicing and maintenance checks or set-up and calibration, equivalent to 2-4% of the purchase cost (depending on type of equipment).
- The number of fields on the farm (as a percentage of the total number) that are assumed to have significant variation are as follows:
 - 50% of fields have variation in soil texture (mainly medium soil, some light and some heavy)
 - 50% of fields have variation in harvest yield (within-field variation of 10% or more above or below the field average)
 - 67% of fields have variation in crop structure (within-field variation in canopy GAI at the start of grain fill of 20% or more above and below the average for the field)
 - 80% of fields have variation in their weed populations (fields are considered to have patchy weeds if a given species occupies less than 67% of the field).

4.0 Machine Control

4.1 Guidance

Guidance (or navigation) covers two discrete components, vehicle positioning and steering. A positioning system can be used alone, to improve the accuracy achieved when steering manually. Alternatively, it can be linked to a device that operates the vehicle steering wheel (assisted steering) or a fully integrated steering system that turns the wheels (auto steer). The costs and benefits of the overall guidance system will depend on both the positioning and steering components, and both of these will affect the level of accuracy achieved during vehicle operation.

Positioning is usually achieved by means of a global navigation satellite system (GNSS), most commonly GPS (Global Positioning System). There are alternatives, for example vision guidance where the guidance system is based on digital colour video cameras that scan and can recognise crop rows. These can achieve accuracies of +/- 3cm or better. There are also systems that use ultra-sonic sensors to follow guides such as tramlines, drill markers or potato ridges. None of these are currently used widely in conventional combinable crop husbandry, so they will not be considered further in this analysis.

There are two key accuracy specifications for positioning systems: day-to-day (static accuracy) and pass-to-pass (relative or dynamic accuracy). Pass-to-pass generally refers to relative accuracy within a fifteen minute interval, and is the key consideration for most uses on farm where the aim is to carry out equally-spaced parallel passes relative to an initial pass (the A-B line). Static accuracy determines repeatability of positioning over a period of days, weeks or longer, and is most relevant to techniques that require vehicles to return to exactly the same place again and again, such as controlled traffic farming.

Standard GPS is only accurate to 1m or more and is not considered suitable for the types of machine control considered in this analysis. Differential GPS (DGPS) corrects inaccuracies caused by satellite shifts due to distances over which signal are transmitted, to provide sub 1m accuracy. Base-level DGPS systems typically have just a single frequency receiver that uses only the free-to-air L1 band. These low accuracy systems are capable of achieving sub-metre pass-to-pass accuracies, typically 30-40cm at best, and are most suited to operations such as lime spreading and wide cultivations. Dual

frequency receivers, which use both the L1 and (encrypted) L2 bands, provide better compensation for atmospheric errors. Medium level systems, suitable for spraying, drilling and harvesting, allow pass-to-pass accuracies of up to within +/- 10cm. Dual frequency systems can give static accuracies of 1m or less over 24 hours.

Satellite drift and lack of repeatability are the main limitations to normal DGPS systems. To achieve pass-to-pass and static accuracies of +/- 1-2cm requires an RTK (Real Time Kinematic) system. The differential correction signal is provided by a local base station (on tripod near field or barn roof), which comprises a DGPS receiver and radio transmitter to give a correction signal. Uneven land, trees, hills and buildings can cause problems due to poor signal reception in their shadows or the loss of 'line of sight'. Repeaters may be used to help overcome these obstructions.

Entry level systems for guidance usually involve a lightbar display. A row of coloured lights illuminate to show when the vehicle is on the correct (or incorrect) heading. The alternative is a graphic display with lines showing the correct heading and the actual vehicle heading. In both cases the vehicle driver must make steering corrections manually by turning the steering wheel. Such systems can easily be moved from vehicle to vehicle. Assisted steering using a device linked to the receiver/display provides higher accuracy as the steering response is instant, but it still has to be delivered through the vehicle steering wheel which can have limitations. Automatic steering systems which activate the steering valves and use a wheel angle sensor are the most accurate.

Auto-steering can be combined with a headland management system to provide 'total implement control'. The operator specifies the type of turn to be performed and its direction before reaching the headland, and the vehicle automatically changes gear, raises or disengages the implement, turns, re-engages or lowers the implement and returns to its previous working speed.

Regardless of the potential of the system, there may be other limitations to accuracy that need to be considered. Vehicles and implements must be correctly set, with appropriate tyre pressures and ballasting. Terrain compensation is vital on sloping ground, and in some situations it may be necessary to have a second receiver on the implement as well as the vehicle pulling it. Finally operator training is essential to ensure correct use.

Costs and Benefits

Griffin *et al.* (2008) compared four possible GPS-based guidance systems against normal methods of positioning equipment on farm (foam, disc or other visual markers) using a linear programming model. The four systems were lightbar navigation using a +/- 30cm accuracy free DGPS signal, lightbar navigation with a +/- 10cm accuracy subscription DGPS signal, auto-steer with a +/-10cm accuracy subscription DGPS signal, and auto-steer with a +/- 1cm accuracy RTK base station. The model was based on a 1200ha farm in the US growing corn and soybeans, and only considered savings in cultivations. In the absence of GPS, overlaps for cultivation equipment (varying in width from 9.8-12.8m) were considered to be 10%. Overlaps for the GPS-based systems were considered to be equal to their accuracies i.e. 30cm or 10cm, except the RTK system where the overlap was considered to be 5cm. Taking into account increases in work rate, and number of hours per day worked and equipment use hours, and assuming a 10 year useful life for the guidance system equipment, the 10cm auto-steer system was found to be most profitable, followed by the RTK auto-steer system. All systems were more profitable than visual methods. If farm size was increased to take advantage of the saved working hours, the RTK system became the most profitable. Where the system technology and equipment were depreciated over shorter periods, the 10cm auto-steer system was still the most profitable down to a 3 year useful life. If it were assumed that equipment must pay for itself in one year, the 30cm lightbar system was the most profitable.

The cost of manual guidance systems varies considerably, depending partly on the other functions that the system can deliver (for example mapping or implement control). Simple lightbar receiver units typically cost from £1000, and systems based on a graphic display with greater functionality from £1500 (but up to £3000). Systems that achieve pass-to-pass accuracies of up to +/- 20-30cm usually rely only on a free signal. Systems that achieve accuracies of +/- 5-10cm may require a slightly higher cost receiver/display unit (up to £4000) and usually require a subscription to the more accurate signal, which might typically add around £650 per year per vehicle. Alternatively an RTK base station would add about an extra £11000-12000 to the cost.

An assisted steering system is likely to cost around £4000-5000. Fully integrated auto-steer systems are more expensive, nearer £7000. However, larger tractors and combines may have the capability for this included as standard in their specification, which requires

activation only at about half the above cost. The combined costs of a receiver/display unit and steering for a vehicle are therefore likely to be from about £9000 upwards. The addition of a total implement control option is likely to add about £1500 to the cost. Table 4.1 shows likely costs per hectare of guidance systems achieving different levels of accuracy for a 500ha farm, based on two receiver/display units in all cases, one assisted steering unit for the low-medium accuracy system, one auto-steer and one assisted steering unit for the medium-high system, and auto-steer on all three main vehicles (cultivator/drill tractor, combine and sprayer) for the high accuracy (RTK) system. Other assumptions are as outlined in section 3.0. The figures in Table 4.1 assume that the costs are not shared with any other tasks for which the same equipment might be used.

Table 4.1. Likely costs (per hectare) for guidance systems achieving different levels of accuracy for a typical 500ha combinable crop farm

Accuracy pass to pass		DGPS signal and display	Cost (£/ha) on 500ha	Steering method	Cost (£/ha) on 500ha	Total (£/ha) on 500ha
Level	(+/- cm)					
Low	40	Free, lightbar	1.25	manual	-	1.25
Low-med	20-30	Free, graphic	2.75	assist/man	2.25	5.00
Med-high	10	Paid, graphic	6.50	auto/assist	5.75	12.25
High	2	RTK, graphic	9.50	auto-steer	10.50	20.00

The economic benefits from guidance are derived primarily from the reduction in overlaps between passes during cultivation, drilling, spraying, fertilising or harvesting. These benefits are therefore dependent on the extent of the overlaps routinely occurring on the farm in the absence of a guidance system. Table 4.2 shows the likely typical overlaps that might be observed on a farm using normal markers for drilling and tramline operations, based on a 6m cultivator and drill and 24m tramline system, and the overlaps assumed for this analysis when using different accuracy level guidance systems.

The overlaps assumed in Table 2 in the absence of guidance assume an alert, competent operator working in daylight with markers correctly set. The overlaps for the guidance systems assume that the machine width would be set to ensure no misses (underlap) e.g. when cultivating using med-high accuracy guidance the implement width would be set at $(6.0 - 0.1) = 5.9$ m. This would mean that the cultivator should overlap by a 0.2m maximum, with a minimum overlap / underlap of 0.0m, so an average of 0.1m. The

overlap for fertilising and spraying when using tramlines is assumed to be four times the drilling overlap, as each tramline comprises four drill widths in the above example.

Table 4.2. Likely typical overlaps between passes for cultivation, application & harvesting operations, and assumed overlaps with different accuracy level guidance systems.

Operation	Equipment width (m)	Usual overlap		Assumed overlap (m) with guidance			
		(m)	(%)	Low	Low-med	Med-high	High
Primary cultivate	6.0	0.5	8.3	0.4	0.25	0.1	0.02
Second cultivate	6.0	0.5	8.3	0.4	0.25	0.1	0.02
Drilling	6.0	0.2	3.3	0.2	0.2	0.1	0.02
Rolling	12.0	1.0	8.3	0.4	0.25	0.1	0.02
Fertilising (tram.)	24.0	0.8	3.3	0.8	0.8	0.4	0.08
Spraying (tram.)	24.0	0.8	3.3	0.8	0.8	0.4	0.08
Pre-em. spraying	24.0	1.2	5.0	0.4	0.25	0.1	0.02
Harvesting	8.0	0.6	7.5	0.4	0.25	0.1	0.02

Observations on farm by John Deere (Mark James, pers. comm.) and others have suggested that the typical tramline width achieved on farms operating on 24m tramlines is between 23 and 23.5m, but less than 23m has been reported. In trials with a 33m sprayer (Farmers Weekly, 28 February 2008) an experienced operator averaged 5m under/overlapping, or about 15% of working width, with nothing at all to guide the vehicle. Foam markers and flags reduced this to 90cm and 70cm (about 3 and 2% of working width) respectively, manual guidance to 19cm (less than 1%) and auto-steer to 7cm (about 0.2%) average deviation.

It is assumed that vehicles would drive in the tramlines even if the guidance system would allow them to be slightly more accurate. This makes relatively little difference for the most accurate system (RTK), but for the low-med accuracy system the limitation imposed by not reducing drill overlaps and sticking to the resulting tramlines means that the potential benefits (input savings) from this system are not fully exploited.

The reduction in overlaps represents a direct operational saving in fuel, time (labour costs), wear and tear on the vehicle and implement, and an indirect saving in input costs (seed, fertiliser, sprays) through the reduction in overlapped (double-dosed) areas. In addition, there may be a small increase in the machine value at replacement due to

having worked less hours (it is assumed here that the loss in value of a machine at replacement is determined 50% by its age and 50% by the hours worked).

Table 4.3 shows the potential savings in operational costs, loss of machine value and input costs, spread over the entire farm area, which might be achieved on a 500ha farm. The savings are based on a fuel cost of £0.50/litre and labour cost of £15/hour, with other values as outlined in Table I in Appendix A. From this analysis, potential savings range from £2.50/ha with the lowest accuracy (and lowest cost) system to £21.75/ha with the highest accuracy (highest cost) system, giving potential net benefits of up to £2.00/ha.

Table 4.3. Potential savings in operational costs, loss of machine value and input costs with different accuracy level guidance systems for a 500ha combinable crop farm.

Production cost saving	Potential savings (£/ha) with different accuracy levels			
	Low	Low-med	Med-high	High
Operational cost	1.25	2.00	3.50	4.50
Loss of machine value	0.75	1.50	2.25	2.75
Inputs	0.50	0.75	8.50	14.50
Total	2.50	4.25	14.25	21.75
Less system costs	1.25	5.00	12.25	20.00
Net benefit (£/ha)	1.25	-0.75	2.00	1.75

The costs per hectare and therefore net benefits for each accuracy level alter with farm size, the chosen equipment/system and assumed overlaps/accuracies.

Fig. 2 illustrates the effect of farm size (within the range 100-1200ha) on the cost per hectare of different accuracy level guidance systems as outlined on page 25 but comprising either one, two or three DGPS receiver / display units. Where these are part of the system, the number of auto or assisted steering units is unchanged (*i.e.* none for low, one for low-medium, two for medium-high and three for the high (RTK) accuracy systems). Where the cost curve meets the benefit line, this represents the minimum farm size required for that system to cover its cost. Where the cost curve is below the line, the vertical distance between the curve and the benefit line is therefore the benefit over cost.

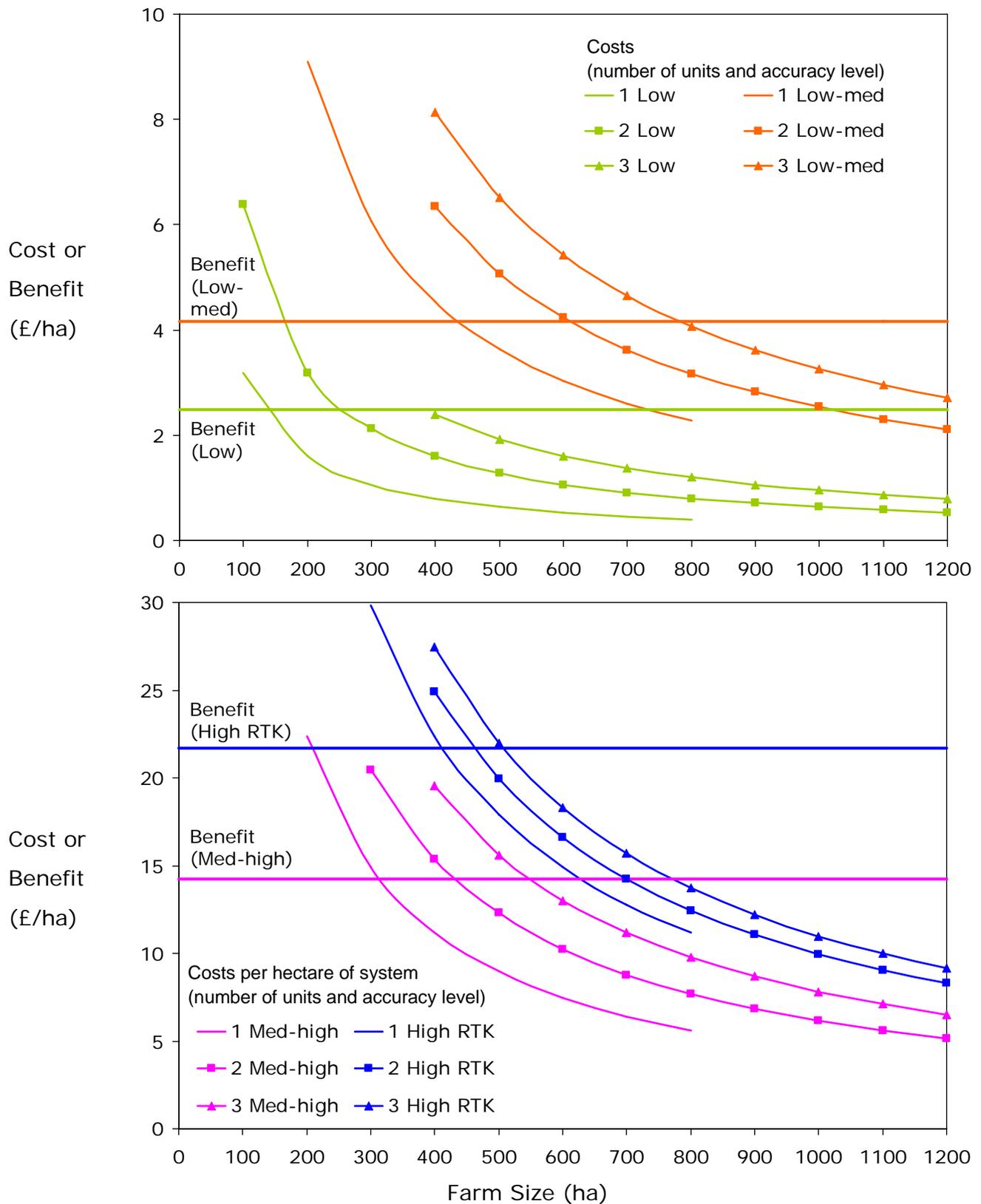


Figure 2. Effect of farm size on costs per hectare compared to benefits of guidance systems with differing levels of accuracy and comprising 1, 2 or 3 receiver units.

For combinable crop farms of less than about 400-500ha, a high accuracy RTK system is unlikely to be cost-effective. For 300ha or less the lowest accuracy system may be the only one that would cover its costs. Within the range 400-800ha, the most profitable option will depend partly on the number of units that are required.

Fig. 3 illustrates the effect of number of years after which the guidance equipment is replaced (not necessarily the machines themselves) on the cost per hectare for different accuracy level systems comprising two DGPS receiver/display units. Value at replacement is assumed to be 15%, such that the straight line depreciation rates represented by each replacement period are as shown in brackets beneath the number of years. If equipment is replaced after less than 4 years with a residual value of only 15% at that stage, then only the lowest cost (and accuracy) system is likely to give a benefit over cost.

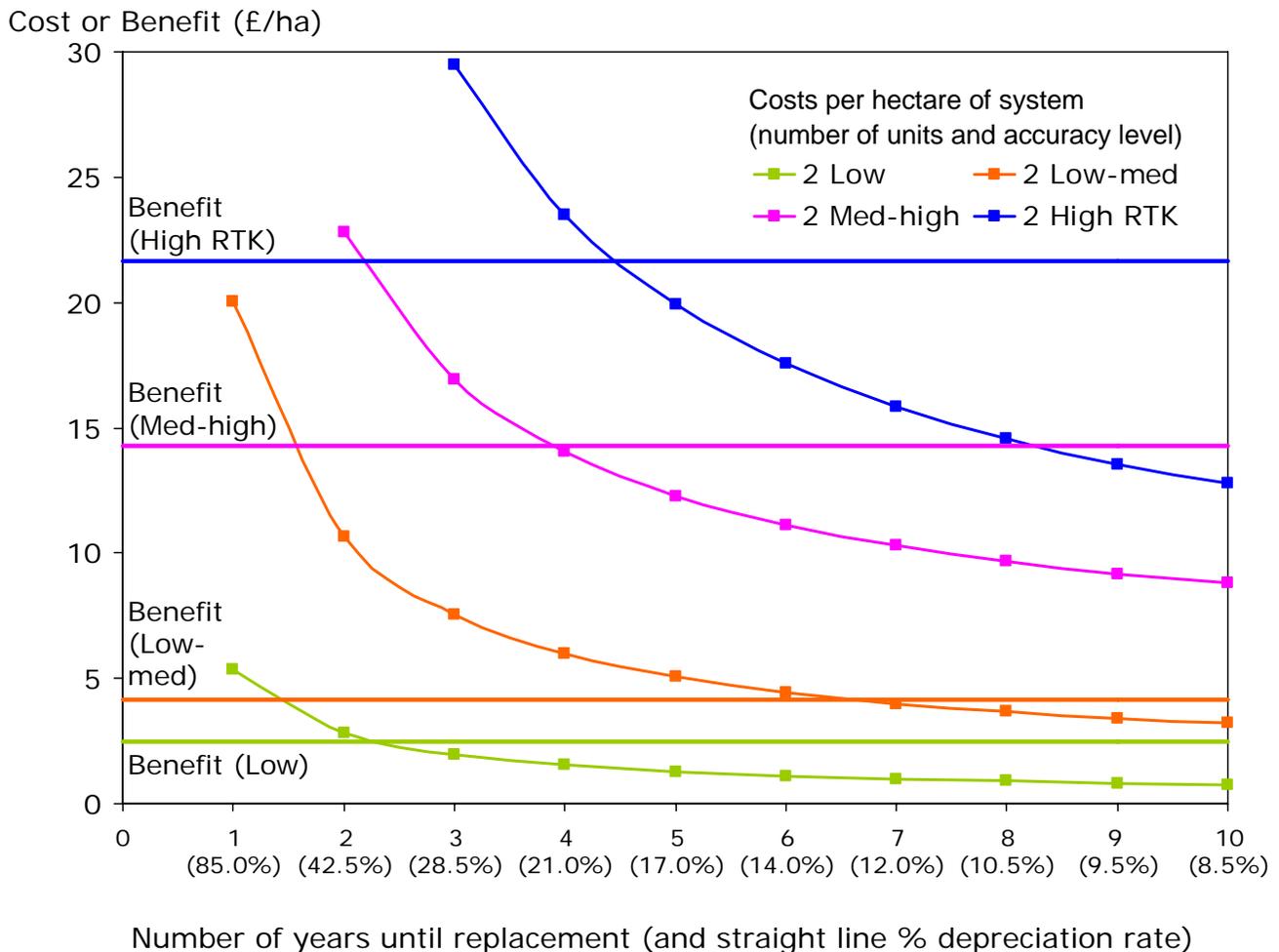


Figure 3. Effect of number of years until replacement (or depreciation rate) on cost per hectare compared to benefit of guidance systems with differing levels of accuracy.

Fig. 4 illustrates the effect of the existing accuracy of cultivation, application and harvest operations (*i.e.* the extent of overlaps) on a farm, on the potential benefits per hectare from using the four different guidance systems. Where the sloping benefits line is above the horizontal costs line, the vertical distance between the two represents the likely benefit over cost for that system. 'Average' existing accuracy is based on the usual overlaps shown in Table 4.2. 'Good' assumes usual overlaps of 0.4m for cultivations, 0.15m for drilling, 0.6m for spraying/fertilising in tramlines and 0.45m for harvesting. 'Below average' assumes usual overlaps of 0.6m for cultivations, 0.25m for drilling, 1.0m for spraying/fertilising and 0.75m for harvesting. 'Poor' assumes usual overlaps of 0.75m for cultivations, 0.3m for drilling, 1.2m for spraying/fertilising and 0.9m for harvesting.

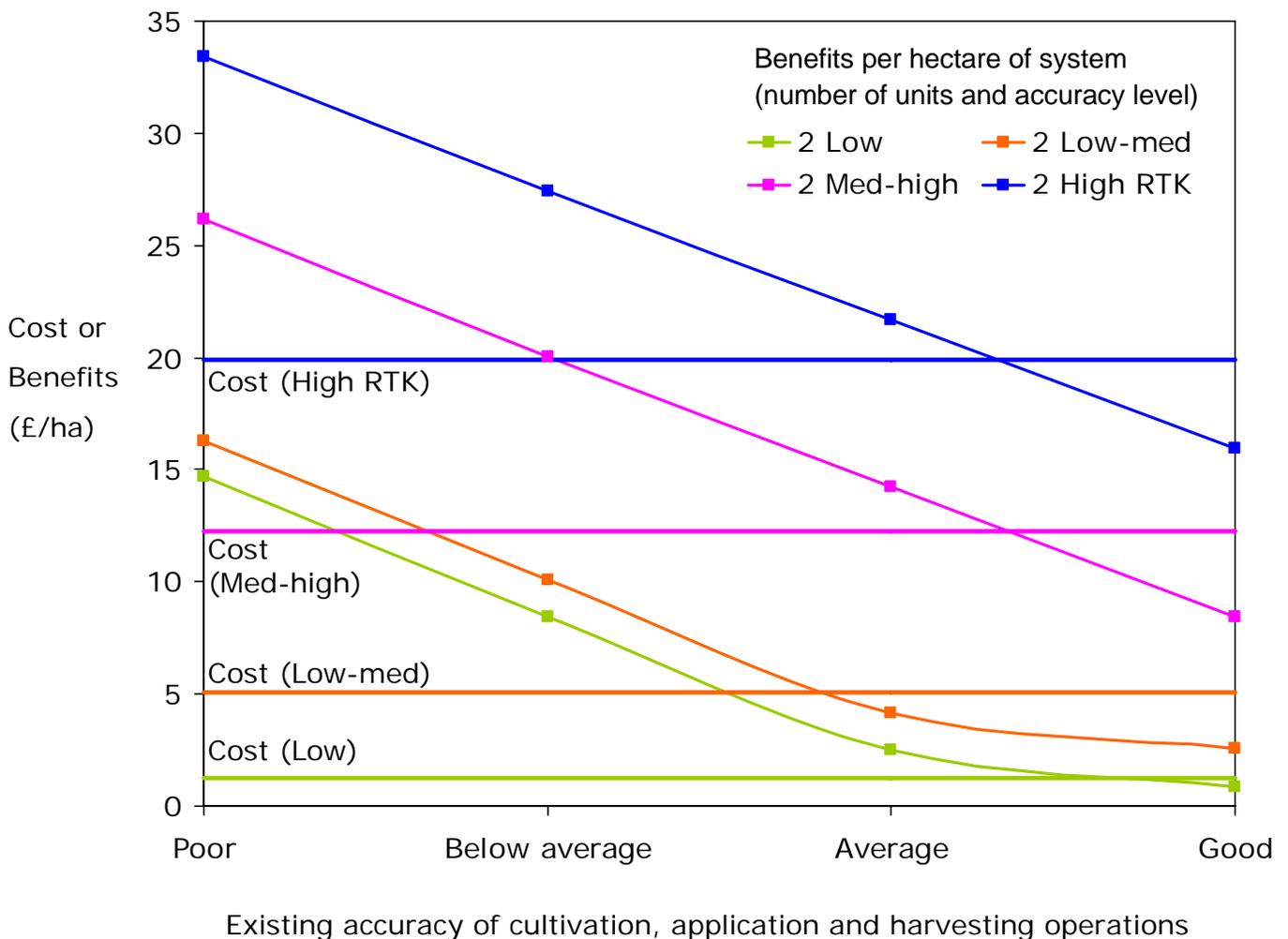


Figure 4. Effect of existing accuracy of operations on farm on the potential benefits (over costs) per hectare of different guidance systems.

For all of the guidance systems, the potential benefits over cost increase sharply as the usual accuracy on farm decreases below the 'average'. However, with the exception of the lowest cost guidance system, the potential economic benefits also quickly disappear where the usual accuracy on farm is better than average.

An analysis of the costs and benefits of guidance by CTF Europe (Crops, 9 February 2008), also based on a 500ha combinable crop farm in the UK, suggested overlap savings of about £16/ha with a +/-10cm accuracy guidance system and auto-steer, which is comparable with the medium-high accuracy system in Table 4.3. However the capital cost of the system (around £16500) was slightly lower than that assumed for this analysis in Table 4.1 (around £21000) due to the inclusion of a second receiver/display unit. The overlap savings from a high accuracy RTK system in the CTF Europe calculation were estimated at £18/ha, again comparable with the same system in Table 4.3. The capital cost of the system, at around £29000, was again lower than that assumed in Table 4.1 (nearer £40000), mainly due to the inclusion in this analysis of a second receiver/display unit and a third auto-steer unit.

It should be noted that the costs in Table 4.1 and 4.3 assume that the equipment is used only for guidance, and therefore all of its costs are allocated to this task. With the exception perhaps of the lower cost/specification guidance unit assumed for the lowest accuracy system, other techniques could make use of the same equipment for mapping, applications or other machine control tasks. This would reduce the costs associated with guidance alone, and increase the net benefits. Examples of this are given in section 11.2. The ability to very accurately re-position equipment in a field after an interval of days or weeks, which only an RTK-based system provides, may be essential on farms where controlled traffic farming has been adopted (see section 4.2) or for strip tillage (Overstreet, 2009; Morris *et al.*, 2007) where there is a mismatch between the number of rows on the cultivator and the drill.

Additional savings and benefits could be derived from increased operator flexibility, the ability to carry out operations at a faster forward speed without loss of accuracy (this may not be fully achievable with manual guidance, especially with wide machinery), or extending the working day (lack of daylight being less of a problem). Saved time not only means a reduction in labour cost, but also an increase in timeliness, which could allow

fieldwork to be completed in optimum conditions (avoiding potential loss of yield in late established crops) or allow doses of crop protection products to be maintained at the optimum level for well-timed applications. Table 4.4 shows the potential saving (in hours) per year for a 500ha farm, with either no increase in forward speed or a 6% increase, assuming that 25% of time is spent turning or filling and that this is no quicker.

Table 4.4. Potential annual saving in working hours with different accuracy level guidance systems for a 500ha combinable crop farm, working at normal or increased speed.

Forward speed	Potential savings (hours) with different accuracy levels			
	Low	Low-med	Med-high	High
Same forward speed	13	24	40	51
Increased speed	(51)	(62)	78	88

Reduced working hours for machines also translates to reduced fuel usage (Table 4.5). Not only does this form part of the cost savings included in Table 4.3, but environmental benefits can be inferred through energy saving and reduced greenhouse gas emissions. Auto or assisted steering also allows the vehicle operator to focus more on optimising machine performance instead of steering it, which could lead to higher efficiency of work.

Table 4.5. Potential fuel saving with different accuracy level guidance systems for a 500ha combinable crop farm (the cost savings have been included in Table 4.3).

Potential fuel savings (litres) with different accuracy levels			
Low	Low-med	Med-high	High
500	950	1550	1900

Part of the cost saving obtained through the use of guidance (and included in Table 4.3) is through the reduction in overlaps (Table 4.6) when applying spray and fertiliser inputs, and when sowing. For the lower accuracy systems, it is assumed that the tramlines created when drilling will be used for applying post-emergence inputs. As there is no reduction in drill overlaps with these systems, input savings are small and restricted to those applied pre-emergence (assuming that drill-mounted tramline markers are not used). For the higher accuracy systems, where drill overlaps are reduced, there are reductions in input use for both pre- and post-emergence (using tramlines) applications, although the savings are slightly greater without tramlines as the accuracy is not then constrained by the tramline widths.

Table 4.6. Potential annual saving in inputs applied, and reduction in the area double-dosed (excluding headland / field edge effects), for a 500ha combinable crop farm.

Input Application Operation	Potential savings (%) with different accuracy levels			
	Reduction in inputs		Reduction in double-dosing	
	Med-high	High (RTK)	Med-high	High (RTK)
Spraying/fertilising using tramlines	1.7	3.0	50	90
Spraying/fertilising without tramlines	4.6	4.9	92	98

From an environmental perspective, the reduction in the amount of overlap or 'double-dosing' is particularly important, as this may represent areas that are at greatest potential risk of losses or adverse impacts.

4.2 Controlled Traffic Farming (CTF)

CTF was initially developed in the 1970s and 1980s when it was proposed that it would be delivered by powered gantries. These machines have not proven practical although there is one farmer in Bedfordshire who has persevered with them. More recently CTF has been adapted to current farm equipment through sharing the same wheelways for cultivations, drilling and spraying. Combine harvesters are on a wider wheelbase but one wheel can be in a main spray tramline wheelway or in one track of the intermediate wheelways that are necessary for cultivations and drilling.

The likely advantages of CTF are better soil structure, water infiltration rates (less erosion) and less draught requirements leading to higher yields with reduced cultivation costs. These have to be balanced against the cost of marking the intermediate wheelways, ensuring matched equipment is purchased and the cost of maintenance of the permanent tramlines. These permanent tramlines could increase pesticide movement to water. CTF benefits from the precision location and steering possible through RTK guidance. This reduces the amount of initial marking out and ensures that traffic is restricted to the main wheelways (tramlines) and intermediate wheelways that are only used for cultivations, drilling and harvesting.

There has been little research done in Europe on CTF, when adapted to currently available farm equipment, but a demonstration project in Bedfordshire is claiming improved margins. These may increase over time should it enable the sustainable adoption of shallow cultivations with light equipment. This will result in increased organic matter in the surface layers of the soil, leading to more flexibility for cultivations and drilling. In addition, research in Australia has indicated improvements in sub-soil structure after five years of CTF (Radford *et al.*, 2007). However, it should be borne in mind that many Australian soils are fragile and soil drying may have more impact than in the UK. Subsoil compaction will still occur under the main and intermediate wheelways unless axle weights of above 8 tonnes are avoided (Hamza & Anderson, 2005).

Costs and benefits

Based on yield data (assessed using the bread-knife technique) generated by a CTF project at Colworth in Bedfordshire, the yield advantage in non-inversion tillage to controlled traffic after the 4 years of adoption on a Hanslope Clay is shown in Table 4.7.

Table 4.7. Yield advantage to controlled traffic after 4 years on Hanslope clay

Field area	Crop	% change in yield compared with trafficked non-inversion
CTF bed	Winter Wheat	+ 30
	Spring Barley	+ 43
CTF traffic intermediate lane*	Winter Wheat	- 21
	Spring Barley	- 9

* It is assumed that losses along the main tramlines are similar

An ongoing study (unpublished) in Norfolk on a lighter Ashley series sandy loam over clay soil, and where the treatments were imposed on 100% of the plot area, produced the following yields in winter wheat in the first year (Table 4.8). The site was sub-soiled immediately prior to the experimental treatments being imposed in autumn 2007.

Table 4.8. Effect of trafficking on fertile tiller number and yield in winter wheat in Norfolk.

Treatment	Fertile tillers (m ²)		Yield (t/ha)	
	Shallow tillage (5-15 cm)	Deep tillage (15-25 cm)	Shallow tillage (5-15 cm)	Deep tillage (15-25 cm)
Zero traffic	444	467	12.52	12.56
Normal traffic	345	362	10.84	10.79
Tracked traffic	378	377	10.45	11.00
Zero traffic with tracked combine	439	434	12.14	11.38
Zero traffic with wheeled combine	367	423	10.77	11.37

Normal traffic represented all cultivation and harvesting traffic (*i.e.* intermediate wheelways). There were also treatments where the additional impact on zero-trafficked soil of the combine harvester was measured. The yield differences did not appear to be as extreme as those recorded at Colworth. However benefits of CTF are difficult to calculate from this data because the normal traffic was imposed on all the plot area and this would not be the case in reality.

The data from both sites suggests where the land is not ploughed that zero traffic can not only lead to overall yield increases but also the more sustainable use of shallow tillage. In the short term, overall yield increases from CTF in the order of 2-5%

(depending on soil type, current standard of soil care and the number of intermediate wheelways *i.e.* the width of the primary cultivation system and the drill) appear to be feasible on most soil types, in addition to the prospect of more sustainable shallow tillage and improved water infiltration rates. Based on an average yield for 8.0 t/ha for winter wheat this would increase returns by £16-40/ha (with wheat at £100/t) in addition to a likely reduction in cultivation costs. The additional costs of CTF are minimal, provided that the appropriate machinery are purchased within their normal replacement cycles and that the cost of RTK can be justified by improvements in work rate and reductions in input costs (avoiding overlaps). However, the width of the cutter bar of the combine appropriate to the size of the area of crop to be harvested may be incompatible with the distances between wheelways established for the other field operations. This could result in reducing the yield benefit of CTF or compromising the harvesting operation. This is a key issue which needs to be carefully considered when the introduction of CTF is being considered. Combine harvester manufacturers are aware of the issue and some plan to introduce cutter bar widths that will be compatible with some inter-wheelway distances.

4.3 Auto-Section Control

Costs and Benefits

Automatic boom section control enables the GPS location of sprayed areas to be recorded, and automatically turns off one or more sections of the sprayer boom when it overlaps an area that has already been sprayed. It then turns the boom section(s) on again when it re-enters an area that has not yet been sprayed. Auto section control can be added to most guidance systems, or comes as standard in some. The typical cost of adding auto-section control to a standard receiver/display unit is around £1500, which with other expenses would equate to an annual cost of less than £1/ha on a 500ha farm.

Estimating the economic benefits from auto-section control is difficult, as the reduction in spray usage will vary from farm to farm and field to field according to field shapes/sizes and procedures for turning on and off at field edges and on headlands. In experiments by Shockley *et al.* (2008) in the USA on three small (c. 3-9ha) fields that were particularly narrow and odd-shaped, the area covered when applying liquid fertiliser and pesticides was reduced by an average of 36% compared to a lightbar guidance system alone, or by 33% compared to an auto-steer guidance system. Reductions of this magnitude, or even

the 20% recorded by Dillon *et al.* (2007) for herbicides alone (in larger fields), are undoubtedly unrealistic for the majority of situations in the UK. However if a saving of 0.5-1.0% of the spray quantity used on a typical 500ha combinable crop farm could be made, this should cover the annual cost. A 2% saving in spray usage could potentially result in a net benefit of £1-2/ha. A grower using auto-section control is reported to have saved £3500 in agrochemical cost on 4000ha, which would equate to a saving (before cost) of just under £1/ha (Farmers Weekly, 14 December 2007).

In addition to auto-section control, some guidance systems can also be linked to spray boom height controllers or self-levelling mechanisms. Fertiliser spreaders that have electronically-actuated spread widths could also be used in conjunction with a suitable guidance system to reduce overlapping or overdosing with fertiliser, especially on headlands and around obstacles.

5.0 Assessment of Variation

Most measurable site, soil or crop parameters show variability. Variation within a field will often be greater than the difference in average between fields. Nevertheless, the factors that cause variability within a field are usually no different to those that cause variability between fields, and most growers will be well aware of what these are. Where there is significant variation within a field, spatially-variable management using precision farming techniques is more likely to be justified and give quantifiable advantages than where fields are more uniform. However it is also important to identify whether or not that variation is likely to affect yield, economic performance, input management or environmental impact.

The specific causes of variation need to be defined and quantifiable measurements made without too much difficulty. A key consideration therefore is how to achieve this and the costs involved in doing so. There are a number of approaches that can be used to obtain an initial assessment of variability within fields and the extent and cause of the variation, at little or no cost. These include:

- Noting differences in crop growth or weed patches during crop walking
- Identifying problem areas (rabbit damage, waterlogging etc.)
- Digging soil pits in good and bad areas of fields
- Accessing free low-resolution satellite images of the farm from previous seasons on the internet
- Reviewing field histories to identify previous boundaries, splits or amalgamations
- Talking to neighbours with similar soils/cropping who have mapped fields

Having established that variability exists within fields on the farm, these can then be assessed in more detail from the perspective of the soil, crop growth or crop yield.

5.1 Soil Mapping

Bourennane *et al.* (2003) showed that the scale of variation in wheat crop yield could be related to that of the soil properties. The availability of, or requirement for, certain crop inputs may also be partly dependent on variation in soil properties. The most common commercial approach to examining variation in soil properties within a field is to map apparent Electrical Conductivity (ECa). This is usually done by means of non-invasive

Electromagnetic Induction (or EM38) mapping. There may be some soil damage as a result of having to travel on the land when at field capacity. Invasive meters that use tines to penetrate the soil are best suited to use on crop stubbles. Electrical conductivity is primarily a function of soil moisture and clay content, such that if mapping is done when soils are at field capacity this can be used to provide an indication of variability in soil texture (Waine *et al.*, 2000). However, the relationship between ECa and soil properties is complex (Frogbrook *et al.*, 2003). King *et al.* (2003) found that subsoil clay and organic matter contents, and topsoil sand, organic matter content and bulk density were key factors affecting ECa. Mapping does not substitute for sampling the soil, but it helps to define boundaries within which soil pits can be dug or cores taken to determine how the actual soil properties differ.

Costs and Benefits

Soil texture mapping based on ECa is currently offered as a commercial service, typically costing £8-12/ha (Simon Griffin, pers. comm.). The technique should only need to be done once, so the cost can be spread over the lifetime of cropping a field. If it is assumed that the cost is spread over 10-15 years, allowing for other expenses, this would equate to a cost of about £1-1.50/ha (independent of farm size). There are no direct benefits, but the information gained can be used to target other inputs or actions.

5.2 Yield Mapping

The assessment of variation within a field should ideally be simple and automatic. Mapping crop yield and quality as the crop is harvested has the advantage of being rapid and data intensive, whilst identifying and recording variation that could be economically important. Two types of variability are important when considering yield maps: spatial trends and temporal trends. Together these can be used to determine areas of high and stable yield, low and stable yield and unstable yield. With wide rotations involving multiple crops, this may require 10 or more years of yield map data. Studies by Lark *et al.* (1999) used pattern recognition methods to analyse a sequence of yield maps and identify field areas that were likely to behave in a consistent manner across seasons (and therefore potentially justify spatially variable management).

A major cause of temporal variability within yield maps is likely to be the interaction between variation in soil type and the seasonal weather. Having good farm weather data

is therefore very important, and will have an additional cost attached. Yield maps tend to be more variable and informative in years with more yield limiting factors (Simon Griffin, pers. comm.). Key stages in the production of usable yield maps from raw data include recognising errors, analysing the variation and defining the lowest meaningful differences between yield zones. This is likely to be a minimum of 5-10% of the field average yield for cereal crops (0.5 t/ha).

Costs and Benefits

The cost of adding yield mapping capability to a combine is typically around £3000-4000 for a retro-fitted or factory-fitted system (assuming that the combine already has yield metering capability). Allowing for other costs, the typical cost per hectare for a 500ha combinable crop farm is likely to be around £3/ha, assuming no other use for the GPS receiver/display unit. However if the latter can be used for other tasks, this could potentially reduce the cost to less than £2/ha.

As with soil texture mapping, it is difficult to assign an economic benefit per hectare to yield mapping per se, as the benefit is in the value of the information obtained. The more uses to which the information can be put, the lower the cost for each specific use. A key benefit is to identify yields trends across fields or levels of variation within (and between) fields. Yield maps can also be used to confirm differences in crop growth seen with earlier remotely-sensed images, identify and target problem areas for further investigation, or to assess the outcome of variable treatments or on-farm trials. Yield maps are not a good indicator of nutrient supply, but they do provide a useful guide to offtake. Even for offtake though, it may be better to use yield trends rather than a single year yield map.

Historically growers have found soil maps more useful in making management decisions than yield maps. For example, a survey of Danish and US farmers (Fountas *et al.*, 2003) found that 49 and 52% respectively of growers found soil sampling maps very useful in making management decisions, compared to only 16 and 33% for yield maps. 10 and 12% respectively found yield maps of no use, compared to 0 and 2% respectively for soil maps. However in the USA growers who had been collecting yield data for more than 5 years generally found it more useful than those who had been collecting for 1-4 years. This lack of value seen in yield maps could be due to lack of spatial variability in their fields, temporal variability or lack of training in how to understand and utilise the data.

5.3 Remote Sensing of Crop Structure

Variability within a field that is related to site or soil features will often be apparent from the growing crop, through variable biomass or colour. Both of these can be measured with sensor technologies (remote sensing). Each surface has a unique spectral reflectance spectrum, with for example cereal canopies reflecting mainly near infrared, which can be used as a measure of canopy size (height, density or green leaf area), and (visible) green light, used as a measure of canopy colour (chlorophyll content).

Satellites capable of measuring reflectance have been operational for about 30 years. Sensors mounted on ground-based vehicles (such as the Yara N-Sensor) or aircraft (known as Aerial Digital Photography or ADP) were developed during the 1990s. Other examples of vehicle-mounted systems include CropCircle and GreenSeeker. CropCircle is available as a single or multiple sensor system mounted on a sprayer or spreader boom, or on folding arms mounted on the front of a tractor.

There are a number of differences between reflectance-based remote sensing systems. Satellites collect large amounts of information quickly as their field of view is large, but spatial resolution is lower (typical pixel size of between 10 and 32m). The main commercial service provided in the UK uses a 30m resolution, as this is currently considered to provide the best balance between cost and benefit, and the ability to acquire data on a daily basis (Griffin, 2008b). One drawback is that around the outside edge of a field part of a pixel might lie beyond the field boundary, so this has to be accurately recorded using DGPS in order to exclude these pixels. Aircraft can also capture large amounts of data quickly, with the amount and quality depending on the height of plane. Vehicle-based systems can capture data at higher resolution due to their proximity to the crop, but may only examine a relatively small proportion of the crop. The four sensors used by the Yara N-sensor for example scan the reflection from an area of about 50m² (each second).

Satellite and (to some extent) aircraft-based sensors are limited by their inability to capture data in cloudy conditions. Vehicle-based sensors can operate in cloudy conditions, but most still rely on the sun to light the crop, so sun angle and cloud cover can have an effect. Some systems can correct for climatic changes during image capture (the N-Sensor has a fifth sensor that adjusts for available light), others can generate

their own light to illuminate the crop when the sun is low in the sky or at night, for example CropCircle or the Active Light Source (ALS) version of the N-Sensor. Satellite or aircraft sensors tend to capture only a limited range of wavelengths. Some systems (such as the N-Sensor) can capture a wider range. Active sensors usually capture fewer wavelengths than passive sensors as it is difficult to get enough light for multispectral measurement.

Systems that are based on remote-sensed images from satellite or aircraft enable input applications to be adjusted in near real-time only, as data must be captured, processed and run through a model to generate an input application map. Vehicle-mounted systems can enable inputs to be adjusted in real time, as data collection, interpretation and input application happen in one pass. The final output from satellite-based systems is typically an application map based on absolute levels of input. Vehicle-mounted systems are often based on varying the input dose around the field average, or a specific in-crop calibration may be used to translate the crop canopy information into a variable input dose.

Scotford & Miller (2003) found that ultrasonic measurements can be used to measure wheat crop height, and provide a measure of crop density (or gaps in the crop canopy), particularly before GS45. Scotford & Miller (2005) also showed that a tractor-mounted sensing system using both radiometer and ultrasonic sensors could be used to assess tiller numbers and Leaf Area Index of wheat. Crop structure can also be determined by optical (LIDAR) or RADAR systems or the crop deflector principle. Ehlert (2003; also Ehlert & Dammer 2006) used a tractor-mounted pendulum-based mechanical sensor (or Crop-meter) to detect differences in relative cereal crop biomass.

Costs and Benefits

Crop canopy maps based on remote sensing by satellites are available as a commercial service from SOYL. The typical cost for at least three whole farm GAI maps ranges from £700-1300, depending on farm size (Simon Griffin, pers. comm.). The cost for a 500ha farm would be around £1000 (or £2/ha). Vehicle-mounted sensor systems can often be purchased or rented. The cost of a standard Yara N-Sensor starts at about £13000. With an allowance for other costs, the typical annual cost for a 500ha farm would be around £6.50/ha. The rental cost would be about £4500 per year, equivalent to around £9/ha for the same farm. An ALS N-Sensor typically starts at around £21500, or from £6500 per

year to rent. The cost of the CropCircle boom or arm-mounted sensor system typically starts at around £3000.

The main use (and therefore benefit) of remote-sensed information on crop structure variation is as a basis for varying the application of N fertiliser. However, the same information could also be used to guide variable rate applications of:

- Plant Growth Regulators, with treatment varied according to lodging risk (assessed by shoot density or canopy size)
- Crop desiccants, with treatment varied according to biomass or crop maturity
- Fungicides, with treatment varied according to the leaf area needing protection

It could also be used simply to provide in-season vigour maps to identify and quantify crop growth restrictions or crop damage within fields, or to identify differences in growth between fields. The potential benefits and likely specific costs associated with variable rate applications of N and PGRs will be considered in sections 8.2 and 9.1 respectively.

5.4 Combining Assessments of Variation

Ideally site specific management within a field should take account of information on spatial variation in a range of soil and crop parameters, through the creation of management zones. Several researchers have used yield to identify management zones. Lark *et al.* (1999) found a clear relation between variation in yield and soil series and individual soil physical properties. Frogbrook *et al.* (2002) showed that the scale of variation in yield often occurred on similar order of magnitude to that for soil. King *et al.* (2003) suggested that ECa and expert site assessment should be used in addition to yield to determine potential management zones. However Ehlert *et al.* (2003) found that the correlation between pendulum-based measurements of canopy size and ECa were poor and field-specific, and correlations between the measurements and grain yield were also weak due to straw yield being more variable than grain yield.

6.0 Managing Limitations to Crop Performance

6.1 Responding to Variation

Having established that variation exists, and mapped it, the most appropriate response to that variation must then be determined. Key questions to then consider include:

- Can worthwhile actions be taken?
- Are these actions likely to improve performance?
- Can the results be monitored?

A first step might be to try to remove or reduce yield limiting factors and increase the average level of performance within the field. The simplest way of doing this is by not cropping the poorest areas of fields, which would not require further use of precision farming techniques. In some situations though, the same outcome may also be achieved by applying remedial treatments to poor performing (low yielding) areas. These may for example result from crop damage caused by waterlogging or rabbits, or areas of low pH or compaction. Having done whatever possible to minimise the amount left, remaining variation (resulting for example from differences in soil properties that cannot be eliminated) can then be managed on an annual basis (Fig. 5).

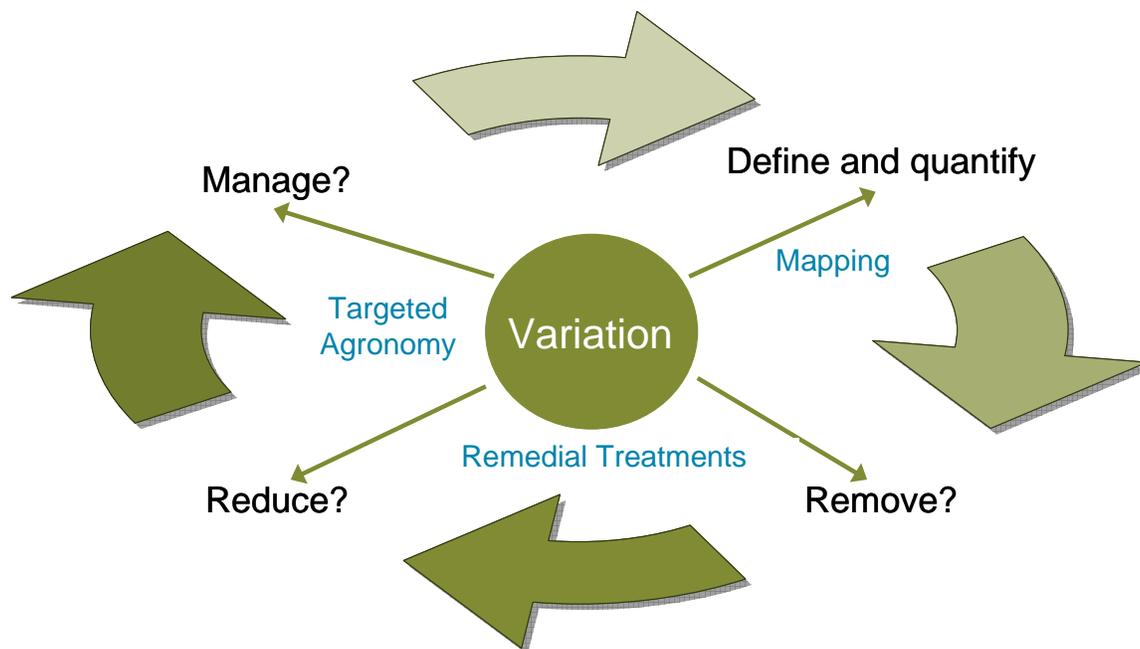


Figure 5. Responding to within-field variation

McBratney *et al.* (2000) defined a management 'opportunity index' for site-specific crop management. This was based on yield monitor data, and accounted for the magnitude of yield variation (relative to a threshold), the spatial structure of variation relative to the minimum area within which variable rate controllers can effectively operate, and the economic (and environmental) benefit of site-specific crop management compared to uniform management. Yield map data could be supplemented with indicators of potential variation in yield *e.g.* crop canopy or soil type, and maps of opportunity index created.

Measurement of improvements in crop performance resulting from changes in management may be difficult in the short term. On-farm strip-type comparisons or trials can be used to identify possible impacts within a field, although they may not fully demonstrate or evaluate the potential benefits from whole-farm adoption. Yield mapping is important in achieving this, both in locating the most suitable layout or arrangement for the strips, and in measuring the yield responses to the different treatments used.

6.2 Targeted Actions to Reduce Crop Damage

Three common causes of patchy poor crop growth and low yield are damage by rabbits, waterlogging and uneven N fertiliser application. Mapping crop canopy growth or yield can enable these to be identified, quantified and targeted. Precision farming enables the scale of the problem and size of the penalty in yield (and output) to be determined, and an informed decision to be made as to whether or not it would be cost-effective to try to remedy the problem. The outcomes would hopefully be more uniform crop growth, and a reduction in the yield penalty in the previously-affected areas.

Godwin *et al.* (2001) reported two such instances encountered during field studies. At one site, a yield reduction of 3 t/ha was indicated in part of a winter wheat field following a wet winter. Based on the value of wheat at that time (£65/t), and an estimated cost of £50/ha for re-moling the site and clearing blocked drain outlets, the net benefit in one year alone would have been £145/ha. At another site, uneven distribution of N fertiliser that had absorbed moisture resulted in a yield penalty in winter barley of up to 1 t/ha.

6.3 Targeted Actions to Reduce Compaction

Another potential cause of low yielding patches might be compaction. Where no 'above-ground' explanation can be identified, digging soil pits or making manual penetrometer

measurements in high and low yielding areas that are targeted using a yield map may identify this as a cause. If so, sub-soiling can be carried out in affected areas to alleviate the problem, and hopefully reduce the yield penalty.

Various approaches to mapping compaction have been investigated. These include the recording of draught force (due to soil mechanical resistance) through draft-sensing pins in the three-point linkage when carrying out deep-cultivation operations. However to achieve this, the draught control system has to be immobilised making it impractical as a commercial option. The use of ECa soil mapping to distinguish between different levels of soil compaction has been attempted commercially (Smith, 2001) however this may only be of value where the patterns seen can be related to known areas of trafficking.

As an alternative method of identifying variation in compaction, use of an ATV-mounted cone penetrometer has been evaluated (Griffin, 2008a). Penetrometer resistance was measured every 2.5cm down to 60cm depth on a 25m grid within a field. A compaction profile was generated at each point, and maps produced at depths of 0-15, 15-30, 30-45 and 45-60cm, based on the mean for all readings taken at that depth. Soil pits were dug to visually inspect soil structure, and it was concluded that subsoiling was unnecessary where the recorded resistance was less than 100psi, and was definitely needed above 400psi, such that (in this field) inspection to calibrate the maps was only necessary between 100 and 300 psi. However, it should be noted that these same values may not apply across different sites, especially where there are differences in soil moisture.

Maps were then used to provide visual (and audible) prompts to the operator to raise and lower the subsoil when moving in and out of areas requiring subsoiling (although this could be automated). Averaged over four fields (100ha) only 55% of the area was found to require subsoiling. Based on an estimated subsoiling cost of £50/ha, potential savings were estimated at £20-25/ha. The cost for a compaction mapping service was estimated separately at around £12/ha (Farmers Weekly, 28 March 2008).

Assuming that the benefits from subsoiling last for three years (after which fields would need to be compaction mapped again), if 50% of fields on a 500ha farm have yield variation, and half of the low yielding areas within these fields are due to compaction, then reducing the yield penalty by half in these areas could potentially be sufficient to

cover the cost of the compaction mapping and subsoiling. If the yield penalty could be reduced by three-quarters in the affected areas, the costs could potentially be recouped if only a quarter of the low yielding areas are due to compaction.

6.4 pH Mapping and Targeted Lime Applications

Low pH can limit yield in sensitive crops such as barley, although sometimes variation in pH may simply be a consequence of variation in soil type or depth such that raising the pH in patches that are low may not remove or reduce yield variation. Determining areas of low pH could be achieved by targeted soil sampling and pH testing in low yielding areas identified from a yield map (for a barley crop), or from soil analysis as part of grid sampling for other nutrients (P, K or Mg). The costs associated with precision soil nutrient sampling techniques will be considered in section 8.1. Based on yield measurements at one site, Godwin *et al.* (2001) estimated the cost of failing to rectify patches of low pH in a field of winter barley to be up to £7/ha.

6.5 Targeted Agronomy

Whelan & McBratney (2000) defined the aim of site-specific or targeted agronomy as being to 'match resource application and agronomic practices with soil attributes and crop requirements as they vary across a site'. If the optimum rate of an input varies significantly at an appropriate scale within a field, then there may be economic benefits from spatially varying its application rate. If the rate of application is more closely matched to crop requirement, this is likely to result in an environmental benefit.

The more 'precise' the information available, the greater the opportunity to match the dose applied to the crop need. However, 'precise' in this context refers to resolution not accuracy, and measurements of crop or soil parameters will only help decision making if there are robust agronomic decision rules for that aspect of crop management. Another important consideration is the scale of the variation in crop requirement compared to the minimum application (spread/boom) width for the input. In most cases technologies in current commercial use do not allow product rates to be varied across the application width of the machine. At the opposite end of the scale, in some cases all that will be necessary is to treat one or two parts of a field differently to the rest. This could be achieved by manually-triggered adjustment rather than with variable rate technology, achieving similar benefits but at little or no additional cost.

7.0 Crop Establishment

Any attempt to reduce variability in crop structure should ideally start with establishment. Differences in seedbed quality (cloddiness), as a result of variation in soil texture within a field, are likely to result in differences in crop establishment and therefore variable plant and shoot populations. It is important to determine the cause of any low plant or shoot populations: poor establishment, plant survival, tillering or tiller survival. Depending on the cause, actions needed may be different (more seed, more slug pellets etc.).

7.1 Seedbed Quality and Variable Seed Rates

Varying the seed rate used at drilling is potentially a way of compensating for variable establishment, but this technique has developed relatively slowly compared to other precision farming technologies. Sensor systems have been evaluated (e.g. Scarlett *et al.*, 1997) that are capable of directly detecting differences in seedbed cloddiness, and which could potentially be used to vary seed rates on-the-move. In practice however soil texture maps based for example on ECa mapping or physical soil surveys are more likely to be used to identify zones that are likely to have a cloddier seedbed (heavy/clay patches) and therefore a lower % establishment, and those that are likely to have better seedbeds (lighter patches) and therefore a higher % establishment. Targeted inspections of field zones post-cultivation and pre-drilling can be done to confirm this.

Costs and Benefits

The cost of ECa mapping was calculated in section 5.1 to equate to about £1-1.50/ha per year. However if this was being done anyway in order to improve knowledge of soil texture variation on the farm, it would be reasonable to allocate only a half share of the cost (£0.75/ha). The capital cost of adding a variable seed rate controller (assuming that the seed drill is already fitted with electrically-operated actuators to adjust seed rate) is likely to be about £2000, or a typical cost for a 500ha farm of around £1/ha, assuming that the GPS receiver/display unit required will also be used for other purposes. A final cost will be to creation a seed rate map based on the soil texture map, which can be estimated at no more than £0.50/ha (in fields where the seed rate is to be varied). This gives a total cost of between £2.00/ha and £2.50/ha for a 500ha farm.

Benefits will depend on the number of fields on the farm that have variation in soil texture, the amounts of each of those fields that are significantly heavier or lighter than the majority of the field, and also the adjustment in seed rate necessary to compensate for differences in establishment. Blake *et al.* (2001) found that light soil textures (sands, loamy sands and sandy loams) averaged 90% establishment for cereals, whereas for medium (sandy silt loams, silty loams, sandy clay loams and silty clay loams) and heavy (clay loams, sandy clays, silty clays and clays) soil textures establishment averaged just over and just under 65% respectively. However the data for medium soils included a high proportion of silty clay loams, at the heavier end of the medium category.

There is very little published information on the costs and benefits of variable seed rates. An in-field zone-seeding approach to adjusting seed rates to soil types evaluated by Courtyard Partnership on a Wiltshire farm in autumn 2007 (Farmers Weekly, 21 March 2008) reduced wheat seed costs by £3/ha, based on varying seed rates by 50 seeds/m² (around 25%) between different soil types.

Assuming that 50% of fields have adequate texture variation to justify varying seed rate, and that within those fields half the area might be classed as medium, a quarter heavy and a quarter light, and using establishment figures of 70%, 65% and 90% respectively, savings in seed costs alone for a typical 500ha farm might be around £1/ha, averaged over the whole farm. This is less than the cost of varying seed rates (if the cost of ECa mapping is included). If the prevention of a 1% loss of yield (due to sub-optimal plant populations) is assumed for the heavy soil areas, the benefits are likely to be nearer £2/ha, sufficient to cover the cost associated with the variable seed rate technique and a share of the ECa mapping cost. If prevention of a 1% loss of yield due to excessive plant populations in light soil areas is also assumed, the total benefits might be around £3/ha, sufficient to cover the whole cost of varying seed rates and ECa mapping.

If all fields on the farm had sufficient texture variation to justify varying seed rates, the benefits would double with only a small increase in costs (producing seeds rate maps for all fields instead of half of them). Savings in seed costs alone could then be sufficient to cover the cost of varying the seed rates and a share of the ECa mapping cost. Adding 1% saved yield as above could increase net benefits to between £1 and £3/ha after deducting the full cost of the ECa mapping.

7.2 Variable Rate Application of Slug Pellets

The soil texture and seedbed quality information used for variable seed rates could also be used as a basis for varying slug pellet applications. The capability to adjust slug pellet application rates (other than manually) is limited at present, so would most likely have to be used in a field zone approach. With a typical application of slug pellets costing up to £10/ha, if the doses applied could be halved on areas with light soil, the saving could be up to £5/ha on those areas, and using the above example of a 500ha farm with 50% of fields showing soil texture variation, this might equate to an additional saving of around £0.50/ha (averaged over the whole farm) per application of pellets, at little extra cost.

8.0 Nutrient Management

8.1 Mapping and Variable Rate Application of P, K & Mg

There are two main approaches that can be used to determine and map variation in crop requirement for P (phosphate), K (potash) and Mg (magnesium) within a field.

The first approach is based on the identification of routinely high and low yielding areas from yield maps. The importance of considering yield trends over several years, not just one single year, was evident in a long term study of grid sampling in the USA (Franzen, 2008). If fields have previously received uniform applications of P, K and Mg (aimed either at maintaining soil indices at the appropriate target levels based on a field average or replacing offtake based on a field average yield), the soil nutrient status is likely to be lower now in high yielding areas and higher in low yielding areas, due to differences in offtake. This can be confirmed by targeted soil sampling. The usual strategy is then to rectify the low nutrient status areas as quickly as possible through significantly higher than maintenance applications. Depending on how these areas are distributed, this may require a treatment map and variable rate application, or simply a targeted treatment in an area that is marked out. Yield maps would then be used to produce a replacement strategy thereafter. Removal of P and K is generally proportional to yield, allowing a single pass with a standard fertiliser blends (rather than two passes with straights) to be used. There may be some areas of high reserve (low yield) where no fertiliser is justified.

Where there is significant variation in topsoil texture, there might be differences in the natural supply or retention of nutrients in the soil, so this would need to be considered, both when targeting sampling and determining application requirements. Potassium-releasing clays are unlikely to need more than maintenance applications of K. There is often also a trend for higher K levels with higher organic matter. Lighter-textured soils may be higher in P. On limestone soils, P indices are likely to be lower on deeper clays than on brash due to higher offtake. Again there is often an association between higher organic matter and higher P levels. Mg indices tend to be lower on stony or shallow land, and higher with deeper soils or where there is more clay. Soil maps are sometimes used as the sole basis for producing nutrient maps, but these could be misleading where other factors that influence nutrient supply (*e.g.* past management) vary in a different way within the field.

The second approach is to map the field on grid basis and produce an annual application map to raise or lower nutrient levels gradually in different parts of the field to meet the target level for maintenance. Grid sampling strategies assume that variation is as likely to occur on one part of a field as another. The number of sub-samples required to produce a reliable sample for each point depends on local variation and the error that can be tolerated. Oliver *et al.* (1997) found that a reasonable rule of thumb for P, K and Mg sampling is 16 cores within a few metres to produce a sample at each point. Even when taking an appropriate number of sub-samples, P and K levels are not spatially dependent at more than 50m. Hence ideally grid sampling needs to be at 50m separation *i.e.* 4 samples per hectare to produce reliable maps (Shiel *et al.*, 1997). This is considered to be too expensive in practice, due to the high costs of collecting and testing soils samples, other than for soil pH which can be measured in the field with a rapid and low cost test.

Commercial soil nutrient mapping services, such as that offered by SOYL, typically use a grid sampling frequency of one bulk sample per hectare (made up of 16 sub-samples), although extra samples may be taken in areas that are known or expected to be very variable. P, K or Mg recommendations are produced in the form of a treatment map based on a 24 x 24m grid. The treatment map is based on that year's cropping, and allows for application rates above or below maintenance level to build or reduce soil reserves as appropriate. Application rates are based on the field average yield level, or where yield maps are available offtake can be overlaid. The life of the maps is assumed to be four years, after which soils are mapped again (Simon Griffin, pers. comm.).

Various authors have compared targeted and grid sampling methods. Thomas *et al.*, (1999) compared a targeting strategy based on crop biomass maps in which 8 zones were sampled, against a 100m grid system in which 26 grid points were sampled. Average values for P, K and Mg indices were similar, although the maximum-minimum range was larger with the grid sampling. Griffin (1999) compared the accuracy of sampling methods for P, K and Mg using grid sizes of 25, 50, 75 and 100m. In addition, soil texture was classified for each sample to produce a soil map and yield contour maps (based on the 3year average yield) were also produced. By overlaying interpolated maps at wider grid spacings on the 25m map, and calculating the % of interpolated soil index points that were incorrect, accuracy could be compared. Increasing grid size from 25 to 50m resulted in 15% 'incorrect' points for P, 4% for K and 8% for Mg. Increasing to

100m increased the number of incorrect points to 25% for P, 13% for K and 16% for Mg. Overlaying the field average instead resulted in 58% incorrect points for P, 29% for K and 35% for Mg. Using information from the yield map to target samples in areas of high or low yield reduced the proportion of incorrect P points for the 100m grid from 25 to 19%. Using soil texture information reduced the proportion of incorrect P points from 25 to 22%, and using yield and texture information reduced the proportion from 25 to 17%.

If it is assumed that high and low indices occur in patches related to yield and offtake then, in general, interpolation should be right most of the time (and wrong mainly at the edges) so the net effect will be an increase in the number of incorrect points with a 1ha grid size, not a completely incorrect map. Accepting that both targeted sampling and 1ha grid sampling will both involve some inaccuracy, where yields have significant variation the costs and benefits of either approach are likely to be similar. In situations where for example fields contain narrow strips of low index soil, but with wider areas of high soil index in between, if the grid points happen to fall in the low index strips interpolation would suggest an incorrect (low) index for the wider area in between. In such situations, grid sampling could produce a misleading map. Equally though, where yields are fairly uniform, the conclusion might be that targeted sampling is not necessary as there would be no basis for defining the areas to sample. Where variation in past management has however resulted in high P and K indices in parts of the field, which are not due to yield differences, unless known about these might only be detected by grid sampling.

Grid sampling is perhaps particularly suitable for those taking on new land or for growers who suspect that fields have yield variation or have had differential fertiliser applications or cropping in the past, but have no detailed information. For growers who know their field histories and soil texture variation, information on yield variation (supplemented by targeted sampling where necessary) may be all that is necessary.

Costs and Benefits

The cost of nutrient index / application maps produced from grid sampling by SOYL is currently around £5.50/ha per year over the four year life of the sampling (Simon Griffin, pers. comm.). This includes pH / lime application maps as well as P, K and Mg. In this analysis the cost of targeted sampling is calculated to be around £4.00/ha per year (for a 500ha farm). This includes sampling and creating an offtake map, plus a share of the

yield mapping cost (as this is necessary to target the sampling in the first place and to create an offtake map). However it is assumed that for the targeted sampling approach this would only be done on the proportion of fields that have significant yield (or soil) variation, such that if only 50% of fields have significant variation the cost spread over the whole farm would be reduced to £2.25/ha.

To achieve variable application requires a spreader-controller. This may be included as standard on larger new machines, or retro-fitted (on most machines). The typical capital cost is likely to be around £2000, equivalent to about £1/ha per year for a 500ha farm. Where nitrogen fertiliser application rates are being varied, this cost may be shared between the two tasks. A GPS receiver/display unit capable of handling variable rate application maps would also be required, although again this is likely to be shared with other uses. Assuming use for both N and P & K application, the overall cost per annum of the variable rate application capability on a 500ha farm is likely to be around £0.75/ha. The likely total costs for a 500ha farm using the two approaches are shown in table 8.1. The figures in brackets would apply if only 50% of fields had significant yield variation.

Table 8.1 Likely costs of mapping and variable rate application of P, K and Mg for a typical 500ha combinable crop farm, averaged over whole farm

Approach	Cost of P, K and Mg mapping and variable rate application (£ per ha, averaged over whole farm)				
	Nutrient mapping	Targeted Sampling	Create offtake map	Variable rate applic.	Total Cost
Targeted Sampling	-	3.75 (2.25)	0.50 (0.25)	0.75	5.00 (3.25)
Grid Sampling	5.50	-	-	0.75	6.25

Calculating the financial benefits obtained by saving P, K or Mg applications on areas with high indices is relatively straightforward. However unless applications to the field have routinely been higher than needed in previous years (such that the average field indices are higher than target), these savings are likely to be equalled by the higher costs of the increased applications needed in areas where indices are below target, assuming that the proportions in each field are similar. The main benefit from areas where indices are below target is likely to be protecting their higher yield potential (assuming that higher offtake is the reason that their soil indices are lower). This is more difficult to attribute an

economic benefit to, as robust information on critical P, K and Mg levels (below which yields start to decline) is limited to a few soil types.

Despite a large number of studies on spatial variation, sampling strategies and mapping for P & K, there is little published research that has examined the benefits of spatially variable application. Havlin & Heiniger (2008), using a 'Variable Rate Decision Support Tool' developed for application of P and K to corn in the USA, concluded that the main advantage to variable rate application was the ability to increase yield through improved fertiliser distribution, such that the ability to quantify the likely yield gain was essential. Where soil testing indicated a wide-enough range in soil nutrient levels to affect yield, benefits to variable over uniform application were greater, and more sensitive to crop and fertiliser price. Where the range of soil nutrient levels was smaller, the benefit to variable application was smaller and less sensitive to prices. Commercial experience (from SOYL) suggests an average £12/ha saving in fertiliser costs (Simon Griffin, pers. comm.). This implies that either many growers have indices that are (on average) above the target for their cropping, or that most growers have more high index (or low yielding) areas within fields that are variable than low index (high yielding) areas.

Table 8.2 shows the potential benefits from a targeted sampling / replacement approach, or from a grid sampling approach, compared to uniform application on a 500ha farm. Only P & K inputs are considered. The analysis assumes that field average indices (or indices in the average-yielding parts of the field) are currently at the target level for combinable crop rotations, but are 1 index above and below target in low and high yielding areas respectively. It is assumed that only 50% of fields have enough variation in yield (or soil nutrient indices) to justify variable application.

Table 8.2. Potential savings and net benefits from variable rate application of P & K for a typical 500ha combinable crop farm, averaged over whole farm

Approach	Savings, costs and net benefit of P and K mapping and variable rate application (£ per ha, averaged over whole farm)			
	P and K Saving	Yield Benefit	Total Cost	Net Benefit
Targeted Sampling	-1.25	5.00	3.25	0.50
Grid Sampling	3.00	5.00	6.25	1.75

In this analysis, targeted sampling would have led to higher usage of P & K than uniform application, as replacement based on offtake at the assumed yield levels has resulted in slightly higher average P & K doses than the standard recommendations (Anon, 2000) assumed for the uniform strategy. In situations where the standard recommendations fail to match offtake, unless these are increased the uniform strategy would eventually lead to a reduction in average soil indices across the whole field, whereas these would be maintained by targeted sampling. Hence this analysis undoubtedly underestimates the benefits of the targeted sampling approach compared to uniform application.

Fig. 6 illustrates the effect of the number of fields on a farm (as a % of the total) that have variation in yield (offtake) or soil indices on the potential benefits of variable rate P&K treatment compared to the likely costs, for approaches based on grid sampling or targeted sampling and replacement of offtake. Where the benefit line is above the cost line for that approach, the vertical distance between them is the benefit over cost.

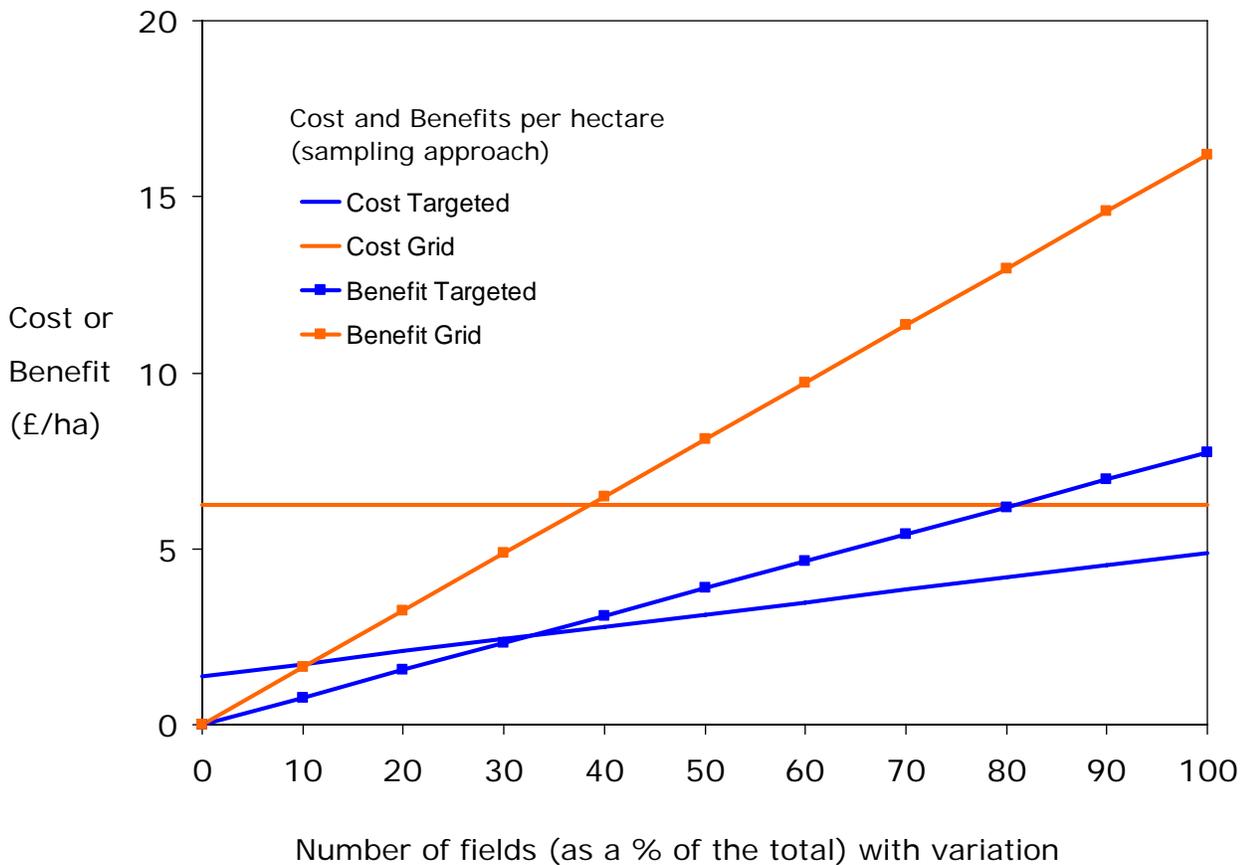


Figure 6. Effect of the number of fields (as a % of the total) on a 500ha farm with variation in P&K indices/offtake, on the potential benefits of variable rate treatment.

If all fields on the farm had sufficient variation in yields (or soil nutrient indices) to justify variable rate application of P & K, the benefits from the grid sampling approach would have increased to £16.25/ha, with no change in costs per hectare, increasing the net benefits to around £10.00/ha. The benefits from the targeted sampling approach would have increased to £7.75/ha, with costs rising to £5.00/ha, giving an increased net benefit of £2.75/ha. Where the number of fields with variation in P & K indices or offtake was less than about 40%, the grid sampling approach would not have been cost-effective. Where the number of fields with variation was less than about 30%, the targeted sampling approach would not have been cost-effective either.

8.2 Variable Rate N Application

The Case for Variable N Application

For spatially-variable application of N fertiliser to be justified, the economic optimum N dose for a crop must vary significantly at a within-field scale. Welsh *et al.* (2003a) examined over three seasons the spatial variability in winter barley crop yield response to applied N in a field with a silty clay loam soil over chalk that varied in depth. Based on three N doses comprising standard farm practice and 30% above or below, in the first season optimum N doses were observed to vary in different parts of the field (relating to soil depth). However, in the following two seasons there was no variation in optimum N dose within the field.

In two parallel experiments, Welsh *et al.* (2003b) examined over three seasons the spatial variability in wheat crop yield response to applied N. In a field with a calcareous silty clay loam soil over limestone that varied in depth, using N doses equating to standard farm practice and 25-30% above or below, in one season there were differences in optimum N doses in different parts of the field (relating to soil depth) but in the other two seasons there were not. In a field with a uniform calcareous clay loam soil, a similar approach revealed a lower optimum N dose in two out of three seasons for a zone consisting of one third of the field, compared to two other zones that made up the rest of the field. However, evidence was subsequently found that the first zone was historically a separate field which could explain this.

Using an experimental and analytical method to determine local response functions, Lark & Wheeler (2003) demonstrated that in most cases there is quite substantial variability in the economic optimum N dose within fields. Benefits were derived mostly from applying locally optimal N doses by reducing the amount of N applied in the least responsive parts of the field, with relatively small benefits from increasing the N dose where the crop was most responsive. At 2001 wheat prices and N costs, the economic optimum dose for one field was found to average 150 kg N/ha, but varied from less than 50 to over 200 kg/ha. The economic benefit from variable rather than (optimum) uniform application was about £3.60/ha, with a reduction of 30 kg N/ha in applied N. Over all experimental fields, economic benefits from variable application were up to £11/ha with a reduction in applied N dose of 40 kg/ha compared to the optimum uniform dose.

Variation in the dose response to applied N might reflect inherent variability in the soil N supply, or may be due to some limiting factor that is preventing the crop from the using additional N. Where there is within-field variation in yield and N response, high and low yielding areas may not be a consequence of the quantity of N applied, but how efficiently that N can be used by the crop. It is clear that, in many fields, N response and optimum N dose can vary with seasonal conditions, such that achieving a benefit from variable N application is likely to require season-specific information about the crop to be taken into account. Uncertainty about seasonal conditions is undoubtedly a major limitation, and the inevitable conclusion might be that the lowest risk strategy for N management would be one in which N dose is not varied. However, there are measures of variability that could be mapped using precision farming techniques to aid seasonal interpretation.

Practical Implementation

The spatial dependence for Soil Mineral Nitrogen (SMN) is 50m or less (Dampney *et al.*, 1997; Stenger *et al.*, 2002). SMN sampling and analysis on a grid basis to 90cm depth as a basis for variable N application would not therefore be cost-effective (Dampney *et al.*, 1997). In addition to a low proportion of structural variance, spatial distribution is not stable with time (Stenger *et al.*, 2002). Baxter *et al.* (2003) analysed spatial variation in SMN and Potentially Available Nitrogen (PAN) within an arable field, and related it to variation in other parameters (gravimetric water content, elevation, soil texture, organic matter content and crop yield). They found that SMN and PAN were spatially related with the cheaper to measure or more permanent features. Moderate relationships were found

between SMN and clay or silt content, and there was a large negative correlation between elevation and SMN. Given the uncertainties around measurement of SMN and its effective impact on crop response to fertiliser N, such information is in any case unlikely to provide a meaningful basis for variable rate N application.

The use of historic yield information as a guide to varying N doses was examined by Welsh *et al.* (2003a and 2003b) for one field of winter barley and two fields of wheat. Four strategies were evaluated: applying 25-30% more N on areas with a historically high yield, and 25-30% less N on areas with a low yield (HY1), less N on high yielding and more N on low yielding areas (HY2), more N on high yielding areas and the standard dose everywhere else (HY3), and more N on low yielding areas and the standard dose everywhere else (HY4). Recalculating margins over N cost using a grain price of £100/t and a N price of £0.80/kg (Table 8.3), the only approach that gave a consistent benefit was to apply more N on the low or high yielding areas of the winter barley (keeping the dose on other areas as standard). This was simply because the standard N dose on the field was restricted in order to ensure a malting premium. Five out of nine fields showed an economic benefit to applying more N on historically low yielding areas, compared to only two or three fields showing a benefit to any of the other strategies.

Table 8.3. Increase or decrease in margin over N cost from variable N application based on historic yield, compared to uniform treatment (after Welsh *et al.*, 2003a & 2003b)

Strategy	Historic yield and decision			Increase or decrease in margin (£/ha)				No. fields benefiting
	High	Average	Low	W Barley	Wheat 1	Wheat 2	Mean	
HY1	more N	standard	less N	-16	+3	-8	-7	3
HY2	less N	standard	more N	-25	+21	-42	-15	2
HY3	more N	standard	standard	+4	-6	-7	-3	3
HY4	standard	standard	more N	+10	+5	-20	-2	5

Even at current prices these experiments do not support varying N dose in response to historic yield, as was concluded at the time. However it is important to acknowledge that research in drier climates (*e.g.* Bonfil *et al.*, 2008) has shown the potential for N removal maps (derived from site-specific yield and protein measurements) to be useful as a basis for variable N application to improve yield and grain protein.

The capability to assess crop canopy variation by remote sensing provides a ready source of season-specific crop information. Nitrogen supply to the crop influences both leaf area index and chlorophyll content (i.e. canopy size and colour). There are essentially two potential responses to variation in the crop canopy: apply more N on the poor areas, and less N on the good areas (often called the 'Robin Hood' approach), or apply less N on the poor areas and more on the good (the 'King John' approach). These were also evaluated in the experiments reported by Welsh *et al.* (2003a and 2003b). Two strategies were compared: applying 25-30% more N on areas with a high shoot density and 25-30% less N on areas with a low density (SD1), and less N on high shoot density and more N on low shoot density areas (SD2). Recalculating margins over N cost using a grain price of £100/t and a N price of £0.80/kg, the greatest overall benefit compared to uniform treatment was obtained where more nitrogen was applied on the areas with relatively low shoot populations, and less on areas with relatively high populations (Table 8.4). However this was not consistent from season to season, with SD2 better than SD1 in two out of three years on wheat, but only in one out of three years on barley.

Table 8.4. Increase or decrease in margin over N cost from variable N application based on relative shoot density, compared to uniform treatment (after Welsh *et al.*, 2003a & 2003b)

Strategy	Shoot density and decision			Increase or decrease in margin (£/ha)			No. fields benefiting
	High	Average	Low	W Barley	Wheat 1	Mean	
SD1	more N	standard	less N	+3	+3	+3	4
SD2	less N	standard	more N	+6	+29	+17	5

It was concluded at the time that the apparent reversal of response to shoot density in the winter barley could be explained by the fact that, in absolute terms, the highest shoot densities in one year were the same as the lowest shoot densities in the other two years, such that the benefit was actually derived from applying more N where shoot densities were too low. In practice, either strategy (more on the poor, less on the good or more on the good, less on the poor) may be the more appropriate, depending on for example growth stage, plant population and the factors that are limiting growth of the canopy. Early in the spring, there might be the potential for thin or backward areas of the crop to 'catch up' with better areas of the field as a result of ensuring that the N supply to the crop is not limiting. At the same time, withholding N on thick or forward areas of the crop may help to hold back growth, to reduce the risk of disease or lodging.

Later in the spring, if areas that were thin or backward haven't already responded to additional N, this probably means that their growth (and potential) is limited by other factors, and therefore N applications should be reduced to avoid wastage. Better areas that have had their earlier N applications restricted can then have higher doses in order to ensure that N supply does not limit their achievement of full yield potential, in the knowledge that at this stage the risk of increasing lodging or disease risk will be less.

Wood *et al.*, (2003) used near real-time measures of crop growth (shoot density or canopy GAI), compared to the target density or GAI at that growth stage, as a basis for varying N dose. Two experiments were established on winter wheat in the 1999/2000 season. Variations in seed rate (150, 250, 350 and 450 seeds/m²) were used to increase the range of initial crop structures present in the fields, with additional natural canopy variation developing subsequently. Each seed rate strip was divided into two, with one half receiving a uniform application of N according to standard farm practice, and the other half a variable N treatment based on near real-time maps of crop growth. N was applied at three timings, mid-late tillering (early March), GS30-31 (mid April) and GS32-33 (early-mid May). At each timing calibrated ADP was used to compare shoot density (at the first timing) or GAI (at the second and third timings) with benchmark values for those growth stages taken from *The wheat growth guide* (HGCA, 1998). Where growth was below target N application was increased, and where growth was above target N application was reduced. At the main April (GS30-31) timing, the treatment decision also took account of what was applied at the first timing.

Margins over N cost achieved with variable N compared to uniform treatment are shown in Tables 8.5 and 8.6, using the original grain price of £65/t and N cost of £0.30/kg (BER of 4.6:1), and recalculated using £100/t and £0.80/kg (BER 8:1) respectively. In Onion field (Table 8.5), which was a relatively late-sown crop of continuous wheat, the variable N strategy resulted in a re-distribution of N, increasing the average amount applied to lower crop density areas compared to uniform treatment, and decreasing the amount applied to higher crop density areas. This resulted in a yield benefit in all cases, with a mean yield improvement of around 0.5 t/ha, and an increase in margin over N costs of £31-44/ha (depending on grain and N price), with only a marginal increase in the average amount of N applied with the variable N strategy.

Table 8.5. Increase or decrease in margin over N cost from variable N application based on canopy size, compared to uniform treatment, for Onion field (after Wood *et al.*, 2003)

Seeds per m ²	Plants per m ²	Nitrogen Strategy	Mean N dose (kg/ N ha)	Yield (t/ha)	Margin advantage (£/ha) to variable N at BER of:	
					4.6:1	8:1
150	100	Uniform	200	5.92		
		Variable	243	6.31	+12	+5
250	143	Uniform	200	6.63		
		Variable	227	7.24	+32	+39
350	177	Uniform	200	6.87		
		Variable	188	7.23	+27	+46
450	200	Uniform	200	6.69		
		Variable	192	7.47	+52	+84
Mean	Mean	Uniform	200	6.53		
		Variable	213	7.06	+31	+44

Table 8.6. Increase or decrease in margin over N cost from variable N application based on canopy size, compared to uniform treatment, for Far Highlands (after Wood *et al.*, 2003)

Seeds per m ²	Plants per m ²	Nitrogen Strategy	Mean N dose (kg/ N ha)	Yield (t/ha)	Margin advantage (£/ha) to variable N at BER of:	
					4.6:1	8:1
150	120	Uniform	200	7.94		
		Variable	197	8.24	+20	+32
250	195	Uniform	200	7.85		
		Variable	189	7.77	-2	+1
350	240	Uniform	200	8.11		
		Variable	135	7.79	-1	+20
450	320	Uniform	200	7.93		
		Variable	144	7.77	+6	+29
Mean	Mean	Uniform	200	7.96		
		Variable	166	7.89	+6	+21

In Far Highlands (Table 8.6) the variable N strategy resulted in a very small reduction in the amount of N amount applied to the lower crop density areas compared to the uniform strategy, but a larger reduction in the amount applied to the higher crop density areas. Yields were maintained or slightly increased in the lower density areas, but reduced in the higher density areas. The net result was a similar average yield but with 17% less N applied overall using the variable N strategy. With the original lower N cost and BER, the

overall improvement in margin over N cost was relatively small. However with the higher cost of N used in this re-analysis, there is a larger improvement in margin over N cost.

When considering which fields are likely to benefit from varying N application based on crop size, it is important to know how much variation in shoot populations or canopy GAI is likely to be needed in order to justify the approach. This is largely unknown at present. However the results from Far Highlands perhaps provide an indication. In this field the largest benefits from variable N, especially in the original analysis, were obtained in the lowest and highest crop density areas. Table 8.7 summarises key crop structure parameters (average values) within the uniform N treated areas of each initial crop density area. For the two middle crop densities, average GAIs between flag leaf emerging and the start of grain fill were close to the 6.0-6.5 target for wheat (HGCA, 1998) even with uniform N. Average GAIs for the two extreme crop densities were more than 20% above or below the target in the uniform N areas, but in the variable N treated areas the average GAIs for these initial crop densities were shifted closer to the target (Fig. 7).

Table 8.7 Winter wheat crop structure development in Far Highlands field under a uniform N management strategy (after Wood *et al.*, 2003).

Seeds/m ² sown in autumn	Plants/m ² in autumn	Shoots/m ² in spring	Mean GAI at GS35 and GS61
150	120	558	4.8
250	195	693	5.7
350	240	1093	6.7
450	320	1607	8.8

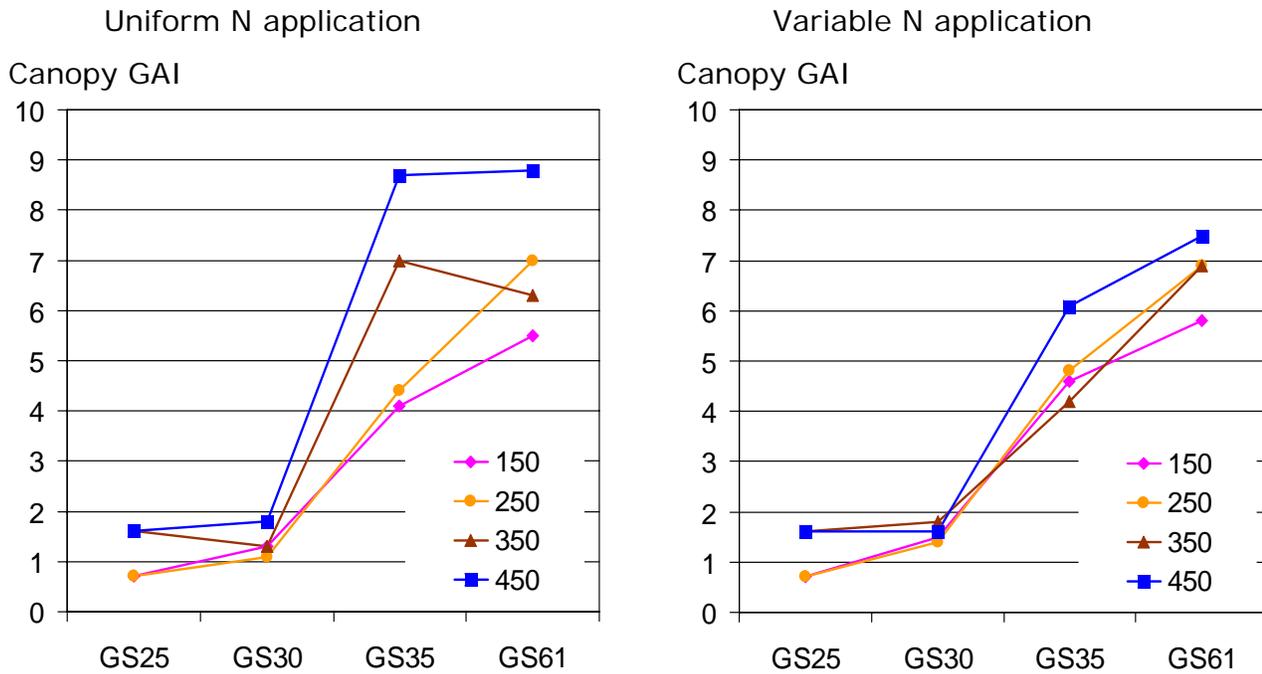


Figure 7. Change in GAI with time under uniform and variable N management strategies for winter wheat established at four different seed rates (150, 250, 350 & 450 seeds/m²) in Far Highlands field (after Wood *et al.*, 2003).

Based on Table 8.7, taking the average of the 250 and 350 seed rate areas as 'optimum' (a GAI of about 6.2), the average autumn plant and spring shoot populations needed to achieve this were around 220 plants/m² and 900 shoots/m² respectively. These values are also not dissimilar to those given as benchmarks in the second edition of The Wheat Growth Guide (HGCA, 2008). Average plant and shoot populations in the highest and lowest crop density areas were more than 40% above or below these levels. Therefore, using this experiment as a guide, it would appear that if the minimum level of variation in canopy GAI for variable N to be justified was considered to be +/-20%, it would appear that variation in autumn plant or shoot populations may need to be double this. The extent to which individual crops compensate for variation in initial crop structure will itself vary, and be field-specific. The analysis above is intended only as a guide to how the decision whether or not it would be appropriate to apply N variably might be made.

Another important consideration is the proportion of fields that are likely to show sufficient variation in crop size or requirement for applied N in order to justify variable N application. Desbourdes *et al.* (2008) studied recommendation maps provided by

Farmstar in France over a three year period from 2005 to 2007 for applications to wheat at the flag leaf stage. 52% of fields were found to have N requirements that were sufficiently heterogeneous to justify variable N. A similar study on oilseed rape revealed that 85% of recommendation maps supported variable N dose about half of which could be achieved manually, the other half requiring automatic rate adjustment.

It should be acknowledged that reflectance is not the only method of mapping differences in crop canopy structure. Ehlert *et al.* (2003) used a tractor-mounted pendulum-meter to detect differences in relative cereal crop biomass, as a basis for adjusting N fertiliser doses at the third or second and third application timings within six winter wheat fields in Germany. Within defined upper and lower limits, N dose was varied directly in proportion to crop biomass (more biomass, more N). For the third application timing, with N doses of 7-68 kg N/ha, savings varied from 9.6 to 23.1%. For the second and third application timings, with N doses of 60–160 kg/ha, savings ranged from 8.3–17.1%.

In practice variation in crop canopy structure is the most commonly used-guide to variation in N supply or availability, and therefore the crop requirement for N fertiliser. The service offered by SOYL (Griffin, 2008b) is based on three variable rate N treatment maps per year, for applications in early-mid March (pre GS30), mid April (GS30-31) and early May (GS32). These are based on at least three satellite-derived crop canopy maps calibrated to GAI obtained between January and May. At the first canopy sensing timing, an image is provided for all fields on the farm, but only those with significant variation are continued thereafter. A global GAI calibration is done based on targeted areas, which include the full range of biomass levels. Variable N doses are based on an adjustment of +/-30 kg N/ha per unit of GAI above or below target, around the grower's intended dose.

The LORIS system uses a single (10m resolution) digital image of crop biomass in February/March, which is then referred to through the growing season. Highs and lows of canopy size are combined with information on growth stage, plant population, soil type and degree of variability (in soil texture or historic yield) and fed into a model which compares two strategies (more on good areas, less on bad areas, and the opposite) and works out the best one, based on the grower's expected yield, sowing date and N dose.

Use of a Yara N-Sensor typically involves a 'dry run' through the crop to identify highs and lows in the crop canopy. This is then used to determine the extent of variation in N dose, either around the intended field average dose or a calculated dose based on spot measurements in the field, with poor areas receiving more N and good areas less. A new calibration module has been developed to allow the system to decide what level of N fertiliser to apply, rather than making relative changes. It is achieved using a scan that calculates how much N is in the crop, and information on the crop, growth stage, target yield, timing of next N application and estimated amount of mineralisation.

Many growers who are using variable N are already doing variable rate applications of other nutrients (Simon Griffin, pers. comm.). The same spreader controller can usually be used for both unless liquid UAN is being used. Compatibility problems with sprayer controllers can sometimes be a problem, and limits on the maximum and minimum dose applied need to be set to match the nozzle/system performance range.

Costs and Benefits

For the satellite-derived map-based system offered by SOYL, in addition to the cost of the canopy GAI maps outlined in section 5.3, there is a cost of £1.50/ha for each variable N application map (Simon Griffin, pers. comm.). For a vehicle-mounted system such as the N-Sensor, the only additional cost over that of the equipment itself is for the time taken/lost during in-field set-up and calibration, which can be estimated at no more than the equivalent of £0.50/ha per application (probably less for larger field sizes).

The likely total costs of variable N application, based on the full cost of the canopy sensing service or equipment and a share of the spreader controller (and GPS/display equipment where necessary), for a 500ha farm using the satellite-based service from SOYL or a purchased N-Sensor as examples, are shown in Table 8.8. It should be noted that there are alternative vehicle-mounted sensor systems such as CropCircle, the costs for which may work out somewhat less. Costs are averaged over the entire farm area, but it is assumed that of the crops being grown only wheat (250ha) and oilseed rape (125ha) are currently suited to variable N, and that only 67% of fields (*i.e.* 250ha in total) have enough variation in them to justify variable N. It is assumed that only these fields will require N application maps or set-up and calibration of the N-Sensor (figures in

brackets in Table 8.9), and that N is applied to wheat in three applications and to oilseed rape in two.

Table 8.8. Likely costs (per hectare) of sensing/mapping the crop canopy and variable rate application of N for a typical 500ha combinable crop farm

System	Cost of crop canopy sensing/mapping and variable rate N application (£ per ha, averaged over whole farm)				
	Canopy map or sensing cost	Calibration cost (x 2/3)	N Application maps (x 2/3)	Spreader control (+ GPS/display)	Approx. total cost
Satellite-based	2.00	-	3.00-4.50 (2.00)	0.75	6.50 (4.75)
Vehicle-mounted	6.50	1.00-1.50 (0.50)	-	0.50	8.25 (7.50)

Commercially the average benefits (before additional costs) in winter wheat from the SOYL variable N system (Griffin, 2008b) were reported to be £27/ha in 2006, based on a wheat price of £70/t and a N price of £0.42/kg, rising to over £60/ha in 2007 (based on a wheat price of £140/t and a N price of £0.52/kg. The major benefit in both years was through increased yield, averaging around 0.4 t/ha in 2007. In 2006, yield increase accounted for £23.77 of the benefit, compared to only £3.58 from N savings. The range of benefits in 2006 was wide, from a benefit of over £100/ha to a loss of over £50/ha. No significant relationship was found between soil type, seed rate or drilling date, but there was some suggestion of a greater benefit with group 3 or 4 wheat varieties that were grown primarily for yield rather than group 1 or 2 varieties being grown for quality. On winter oilseed rape in 2007 initial results on three fields, using similar principles to those used for wheat, showed benefits of £15-25/ha (Griffin, 2008b).

Yara data shows a typical 3-4% yield benefit from using the N-Sensor to vary N application, with no extra fertiliser used (Clive Blacker, pers. comm.). The LORIS system is claimed to increase yields typically by 3.0% (ASI, 22 December 2006), based on redistribution of the same amount of nitrogen.

Using trials in commercial fields between 2005 and 2007, Desbourdes *et al.* (2008) examined the yield benefit from use of the Farmstar system in France to vary the final (third) N dose in wheat. Yield increases up to 0.25 t/ha were recorded in the most heterogeneous fields where clear management zones could be defined. A similar study

was conducted using the N-Sensor to vary the dose of the second and third applications. Yield increases up to 0.3 t/ha were obtained. Jørgensen & Jørgensen (2007) conducted field trials in winter wheat in Denmark to examine the grain yield and protein content response to variable rate N based on the N-Sensor. Using an N rate of 167 kg N/ha (90% of economic optimum) applied in three splits, the N-Sensor was used to direct the second and third applications, and compared to uniform treatment. No significant differences were observed in yield or protein between the variable and uniform N strategies.

For this analysis, assuming a potential yield benefit of about 2%, slightly less than that observed commercially or in the Onion Field winter wheat experiment by Wood *et al.* (2003), from redistribution of the same quantity of N, or alternatively a reduction in the N dose required to achieve the same yield of around 10% (again slightly less than that observed in the Far Highlands winter wheat experiment by Wood *et al.*), the potential improvement in margin over N cost would be around £15-20/ha for a field of winter wheat or oilseed rape with sufficiently large canopy variation. Other benefits of variable N application could include easier/faster combining and lower drying costs, as a result of a more uniform crop at harvest.

For a 500ha farm growing 250ha of wheat and 125ha of oilseed rape, of which 67% is assumed to have enough variation to justify variable N, the benefits (averaged over the whole farm) are likely to be around £9.50/ha. This would give a potential net benefit of £4.75/ha using the satellite-based system, or £2.00/ha using the vehicle-mounted system (N-Sensor). Increasing the farm size to £750ha (a total of 375ha of wheat and oilseed rape receiving variable N) would reduce the cost of the satellite-based system to £4.25/ha and the vehicle-mounted system to nearer £5.25/ha, increasing the potential net benefits to around £5.25/ha and £4.25/ha respectively.

Fig.8 illustrates the effect of number of fields (as a % of the total) with variation in crop canopy on the potential benefits of variable rate N treatment, for satellite-based or vehicle-mounted systems on farms of 500 and 750ha. Where the benefit line is above the costs line for a particular system and farm size, the vertical distance between them represents the benefit over cost. For the satellite-based system, farm size has less impact on the benefit over cost from variable N than the number of fields that have canopy variation. For the vehicle-mounted system farm size has a greater impact, and

the proportion of fields that would need to have canopy variation in order to cover the cost of variable N application decreases from about half on the 500ha farm to about a third on the 750ha farm.

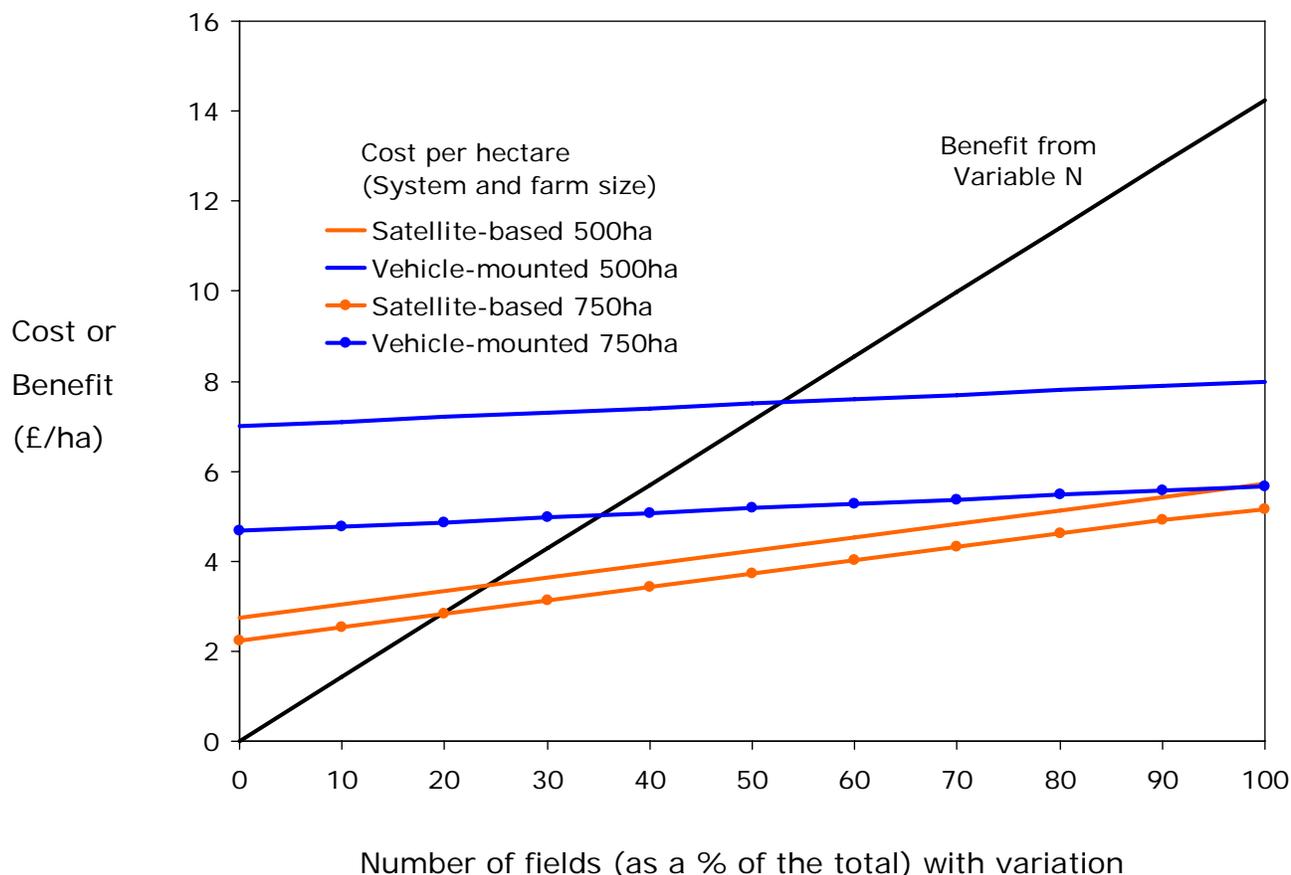


Figure 8. Effect of the number of fields (as a % of the total on the farm) with crop canopy variation, on the likely costs and potential benefits of variable rate N treatment.

Although they are not a good guide to varying N applications for optimum yield, historic yield maps could be a useful indicator of likely variation in grain quality, including grain protein or N content. Grain from high and low yielding areas could be sampled and tested to confirm this. Proteins might be lower in areas of high yield than in areas of low yield where N is applied uniformly. If this is consistently the case, application of foliar urea could be increased in high yielding areas and reduced in low yielding areas in order to compensate. This could potentially have an economic benefit, especially in situations where mixing grain from different parts of the field (in order to even out the protein content) is not feasible. The analysis in Table 8.9 assumes that 30 kg N/ha is needed as

foliar urea to increase grain protein by 0.5% (at a cost of £1.50 per kg N), with a wheat price of £110/t for 12%, £120/t for 12.5% and £130/t for 13% or above grain protein.

Table 8.9. Calculated comparison of potential benefits of a variable treatment strategy for late foliar urea N applications to breadmaking wheat, compared to uniform treatment

Proportion of field (%)	Average yield (t/ha)	no extra N applied		+ 30kg N/ha uniform		variable treatment	
		Protein (%)	Output (£/ha)	Protein (%)	Output* (£/ha)	Extra N to get 13% protein	Output* with extra N (£/ha)
25	7.5	13.0	975	>13.0	930	0	975
50	8.5	12.5	1020	13.0	1060	30	1060
25	9.5	12.0	1045	12.5	1095	60	1145
Mean			1015		1036	30	1060

*Less cost of extra N as foliar urea

9.0 Crop Protection

9.1 Lodging Control and Variable Rate Application of PGRs

Crop structure in spring can be a useful indicator of lodging risk. In wheat, root lodging risk has been found to increase at plant populations of more than 200 plants/m², and stem lodging risk when the canopy GAI at GS31 is above 2 or ground cover is over 60% (HGCA, 2005). Maps obtained using reflectance-based sensors may therefore provide an indication of how risk varies within a field, but these require detailed calibration to shoot density and GAI in order for the structure of the crop canopy to be correctly interpreted. A large GAI could consist of a large number of small shoots or a small number of large shoots, which may present a different risk or require a different approach to managing the risk. At later PGR timings or in seasons where crop growth is very lush reflectance sensors alone may be insufficiently sensitive to determine areas of high and low risk.

Having generated a map of crop structure, this then requires conversion to a treatment map. Where N application is also being varied, areas of crop with a high shoot population or a relatively large GAI at an early growth stage are likely to receive a reduced or possibly no early N dose, and this in itself will have a benefit in reducing lodging risk. In most cases, it is unlikely that a grower would omit PGR treatments altogether at the early stem extension timings, as the potential penalties caused by lodging in terms of yield and quality loss, harvesting difficulties and increased drying costs vastly outweigh the likely savings in input cost. A more likely scenario is that the grower might choose to vary the dose applied in different parts of the field. An alternative to this might be to vary the inclusion of a 'stronger' but higher-cost PGR in the mix, although this may be technically more difficult to achieve at present. For later follow-up PGR applications, which at a whole-field scale a grower might often decide to apply or not, this same strategy could readily be adopted for within-field variable treatment.

Costs and Benefits

The equipment needed to achieve variable application of PGRs would be the same as that need for variable application of herbicides, described in section 9.3. The net benefits of variable rate PGR application are likely to depend on whether or not the canopy maps and patch spraying capability needed are also being used for other purposes. If they are not, the benefits from variable rate PGR application are unlikely to cover the costs. The

greatest benefits are likely to result from saved output (in high lodging risk areas) and reduced yield penalty (in backward or stressed areas) through redistribution of the same total PGR input (provided that the maximum permitted dose is not exceeded in any area), and potentially a reduced risk of 'quat' residues in the grain through the avoidance of unnecessarily high doses in areas with low risk.

There is very little published information from studies involving variable rate application of PGRs. Table 9.1 shows an analysis of the potential benefits and likely costs for a 500ha farm growing 250ha of wheat of which two-thirds has sufficient canopy variation to justify variable PGR treatment. For fields with variation, it is assumed that in 25% of their area the canopy is large (requiring an increase in PGR spend of 20%), in 25% of their area the canopy is small (enabling a 40% saving in PGR spend) and in the remaining 50% the canopy size and PGR input are normal. The calculation assumes that the costs of sensing or mapping the canopy are shared with variable N treatment, and patch spraying costs (section 9.3) are shared with variable herbicide treatment. Three scenarios are examined:

- A net saving in PGR cost only (the decrease in PGR cost in small canopy areas minus the increase in PGR cost in large canopy areas)
- PGR saving plus a 5% potential yield loss prevented in the large canopy areas (due to lodging) or small canopy areas (due to stress), or 2.5% yield loss prevented in both
- PGR saving plus a 10% potential yield loss prevented in the large or small canopy areas, or 5% yield loss prevented in both areas.

Table 9.1 Likely costs and potential benefits of variable rate PGR maps and application for a 500ha farm with 167ha of wheat treated variably, averaged over whole farm.

Saving	Canopy map cost (£/ha)	Variable PGR map cost (x 2)	Patch spray cost (£/ha)	Total Cost (£/ha)	Benefit (£/ha)	Net Benefit (£/ha)
PGR cost only	1.00	0.75	2.00	3.75	0.25	-3.50
plus 5% yield saved					3.75	0.00
plus 10% yield saved					7.50	+3.75

In this analysis variable rate PGR application would just about break even if at least a 5% yield loss in small or large canopy areas was prevented. However there may in addition be benefits associated with easier or faster harvesting, lower grain drying costs and higher grain quality that have not been included here. If all 250ha of wheat on the farm had sufficient canopy variation to justify variable PGR treatment, the benefit (assuming 5% yield loss prevented) would increase from £3.75 to £5.75/ha, with cost only rising to £4.00/ha, resulting in a net benefit of around £1.75/ha.

9.2 Disease Management and Variable Rate Fungicide Application

In order to achieve real-time spatially variable management of fungal diseases, the ability to determine the spatial and temporal dynamics of infections at a very early stage would be essential. Research to date, for example using multi-spectral remote sensing to monitor powdery mildew and brown rust in wheat (Franke & Menz, 2007), has indicated that the potential for early detection of fungal infections is very limited.

Several authors (including Bjerre, 1999 and Miller *et al.*, 2000) have suggested that the application of surface acting chemicals such as fungicides should be adjusted according to canopy characteristics, in particular the density of the target to which they are applied. Miller *et al.* (2003) suggested that since many fungicides have a mode of action that is predominately via surface contact, the quantity of spray liquid applied at a given concentration should be directly related to LAI. However the relationship between canopy size and optimum fungicide input remains uncertain, with a number of possibilities:

1. A rising fungicide requirement with increasing canopy size, either due to increased disease risk or to maintain a constant dose per unit area of canopy.
2. A higher level of disease control (and therefore more fungicide) required where the canopy is thin, to maintain GLA for light interception.
3. The effects of 1 and 2 could cancel one another out, such that canopy size has no net effect on fungicide requirement.
4. The optimum fungicide dose is lowest where the canopy is neither too dense nor too thin.

Costs and Benefits

The evidence for a benefit from variable rate fungicide application is not strong. Secher (1997) obtained a yield increase of 0.3 t/ha (£30/ha benefit before cost) from varying fungicide dose according to canopy density. Bjerre (1999) found no yield benefit from

varying fungicide dose according to vegetation index. Miller *et al.* (2002) concluded that there was little to be gained from spatially-variable application of fungicides applied at GS39 in wheat, but that savings might be possible from changes to application parameters in response to canopy characteristics. Dammer *et al.* (2003) examined variable rate fungicide applications based on LAI (determined using a pendulum-meter) in winter wheat and spring barley in Germany. Fungicide application rate was reduced where LAI was below the maximum. The level of fungicide savings in the four fields depended on the amount of variation in LAI, but averaged 19% (range 7-35%). No differences in disease incidence were observed. Yields with variable treatment ranged from 0.6 t/ha higher to 0.1 t/ha lower than with the uniform approach.

Grenzdörffer (2003) used ADP for determination of biomass or crop density in winter barley, as a basis for varying the application of fungicides (and PGRs). The strategy for varying the inputs of fungicides assumed that:

- The amount of fungicide deposition should be equal on all plants
- The microclimate conditions in areas with high crop densities favour disease infections
- The economic risk attached to fungicide use is larger in areas with a high crop density (high yield) than in areas with low crop densities.

The site-specific approach generally resulted in lower fungicide inputs, of between 6 and 30% for an 'unlimited' approach and 4-12% where the amount of input variation was constrained. Assuming no yield benefit from variable rate fungicides, it was concluded that only high priced fungicides and/or high potential savings would be likely to justify the cost of variable rate treatment.

In practice the relationship between canopy size and fungicide requirement is likely to be highly field-specific, and therefore difficult to develop a workable algorithm for use within a precision farming based approach. Hence the conclusion must be that there is little to be gained from attempting to apply variable rate fungicides to combinable crops given our current capabilities and understanding.

9.3 Weed Mapping and Patch Spraying of Herbicides

Key considerations for spatially variable herbicide application were reviewed recently by Lutman & Miller (2007). Their key conclusions are summarised below.

Evidence continues to suggest that large seeded weed species have more aggregated distributions than small seeded species, making them more suited to patch treatment. Patch stability is more debatable: core patches of large seeded weeds are quite stable, but can expand and contract as a result of weather conditions and agronomic practices. These two considerations have an influence on the most appropriate mapping frequency of the weeds, and potentially on treatment strategies (including the size of the 'safety margin' around the patches).

Visual mapping of weeds whilst travelling through the crop on a quad bike, tractor or combine is the main capability that exists. The best time to achieve this will vary with the weed species, but is complicated now by the increasing reliance on pre-emergence herbicides for the control of some weed species. However, adoption by growers or service providers has been limited due to practicality and time considerations. Automatic detection is not yet possible commercially, and one-pass detection and treatment in real-time may be impractical due to the need to know in advance (as near as possible) the quantities and doses of herbicide needed.

Current positional accuracy of DGPS is adequate for creation of patch spray maps and subsequent treatment. Modern sprayers, with computer based controlled systems, in most cases can readily be adapted to making spatially variable applications. Multiple boom lines, nozzle clusters, and independently-operated boom/nozzle sections provide the main capability to patch spray, with the use of twin-fluid or direct injection methods to deliver variable doses over the full boom width still uncommon. A spray / no spray or 'on-off' approach to variable treatment based on presence or absence of the weed (or a threshold population) may only be effective for the first one or two times it is used (due to spread of seed from survivors). Variable treatment strategies based on high and low doses (appropriate to the weed species present) represent a lower risk, especially for smaller seeded weeds or where patches are less well defined, but the capability is more costly and is not yet in widespread use.

Costs and Benefits

The economic benefits of spatially-variable herbicide treatments are likely to depend on the proportion of the field that is weed infested, the size of the weed patches relative to the spatial resolution of the mapping and spraying capabilities, and the cost of the herbicides. For two or more patchy weeds that are controlled by a single herbicide, it is unlikely that all the patches will occur in the same places, such that the whole field may need to be sprayed even if individually neither weed occupies more than half of the area.

Nordmeyer & Henning (2006) carried out site-specific weed control in the same fields of winter cereals every year for a 5-year period from 1999-2003. The most common weeds were loose silky bent, ivy-leaved speedwell, field pansy and cleavers. Averaged over all fields and years, the total field area treated for silky bent was 39%, 44% for speedwell and pansy, and 49% for cleavers, demonstrating the potential for economic and environmental benefits from a patch spraying approach. Lutman & Miller (2007) found insufficient data to assess the benefits of patch spraying herbicides in commercial practice, but reviewed evidence from previous research. Their calculations assumed that 65% of a field would require treatment, based on the average infestation levels in the previous experiments. This assumption is supported for example by Barroso *et al.* (2003), who obtained a positive net benefit when controlling wild oats with an on/off patch spraying technique (compared to uniform treatment) only when the weed infested area was smaller than 64%.

Based on a sequence of a pre- and a post-emergence herbicide for black-grass control, plus a post-emergence treatment for cleaver control, in winter wheat, Lutman & Miller (2007) concluded that a cost saving of £10/ha might be possible with an on-off strategy, but less than £5/ha for a high dose / low dose strategy. Based on a patch spraying equipment cost equivalent to £1600 per year, a GPS cost of £500 per year and a weed mapping cost of £6/ha every two years (£3/ha per year), the likely total cost on a 500ha farm was calculated at £7/ha.

Table 9.2 shows the potential costs and benefits calculated within this analysis for a 500ha farm growing 250ha of winter wheat and 62.5ha of spring barley, with 80% of fields having black-grass, cleavers and wild oats present as patchy weeds (defined as

situations where the weeds occupy less than two-thirds of the field). For those fields with patchy weeds, black-grass and cleavers are assumed to occupy 67% of each field and wild oats 33% of each field. Treatment costs assume a single specific post-emergence herbicide for each weed.

Assuming an equipment cost of £7250, and a share of the GPS receiver/display and other expenses, the capability to patch spray would equate to an annual cost of around £2000, or £4.00/ha over 500ha. Three mapping and treatment scenarios are examined:

- Mapping every three years, with a low dose / high dose treatment strategy for all three weed species.
- Mapping every two years, with a low dose / high dose treatment strategy for black-grass and cleavers, and an on-off strategy for wild oats.
- Mapping every year, with an on-off treatment strategy for all three weed species.

Table 9.2. Likely costs and potential benefits of weed maps and patch herbicide spraying for a 500ha farm with 250ha of cereals treated variably, averaged over whole farm.

Strategy	Weed map cost (£/ha)	Equipment Cost (£/ha)	Total Cost (£/ha)	Benefit (£/ha)	Net Benefit (£/ha)
Map every year. On/off strategy	6.00	4.00	10.00	15.00	5.00
Map every 2 yrs. Weed-specific strategy	3.00	4.00	7.00	9.00	2.00
Map every 3 years. Low/high dose strategy	2.00	4.00	6.00	4.50	-1.50

The lowest risk treatment strategy (low/high dose for all three weed species) would not be cost-effective, but net benefits of £2.00 and £5.00/ha could potentially be achieved with the other two strategies. Fig. 9 illustrates the effect of the number of fields on a farm (as a % of the total) that have patchy weeds on the potential benefits of patch spraying herbicides compared to the likely costs, for the three different mapping and treatment strategies. Where the sloping benefits line is above the horizontal costs line for that strategy, the vertical distance between them represents the benefit over cost.

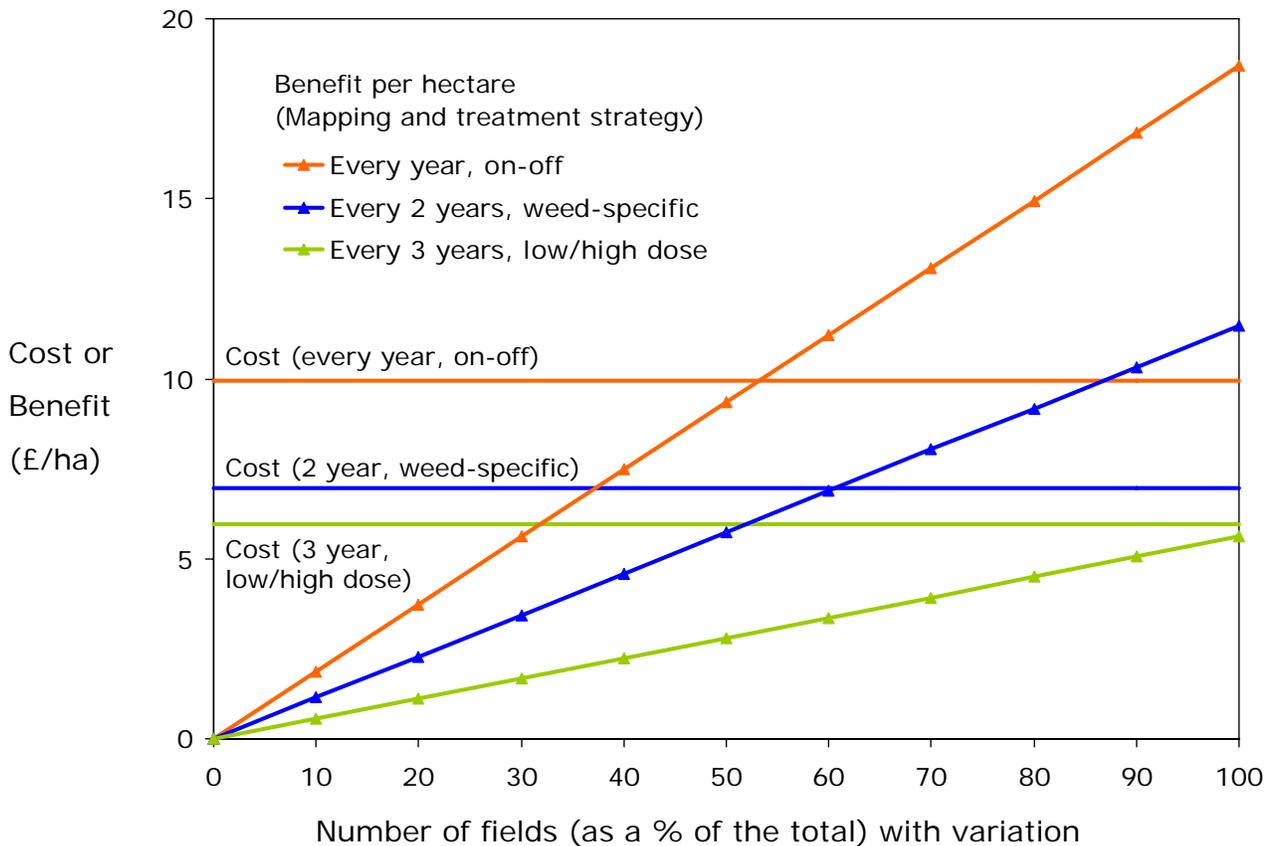


Figure 9. Effect of the number of fields (as a % of the total) on a 500ha farm with patchy weeds, on the potential benefits (compared to costs) of patch herbicide spraying.

If patchy weeds were present in 50% or less of fields on the farm instead of 80%, none of the strategies would have been cost-effective for this farm size. However, using the patch spraying equipment to apply variable rate PGRs as well as herbicides would reduce the equipment cost allocated to this task to nearer £2.00/ha, such that small net benefits of around £1.00/ha could then be achieved even if only 50% of fields had patchy weeds, with the strategies based on mapping every year or every 2 years.

In addition to the potential for an economic benefit to be obtained on farms with a large enough area of crops affected by patchy weeds, spatially variable herbicide treatment could help to reduce pesticide use, and improve plant (and therefore invertebrate and bird) biodiversity within fields. There might also be some positive implications for strategies aimed at delaying or slowing the development and spread of resistance over a field (or farm) as a whole, but this is unclear and selection pressure would remain the same in the weed patches themselves.

10.0 Record Keeping and Traceability

10.1 Records of Crop Inputs

There is a legal requirement to generate and maintain records relating to the use of plant protection products (pesticides) and some fertiliser inputs (e.g. nitrogen applications within Nitrate Vulnerable Zones, NVZs). For example, The Code of Practice for Using Plant Protection Products (Anon, 2005) outlines recommendations for the creation of records of a pesticide application that are needed to comply with EC Regulations (852/2004 & 183/2005) concerning traceability that came into force in January 2006. These records need to include:

- Date of application;
- Site of application;
- Crop sprayed and the reason for treatment;
- Formulated products used and the reference relating to the approval of the product;
- Dose(s) applied and the volume used to make the application;
- Weather conditions at the time of application;
- Other relevant information.

Precision farming technologies have the potential to contribute to the generation of such records by automatically recording the time and position when applications are being made and to provide a framework for the manipulation and storage of these records. However, as indicated above, a complete record of an application of a fertiliser or pesticide spray needs details of the:

- products applied, e.g. fertiliser specification, tank mix components (quantity and formulation details) in a sprayer tank;
- application rates, particularly if these have been varied across a field area.

Most variable rate application systems will operate from a field map and, in a fully traceable system, the control system should generate and maintain records of the intended application rate and the rate actually applied as deduced from sensors monitoring the performance of the application system. In this way, the control system of the application machinery becomes the first step towards the automatic generation of records with information about date, location, and applied rate of liquid or formulated fertiliser product. Information about the crop and weather conditions at the time of

application can come via a farm management system and/or other sensors. Information relating to the materials loaded (tank mix components in a sprayer or fertiliser composition in a spreader) must currently be entered manually.

There are currently no commercially available units that will automatically record the detailed identification/specification of substances loaded into a sprayer tank or fertiliser hopper. A number of research studies have examined how products being loaded into such machines might be recorded in the implement control system using:

- (i) bar codes and bar code readers on the machine;
- (ii) RFID (Radio Frequency Identifiers).

The use of bar codes would have the advantage that the approach is well established in a range of applications including on pesticide containers where they are used mainly for identification at the point of manufacture. They are therefore an integral part of the label. There is no industry standard relating to the use of bar codes for pesticide containers although European projects such as Cristal (Debecker, 2001) have considered the use of EAN (European Article Numbering Association) codes on such containers. The amount of information stored on a bar code can be substantially increased by using two-dimensional rather than simple linear codes. The main disadvantages of bar codes relate to the relatively fragile nature of the code on a pesticide container that is likely to be subjected to harsh environments and problems of contamination of both the code and reading optics. A study reported by Watts et al., (2004) showed that the use of bar code technologies for labelling pesticide or fertiliser containers was unlikely to be successful because of surface contamination of both the code and the reader when using both CCD and laser-based scanners although the CCD type of reader was able to operate successfully with higher levels of contamination. The need for line of sight access between the bar code and reader and good presentation of the code to the reader are also limitations when considering applications on crop sprayers and fertiliser spreaders.

RFID technologies have been identified as appropriate for labelling pesticide containers with the following features:

- High reliability in a harsh environment;
- Read range in the order of 1.0 m with passive rather than active tags and both types not requiring line of sight;

- The ability to read and write to a label tag if appropriate;
- A higher cost than for bar codes although this cost is reducing as the technology develops.

The use of RFID technologies in agricultural environments has recently been reviewed by Blackburn *et al.*, (2008) who concluded that the relative cost, robustness and insensitivity of such tags to surface contamination meant that they were very suited to agricultural environments. These technologies have already been used on small bulk containers used to deliver pesticides to farms in a pilot study in Europe. The tags were mainly used to monitor the use of the containers rather than to provide a means of transferring information from the container to the sprayer control system but the scheme did demonstrate that such technologies could be successfully used in this type of application.

In addition to identifying the materials being loaded into a spreader or sprayer, there is a need to monitor the quantities of such materials. For spreaders with active rate controllers, materials loaded in to the hopper can be monitored, for example, by supporting the hopper on weigh cells. Methods of measuring the quantity of pesticide loaded into a sprayer tank can be based on either volumetric or mass flow measurement. A study reported by Hughes and Frost (1985) concluded that measuring volumetric flows of agricultural pesticide formulations in the un-diluted state was unlikely to be satisfactory because of the wide range of liquid properties associated with such formulations. Volumetric measurements are also unlikely to be appropriate when using granular and other solid formulations. For this reason the work reported by Watts *et al.*, (2003) and Peets *et al.*, (2008) used load cells to monitor the quantity of material loaded into an experimental sprayer fitted with an experimental recording and control system.

Full doses of agricultural spray chemicals range from 50 ml/ha for some insecticide materials and up to 5.0 l/ha for some herbicide formulations. While recent trends are towards reducing this range by not developing formulated products that will be applied in volumes much above 2.0 l/ha, there remains a wide range of use rates relevant to formulations that have to be measured. Many application strategies involve using product at less than the maximum full dose. Container sizes for single trip disposable containers are generally in the range 1.0 to 20 litres with larger returnable containers used for some formulated products. Standards relating to the specification of spray

nozzles for agricultural pesticide application require flow rates to be within +/- 5.0% of the nominal value. It is therefore appropriate that the specification for measuring and recording the quantity of material loaded in to the sprayer should be resolved to this level – i.e. down to 1.25g of formulated product used at full dose and less than this when lower dose applications are to be made. For this reason, the work reported by Watts *et al.*, (2005) and Peets *et al.*, (2008) used a specification for recording the weight of formulated product loaded in to the sprayer of better than 1.0g and 5.0g respectively and found that this was difficult to achieve in the vibrating environment at the loading station on a crop sprayer. Flow meters have also been used to record the transfer of liquid formulations from small bulk containers but there are no published records of systems where the output signals from such flow meters have been directly linked to the sprayer control system.

A study reported by Gasparin *et al.*, (2008) indicated that farmers would be prepared to pay on average between £1,420 and £2,200 (at 2008 prices) for an automated system for generating records of pesticide applications. In addition to the generation of records, the main advantages of such a system were considered in order of importance to be the prevention of mis-application, improved operator safety, improved accuracy of records and labour saving in relation to data handling and management.

Costs and benefits

Because there are currently no commercially available units for automatically generating a complete fertiliser or pesticide application record, this study has assumed that data relating to the chemical products applied by a fertiliser spreader or crop sprayer would be input manually with precision farming technologies aiding the record generation. No added value has been assigned to more accurate records and the benefits have been related only to time saved in generating the records.

It has been assumed that to generate complete pesticide application records would take on average just over two minutes per hectare of treated crop based on the study reported by Watts *et al.*, (2005) and that the savings associated with precision farming techniques would be approximately 10% of the time. On a typical 500 ha arable farm this would give a cost saving of £0.27/ha with costs of £0.21/ha assuming that the equipment costs have been spread over other operations. In this way, precision farming

aids to spray record generation are just cost effective at this scale (500ha) whereas using a similar analysis for fertiliser application records needs at least 700ha before positive financial return results.

10.2 Records of Cultivations and Harvest Yields

The use of a tractor/implement control system with an interface to an in-field location system and the ability to transfer information to the farm office computer is able to generate records of such operations automatically and at a low additional cost. Such records can relate to the time taken to complete the operation, date and area covered. As with crop input records, the type of implement and the operating width would normally be entered manually. There are potential future options for using RFID tags to automatically identify the implant or, in the case of a powered unit with a control system, to use the CAN connection. Data transfer from the vehicle system can be via a direct connection with the office/management computer, via a data transfer unit or via a web-based link (R Price, pers. comm., 2008). Such records can then be used as part of farm management and cost control strategies.

The use of a yield mapping combine that has been correctly calibrated and operated in the field provides records of harvested yield that can be used as an alternative to, for example, monitoring loads going into store over a weighbridge. The records generated provide data relating to the management of cropped areas and also a basis for planning the marketing of grain produced.

Costs and benefits

As with crop inputs, the benefits of using precision farming equipment to contribute to generating records of cultivation and harvesting operations relate to the saving in time and labour and no value has been allocated to the more accurate and reliable records that might result. For cultivations it has been assumed that it would typically take just over a minute per treated hectare and that the cost savings would be in the order of 10% of the total time. This typically gives a cost saving on a 500ha arable farm of £0.12/ha which is unlikely to give an overall benefit if the shared costs of the equipment are included in the analysis. However, if improved cultivation records are seen only as an opportunity cost saving, then this may be a worthwhile benefit particularly if the quality of records are taken into account.

For yield mapping the time savings compared to weighing loads over a weighbridge are likely to be much greater. Assuming an 80% saving in time (allowing for calibration of the yield mapping system) a cost saving of around £1.20/ha might be achievable on a 500ha farm. The cost of the yield mapping equipment is higher and would not be justified for the generation of yield records alone. However, assuming that the same information can be used for multiple tasks, the share of the yield mapping costs could be as little as £0.70/ha for a 500ha farm, giving a potential benefit over cost of about £0.50/ha.

10.3 Traceability

Accurate records go some way to providing a traceable system and will meet the needs of schemes concerned with crop assurance for example. Full traceability of crops involving discrete, high value units such as lettuce or cauliflower can be achieved by tagging produce from different parts of a field area and building records for that area in a spatially linked database (Blackburn, *et al.*, 2008) For bulked crops such as grains this is not a feasible approach and therefore a "passport" approach can be taken where criteria relating to crop inputs and other treatments are checked against a specification within a spatial framework as the crop is produced. Crops that satisfy the specification can then be harvested and sold with a traceable label.

The generation of automated records that are manipulated in a management system enables on-farm inventories to be maintained automatically in, for example, chemical and crop stores. Such elements of a traceability system have an important role to play for example in monitoring the handling and storage of nitrogen fertilisers on-farm (Heather, 2007). Miller *et al.*, (2008 a & b) also noted that the implementation of an automated recording system on crop sprayers and fertiliser spreaders offers opportunities relating to the automatic control of such applicators including the ability to adjust for the physical characteristics of the materials being applied.

11. Whole Farm Systems

11.1 Systems Comprising Multiple Techniques

Many precision farming techniques involve the use of equipment, services or information that are common to two or more procedures. The GPS receiver and display needed for a guidance system could, with the correct specification, also be used for variable rate input application or in yield mapping. Remote sensing and mapping of the crop canopy could be used to guide variable rate application of PGRs, desiccants or fungicides as well as N fertiliser. Information collected through yield mapping could be used to generate offtake maps for P and K, target remedial treatments in under-performing areas and quantify the benefits of variable treatments in addition to providing a record of yield variation. Having made the decision to invest in DGPS, sensing or mapping therefore, the benefits will often be optimised by making as much use of them as possible. Even if a technique is not cost-effective in its own right, if it can cover part of the cost of components used in other procedures, the profitability of the overall system may be improved.

Various authors have examined the economics associated with multiple precision farming techniques. Leiva *et al.* (1997) assessed costs and benefits for a whole system for two farms, one of 150ha and one of 800ha. Costs of technology were estimated at £21050, made up of £3450 for a computer and software, £13000 for GPS, monitoring, mapping and recording for a tractor and a combine, £600 for a GPS signal subscription and £2000 each for variable rate controllers for a sprayer and spreader. An extra £7500 was added for a second tractor unit for the 800ha farm. For the 150ha farm, the average increase in yield needed across the farm was calculated to be 8%, or the reduction in variable costs nearly 30%, with a long pay back period. But for the 800ha farm, the increase in yield needed was only 2%, or the variable cost saving about 8%, to pay back over 5 years.

Østergaard (1997) estimated the potential economic benefit from variable application of N, P, K and lime in five fields in Denmark. Based on a three-year experiment, the overall benefit was calculated to be \$40-50/ha, compared to uniform applications. Schmerler & Basten (1999) recorded an average benefit in Germany of 60DM/ha from wheat grown in farm scale trials on three fields over three seasons where seed and agrochemical rates were varied. Of this, 15DM were derived from N savings (mean 19 kg N/ha), 40DM from increased yield (mean 0.2 t/ha or 3.5%), and 5DM/ha from saved seed (50 seeds/m² or

12%, based on one field / year only). Similar experiments on spring barley in just two field scale trials revealed N savings worth 7 DM/ha and a yield increase of 0.2 t/ha worth 40DM/ha. The same authors calculated system costs of 49DM/ha for a 7100ha farm of which around 50% was suitable for site-specific management. This included DGPS and signal costs, and the capabilities to apply variable rate herbicides, fertiliser and seed rates, map yields and analyse data with a computer.

Godwin *et al.* (2003) defined four different systems for a 250ha farm, ranging in cost from £5/ha for the most basic to £18/ha for the most sophisticated. Assuming that 30% of the farmed area would respond to variable treatments, and for wheat priced at £65/t, it was calculated that the yield increase required in the responsive areas would range from 0.25 to 1.0 t/ha depending on the cost of the system. Alternatively, based on the economic benefits from variable N alone obtained in the experiments by Wood *et al.* (2003), it was concluded that the break even area from this technique would be 80ha for the basic system and 300ha for the most sophisticated.

Coquil & Bordes (2005) reported benefits from the FARMSTAR service in France, based on the use of satellite-derived crop images to generate variable (or uniform) application maps to apply N and agrochemicals, detect stress and organise field walking. Savings of 25-50 kg N/ha were claimed for winter oilseed rape, without reducing yield (and with an increased oil content of 0.5-1.0%), and profits of more than €50/ha. For wheat, profits of around €15-20/ha were claimed from improved targeting of PGRs and management of lodging risk, and reductions in N input.

Courtyard Partnership (Farmers Weekly, 10 September 2008) estimated savings of £21/ha through the use of field management zones, mainly to target variable seed rates and P & K applications. Their calculations suggested that savings from variable N could amount to an extra £50/ha.

McCallum & Sargent (2008) conducted a study based on 8 growers in southern Australia with varying levels of precision farming experience. This was in response to significant uptake of GPS guidance and auto-steer, but little change in the use of yield mapping or variable rate application, due (it was considered) to a lack of evidence of a return on investment. An analysis of costs and benefits was carried out using information on

cropped area, crops grown, soil type, yields, fuel costs, labour costs, input costs, machinery costs, and evidence on benefits from the precision farming techniques being used on the farm (for example reductions in overlaps). The average cost of equipment was calculated at \$44/ha, and the average annual benefit \$18/ha. Average payback period for guidance and auto-steer was calculated at 3 years, compared to 7 years for yield mapping and variable rate equipment.

11.2 A Tool for Calculating Farm-Specific System Costs and Benefits

An objective of this project was to produce an interactive tool that could be used by individual growers of combinable crops in the UK to obtain an indication of the techniques, or combination of techniques, that might produce a benefit over cost for their particular farm. The tool was originally created in Microsoft Office Excel (2003), and consisted of a series of interconnected spreadsheets within one workbook, with the intention of this being adapted to enable web-based access.

A 'main' sheet was created where information on area farmed, crops grown, average yields, expected prices and input costs (including sprays, fertiliser, seed, labour and fuel) could be stored and modified. A facility to enter (separately) the known or estimated proportion of fields on the farm having variation in soil type, crop yield or crop canopy size, and the proportion of fields with patchy weeds, was included, along with the option to specify in more detail the range of variation *e.g.* the (typical) split within-fields between light, medium and heavy soils, the split between small, medium and large canopy areas within-fields, the split between low, average and high yielding areas, and the typical areas within fields containing specified weed species. Finally a 'system generator' was constructed whereby individual techniques could be added or removed, and their individual costs and benefits, and the overall net benefit of the system, displayed.

For each particular technique, a spreadsheet was created to calculate the likely costs specific to that task, the potential benefits, and the net benefit. Benefits were based on the information reported in this review, taking into account published research and commercial experience, or where appropriate calculated from standard figures. Costs associated with equipment, services or procedures that could be used for more than one purpose were calculated in a separate sheet, and their cost then shared according to the

number of techniques chosen that involved them. Where more than one method of achieving a particular technique existed, for example using satellite images or a vehicle-mounted system to provide crop canopy information, or using a low, medium or high accuracy guidance system, an ability to select from two or more options was provided. Where the yield benefits or savings achievable from a particular technique were unknown or very uncertain, an ability to choose different levels of potential yield response or saving (within what were considered likely minimum and maximum values) was included.

To make entry and reporting of key information more straightforward, a 'start' sheet was produced where a grower can enter key information about their farm, its variation and the techniques that they might want to consider. By altering the techniques chosen, the estimates of variability, and the farm size or crop details entered, the calculator provides a means of rapidly identifying the likely impact of changing these parameters on the costs and benefits of each technique, and the system as a whole. By updating some of the default values or over-riding the default options on the main sheet, the calculator can be updated or customised to match even more closely the specific circumstances or requirements on a particular farm.

The output on the 'start' sheet is in the form of a traffic-light style table which indicates, for the chosen techniques, which are unlikely give an economic benefit (cost more than benefit), which might possibly give an economic benefit (benefit equal to 1-1.5 times the cost) and which would probably give an economic benefit (benefit equal to more than 1.5 times the cost) based on the information entered about the farm and its variation. In addition, the net economic benefit of the overall system is displayed.

Based on the output from the calculator tool, Tables 11.1-11.3 show the likely costs and potential benefits from precision farming techniques based on example systems for farms of 300, 500 and 750ha. All are based on the same cropping split (50% winter wheat, 25% winter oilseed rape 12.5% spring barley and 12.5% winter or spring beans). Other assumptions are as outlined in section 3.0. All costs assume common use of equipment (where possible). Therefore although some techniques may only just cover their costs, or may even result in small losses, by covering part of the cost of shared components their inclusion results in a higher margin over cost for the system as a whole.

Table 11.1 Likely costs and potential benefits (averaged over whole farm) from precision farming techniques based on example system for a 300ha combinable farm

Technique	System Details	Costs and Benefits (£/ha)		
		Benefit	Cost	Net
Guidance	Low accuracy, free signal, lightbar display	2.50	0.50	2.00
Variable N application	Use N maps based on canopy images from service provider	9.50	6.75	2.75
Variable PK application	Use PK maps based on grid sampling from service provider	8.00	7.00	1.00
Overall System		20.00	14.25	5.75

Table 11.2 Likely costs and potential benefits (averaged over whole farm) from precision farming techniques based on example system for a 500ha combinable farm

Technique	System Details	Costs and Benefits (£/ha)		
		Benefit	Cost	Net
Guidance	Med-high accuracy, paid-for signal, part auto/assisted steer	14.25	10.75	3.50
Auto-section sprayer boom control	1% saving in spray costs from minimising headland overlaps	1.25	0.75	0.50
Targeted actions to reduce yield limitations	Use yield maps to target compaction	2.00	2.00	0.00
Variable N application	Use N maps based on satellite images from service provider	9.50	4.75	4.75
Variable PK application	Use PK maps based on grid sampling from service provider	8.00	6.25	1.75
Yield mapping	Use yield maps to identify and quantify yield variation	0.00	1.00	-1.00
Yield mapping	Use yield maps to improve farm management records	1.25	1.00	0.25
Overall System		36.25	26.50	9.75

Table 11.3 Likely costs and potential benefits (averaged over whole farm) from precision farming techniques based on example system for a 750ha combinable farm

Technique	System Details	Costs and Benefits (£/ha)		
		Benefit	Cost	Net
Guidance	High accuracy, RTK signal, auto-steer on all vehicles	21.00	12.00	9.00
Auto-section sprayer boom control	1% saving in spray costs from minimising headland overlaps	1.25	0.50	0.75
Map soil textures	One-off EC mapping by service provider (spread over 10 years)	0.00	0.75	-0.75
Targeted actions to reduce yield limitations	Use yield maps to target compaction	2.00	1.75	0.25
Variable seed rates	Use soil texture maps to vary seed rates in variable fields	2.00	1.75	0.25
Variable N application	Use own tractor-mounted sensing system e.g. N-Sensor	9.50	3.25	6.25
Variable PK application	Use PK maps based on grid sampling from service provider	8.00	6.00	2.00
Variable PGR application	Use canopy data from sensing system to vary PGR dose/input	3.75	3.75	0.00
Patch spray herbicides	Map every 2 years. Use weed-specific treatment strategy	5.75	4.25	1.50
Improved fertiliser application records	Use manual product entry to create records	0.25	0.25	0.00
Improved spray application records	Use manual product entry to create records	0.25	0.25	0.00
Yield mapping	Use yield maps to identify and quantify yield variation	0.00	0.75	-0.75
Yield mapping	Use yield maps to improve farm management records	1.25	0.75	0.50
Overall System		55.00	36.00	19.00

As farm size increases, the number of precision farming techniques that could potentially be cost-effective, and the overall margin over cost of the system, increases. Other consequences of farm size include an increase in the level of sophistication that is justified within an individual technique or the system as a whole, and also a greater

probability of owned equipment giving an equal or higher margin over cost compared to a bought-in service from a service provider.

The cost/benefit calculator and the example systems illustrated above are not intended to produce an estimate of the actual costs and benefits that an individual grower would encounter should they choose to use those techniques within that particular system. However, alongside other information sources, the calculator provides a useful scenario-exploration tool to assist decision making by a grower as to which of the available techniques are most likely to be worth further investigation, and the key parameters related to their farm that are likely to influence the economic benefits obtained.

12. Conclusions

The potential for precision farming technologies and techniques to help growers improve their production efficiency whilst simultaneously achieving worthwhile environmental and practical benefits is clear. However, the evidence base of published independent research on the cost-effectiveness of the options available remains small compared to the wealth of services and equipment that are now available commercially. It is vital to ensure that the necessary investment in equipment and time is appropriate, and to enable growers to evaluate for themselves the opportunities that are most likely to benefit their own farms.

The commercialisation of guidance systems for agricultural vehicles has added a new perspective to the integration of precision farming into modern production systems. A key advantage (compared to other techniques) is the relative confidence with which the likely costs and potential benefits can be calculated for an individual farm. With the right system, even smaller farms can achieve some important benefits for a capital investment of little more than £1000. Undoubtedly though, for larger farms investing in a system capable of improving tramline accuracy is imperative to maximise returns.

Where the cost of a DGPS receiver/display could be justified based on guidance benefits alone, the opportunity to upgrade to a system capable of achieving other tasks should be carefully considered. In particular, auto-section control as standard must surely be the aim for larger sprayers of 24m boom width or above, not just for economic reasons but also for the proactive message on targeting of pesticides that this sends out.

The next step in the decision-making process is perhaps the most difficult. The rest of precision farming is largely about variation: identifying, mapping, reducing, managing or monitoring change in it. For farms with little variation the benefits from variable inputs are likely to be small and may not cover the associated costs. However, in many cases growers will only have a rough idea as to how much variation they have unless they have invested in techniques to measure it. The development of systems or services aimed at providing growers with a means of measuring and interpreting underlying variation has progressed less than those aimed at managing it. In particular the benefits that could be obtained from yield map information are undoubtedly being under-exploited, either

because the capability exists on machines but is not being utilised, or because data is being collected but cannot then be analysed or interpreted.

Once the extent of any variation has been determined, an important question is how sophisticated (or expensive) does the management of this need to be? The analysis in this report has generally focused on benefit over cost when using technologies and equipment to automatically map and manage variation at reasonably high resolution within a field. For some growers there may be the opportunity to derive much of the benefit from targeted inputs or agronomy simply by managing part or parts of a field differently to the rest, through manual adjustments to equipment. The possibilities for doing this should always be explored first before investing in variable rate capabilities (although it is acknowledged that many growers will already be doing all that they can without the aid of technology). In some cases this may be facilitated by the use of autosteer, allowing the operator to focus more on adjusting machine settings and less on direction of travel.

The technique of varying seed rates in response to differences in seedbed quality has seen limited uptake by growers, but this may increase as more drills are sold that have the capability. Analysis suggests that the economic benefits are likely to be quite small, and restricted to farms where soils frequently vary from lighter sandy or loamy soils to heavy clays in the same field. If so ECa mapping provides a useful basis for determining the boundaries between soil textures, with appropriate soil inspections.

For the major crop nutrients (N, P & K) the analyses carried out as part of this project appear to indicate somewhat smaller benefits from variable rate application than have been reported commercially (or in some previous research). This is partly because the assumption here is that not all crops on the farm will be suited to a particular technique, and not all fields will have adequate variation to justify varying a particular input. The benefits calculated here have generally been presented as averages over the whole farm, and do not represent the maximum benefit that could be obtained on a particular crop. However this does not mean that the net benefits are understated, because the costs too are presented as an average over the whole farm area. It has also been assumed that existing (average) soil indices or uniform applications on the farm are at the optimum level. In practice this may not always be the case in commercial situations. Nevertheless,

provided that adequate variation exists and the most appropriate option for implementing a technique is chosen, variable application of P & K and N should each result in net benefits equivalent to a few pounds per hectare (slightly more for N on larger farms).

The case for variable rate application of crop protection chemicals is weaker. The potential economic benefits of varying PGR applications within a field are small, and the technique can only really be justified in terms of preventing yield loss (through lodging). If PGR use is further restricted, either by government policy or by end-user requirements, or if their costs were to increase significantly, this could change. The information and equipment used within other techniques could be used to deliver the capability at little extra cost. Although the same could be said for variable application of fungicides, the difference here is that the evidence for a relationship between measurable variation in a crop and its fungicide requirement is lacking, and is likely to be complicated. This technique is very unlikely to be practical or cost-effective therefore in the foreseeable future.

The principles for variable rate application of herbicides are reasonably well established. The necessary capabilities also exist, although not the utopian scenario of on-the-move simultaneous detection and treatment of multiple weed species through varying doses or mixtures. However there are significant barriers to uptake, notably the inconvenience of having to map weeds whilst carrying out other operations or as a separate pass, the difficulty in producing reliable maps, the (understandable) tendency for growers and agronomists to adopt a zero-tolerance strategy for those weeds that have so far shown the potential for management through patch spraying (black-grass, cleavers, wild oats and couch) and the relatively high costs involved. Although there could be economic benefits for growers on larger farms with a high proportion of fields having patchy weeds, the incentive to make use of this technique may depend more in future on issues such as herbicide availability, use restrictions and biodiversity targets.

Precision farming systems have an important role in aiding the generation of records for an arable farming enterprise. Some records are needed to satisfy legal requirements and to provide a means of demonstrating compliance with environmental safety and other regulatory controls. Others provide an important component in the overall management

of the farm. It is unlikely that complete records will be generated with current systems and therefore it is likely that some manual data entry will be necessary. In the future it is likely that RFID labels on fertiliser and crop protection products will enable product labels to be read by the applicator controller with implications for more reliable and accurate records and improved control of the application system. Even with manual entry of some data, it is likely that records generated with the input from precision farming units will be more accurate and reliable than those created by solely manual means and will lead to some time savings. The costs of precision farming equipment is very unlikely to be justified by record generation alone but, once systems have been obtained, the contribution to record generation is likely to have a positive value on most farms of 500ha and above.

The extent to which precision farming techniques are successful and contribute usefully to the management and profitability of a farm is likely to depend upon getting the most out of the investment in time and money. While it is important to consider the costs and benefits associated with each individual technique in order to identify which should be priorities for further investigation or introduction, maximising the net benefit of the system as whole should be the longer-term objective. Farm size, cropping and the extent of variation on the farm will all influence the scope and complexity of the system that is most appropriate. In general though, the larger the farm, the more techniques are likely to be cost-effective and (through shared or spread costs) the greater the likely net benefit of the overall system. However, timeliness is also crucial for most operations and any delays introduced as a result of precision farming methods being adopted could easily result in their advantages being negated in the short term.

This analysis suggests that an appropriate system could deliver average net benefits equivalent to around £6/ha on a 300ha combinable crop farm, £10/ha on a 500ha farm, or £19/ha on a 750ha farm. Between them variable N application and guidance contribute about 80% of the net benefit in each case. However, as the contribution from variable N application depends heavily on the amount of canopy variation present, for many growers guidance will give the highest probability of an economic benefit over cost and is likely therefore to represent their lowest risk entry point into precision farming.

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Appendices

Appendix A. Parameters for 500ha Farm in Cost/Benefit Analyses

Table I. Key parameters assumed for the 500ha combinable crop farm in the analyses

Crop	W Wheat (feed)	W Wheat (bread)	S Barley (malting)	W Oilseed Rape	W/S Beans
Area (ha)	125	125	62.5	125	62.5
Yield (t/ha)	8.00	8.00	6.50	3.50	3.25
Price (£/t)	100	120	130	240	120
NUTRIENTS					
N Dose (kg/ha)	180	240	110	200	0
N Cost (£/ha)	144	192	88	160	0
P Dose (kg/ha)	60	60	55	50	35
P Cost (£/ha)	72	72	66	60	42
K Dose (kg/ha)	45	45	⁽¹⁾ 80	40	40
K Cost (£/ha)	36	36	64	32	32
SPRAYS (£/ha)					
Pre-M Herbicides	15	15	0	20	35
Post-M Herbicides	40	40	31	37	22
Plant Growth Regs.	10	10	4	0	0
Fungicides	74	74	37	38	35
Other	12	12	3	20	8
Seed Costs (£/ha)	54	54	71	38	84
NO. OF PASSES					
Primary Cultivate	1	1	1	1	1
Second Cultivate	1	1	1	1	1
Drill	1	1	1	1	1
Roll	1	1	1	1	1
Spray pre-em	1	1	0	1	1
Spray post-em	5	5	3	4	3
Fertilise N	3	3	2	2	0
Fertilise PK	1	1	1	1	1

⁽¹⁾ Straw removed

Fuel cost £0.50 per litre

Labour cost £15.00 per hour

Appendix B. Stakeholder Meeting Report

A meeting of the Precision Farming Alliance was convened at Peterborough on 7 January 2009. Attendees included growers, agronomists, researchers, equipment manufacturers and service providers, as representatives of key stakeholders in the development and utilisation of precision farming techniques, and with considerable practical experience of their commercial implementation. For the five main topics considered, areas of discussion and debate (during or after the meeting) are summarised below.

Progress in the Development of Tractor and Implement Control Systems

It was recognised that significant technical developments had taken place over the last decade relating to:

- Computing systems
 - On vehicles with functions controlled by micro-computers and with the development and standardisation of CAN bus networks for data transfer within the vehicle and between a vehicle and implement;
 - In the farm office where much greater computing power was now available at a lower cost than a decade ago;
- Sensing approaches
 - Using computer systems to provide interfaces with sensing elements and to enable factors such as calibration and correction functions to be built in to a sensing system;
- Positioning systems
 - The improved performance and reduced costs of satellite-based in-field location systems with established links to vehicle and implement control systems so that, for example, auto-steer systems were now a commercial reality.

Most vehicle and implement control systems were now based on a computing framework providing good linkages for data transfer to the farm office and so providing a framework from which precision farming systems could operate effectively and efficiently. The development of a standardised CAN bus network had important implications for simplifying the wiring on large vehicles such as combine harvesters and facilitating good connections between tractors and implements.

Financial, Practical and Environmental Benefits of Positioning and Guidance

Reducing overlaps during application of fertiliser and spray inputs represents a significant proportion of the potential savings from improved guidance. Observations suggest typical tramline widths of 23.0-23.5m for a farm operating on a 24m system. Assuming a 6m drill, this equates to average drilling overlaps of about 0.2m. Only the more accurate DGPS (+/- 10cm) or RTK (+/- 2cm) systems are capable of improving drilling and thus tramline accuracy. For application passes made using the tramlines, only these systems will result in a reduction in overlaps and therefore input savings.

Unlike manual guidance (where positioning and steering of equipment is likely to be 'biased' towards overlap rather than underlap) GPS positioning is in theory 'unbiased'. However, in practice it is assumed that the implement width would be set at a value to ensure no 'underlap' when the positioning system is at its least accurate *e.g.* 5.90m for a 6m drill when using +/- 10cm accuracy DGPS. Although technically the pass-to-pass accuracy for a 24m sprayer using the more accurate DGPS might still be +/- 10cm, in practice if tramlines are used then the assumed overlap for input applications must be the average drill overlap multiplied by the number of drill widths per tramline width (in this example four), to give an unbiased cost/benefit comparison with manual guidance. There was some debate about this approach, but no agreement on a workable alternative.

It was acknowledged that, when using manual guidance, sustaining overlaps at a level considered to be the 'best achievable' might be unrealistic when cultivating or drilling for an extended period. However, it was also recognised that increases in work rates with GPS guidance may be overestimated when based on overlap reduction alone as this does not account for 'down-time' due to set-up or signal problems. In practice there would be an unknown field/circumstance specific 'relative efficiency factor' that would apply for all comparisons between manual and GPS guidance, but it was accepted that it would be difficult to incorporate this objectively into a cost/benefit analysis.

It was noted that the benefits obtained from auto-section control will partly depend on the accuracy of the DGPS system and signal being used. However anecdotal evidence from practitioners present indicated that the reduction in area sprayed could be as much as 5% in some circumstances.

Traceability and Recording

The importance of generating reliable records was accepted by the meeting with important roles in managing a farming enterprise and demonstrating compliance with food and environmental safety legislation. Good records were vital when analysing the overall performance of a crop or treatment in a given season and also in providing information to other relevant authorities and people.

Precision farming systems had an important role as an aid to record generation by monitoring the time and place of field operations. However, key data such as the fertiliser loaded in to the hopper of the components in a tank mix of spray chemicals had to be entered manually. Research and development had investigated the use of both bar codes and RFID tags as a basis for identifying materials loaded in to application machinery. Bar codes had been shown to suffer from reliability problems in the relatively harsh environment of farm operations but RFID tags had been shown to operate effectively. It was likely that the use of such tags would increase in the future with implications for improved automatic control of application machinery as well as better record generation and handling. Industry standards were needed to aid such developments.

As well identifying materials to be applied, records need to indicate the applied dose particularly where this might be varied across a field area. Commercial systems existed for fertiliser spreaders by, for example, weighing the complete hopper and experimental/prototype loading systems had been developed for crop sprayers.

Complete traceability needed the field machinery to be integrated into a network that involved the farm office, suppliers/supplies on to the farm and the tracking of produce leaving the farm. While this was feasible and practiced for discrete outputs such as some vegetable crops, a different approach was needed for grains. In such cases a passport approach could be operated where 'as applied' maps were integrated into a spatial database so that field areas meeting defined criteria could be identified and mapped if required.

It was recognised that records are often used defensively on farms. It was difficult to ascribe a value to the improved accuracy of record generation and the cost/benefit to the

farming enterprise probably related to the reduced time involved in generating records with precision farming inputs. Improved record keeping and traceability was unlikely to be a prime objective when implementing a precision farming system but should be a useful outcome.

Current and Future Crop and Weed Sensing Capabilities

The implementation of established management strategies for producing arable crops needs a measure of crop development within both temporal and spatial frameworks. For cereals, a number of sensing approaches have been developed mainly based on spectral reflectance measurements. These have been shown to be particularly effective at early stages of growth where, for example, sensed vegetation indices vary substantially with green or leaf area index (GAI or LAI). At later growth stages (LAI > 2.5) the response of such systems is less pronounced. Possible future developments are examining:

- Different ways of interpreting the signals from existing sensing systems using, for example, different wavelengths or the variability of output signal with time/distance;
- Using combinations of sensor types
- Using new types of sensor (e.g. LIDAR).

Commercial sensing systems had recently been developed that used active light sources so as to minimise the effects of variation in ambient light levels. Methods for using the output of such commercial systems had been developed over a number of seasons and growing conditions.

Weed and weed patch detection in arable crops was still by manual identification with no immediate prospect of being able to detect different weeds in different crop conditions automatically. Grass weeds in a grass crop were particularly challenging for automatic detection systems. Methods for generating weed maps from visual detection had been developed and could be converted in to a patch spraying map using analysis methods that would account for factors influencing weed seed movement.

Weeds could be automatically detected in defined environments such as:

- Against a soil (or pavement) background where the sensing was primarily of green leaf material against a dark background;

- Using image analysis approaches in widely spaced row crops where the row structure and plant spacing within the row could provide additional information about crop plant positions.

There was substantial evidence that weed distributions were patchy and if these could be sensed automatically then there would be both financial and environmental advantages from patch spraying. However, manual scouting was slow and expensive and was an important factor influencing the cost/benefit of patch spraying approaches with herbicides.

Targeted Agronomy: Yield Limiting Factors and Responding to Variation

The importance of taking into account seasonal (temporal) as well as within-field (spatial) variation was stressed. It was noted that the value of information on soil, crop or yield variation as a means of targeting field walking should be considered. Benefits from variable N application could include a more uniform crop (easier harvesting, less drying cost) and less lodging as well as increased yield per kg of N. The economic benefit of the latter could increase under more severe restrictions on N use.

The best approach to identifying, mapping and responding to variation in soil P, K or Mg indices or (or fertiliser requirement) is still an area of considerable divergence of opinion. Assuming that average indices on the farm are 'on target' for the crops being grown, and that areas of fields not at the target indices are equally split above and below this, the potential for significant savings in fertiliser use within a single crop in order to cover the annual cost of the technique may be limited. It might be more appropriate to take a longer term view of the benefits, in terms of protecting the yield potential and value of the land. Areas with low soil nutrient levels within fields are usually those in which yield potential is higher (resulting in greater offtake at harvest). Quantifying the yield penalty that is likely to occur if soil nutrient levels drop below target is difficult, and may vary from field to field, farm to farm and season to season. However, to calculate a potential economic benefit over cost, it must be assumed that failing to maintain indices at the target level (or applying adequate fertiliser in high yielding areas to replace the higher offtake) would eventually lead to a decline in yield potential of those parts of the field.

Grid sampling is the main commercial approach to determining variation in soil P, K, Mg (and pH variation on farm). A debate has centred on whether or not the slightly higher cost associated with this approach is necessary, and whether or not interpolation between sample points that are 100m apart (1 sample per hectare in order to keep the sampling and analysis costs to a reasonable level) is valid. There was no consensus on this at the stakeholder meeting or in previous and subsequent discussions. Both approaches are considered likely to have an element of inaccuracy or error. Effective targeted sampling requires a sound knowledge of variation in yield (and/or possibly soil type/depth and field history) in order to determine where to target the samples. Without this, an unbiased grid sampling may be the only option. Where the variation in soil nutrient levels is essentially in the form of a relatively small number of large, well defined areas of high or low status, the two approaches should give similar results, with perhaps slightly greater error in defining the margins with the grid sampling approach. Where the pattern of variation in soil indices is unusual or complicated, for example large areas or wide strips of one soil type interspersed with small areas or narrow strips of a different soil type, there is a risk that grid sampling could result in an inaccurate or misleading map.

Developing a Cost/benefit Tool for Growers of Cereals and Oilseeds

It was suggested that any examination of costs and benefits should allow for smaller farms, not just those of 500-600ha or more. Although yield variation is acknowledged to be a useful indicator of the potential for a farm to benefit from precision farming, many growers are currently not making use of yield map data that they are collecting due to difficulties with processing and interpreting. Perhaps surprisingly, this aspect of precision farming has so far seen little commercial exploitation. There also needs to be an alternative for those growers who don't have yield mapping capability. This might include visual assessments related to the crop, soil variation, or variability in slope, aspect or altitude within or between fields. The possibility of a scheme to provide or assist growers with access to free or subsidised satellite-derived images of crop growth was also raised. The overall cost/benefit calculation when analysing multiple techniques was considered to be very complicated. There was general agreement that a cost/benefit calculator could be a useful tool to assist decision making by growers, but should be used alongside other sources of information. It should also be made clear that the tool is intended to indicate the likelihood of their being a net benefit over cost, and factors that affect this, not to provide growers with an estimate of the actual net benefit they will get on their farm.

Appendix C. Relevant HGCA Publications

Chamen T. (2006). Controlled traffic farming: Literature review and appraisal of potential use in the UK. *Research Review 59*, HGCA, London.

Godwin R J, Earl R, Taylor J C, Wood G A, Bradley R I, Welsh J P, Richards T, Blackmore B S, Carver M J, Knight S, Welte B. (2002). 'Precision farming' of cereal crops: A five year experiment to develop management guidelines. *Project Report 267*, HGCA, London.

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Miller P C H, Lane A G, Wheeler H C. (2002). Optimising fungicide application according to crop canopy characteristics in wheat. *Project Report 277*, HGCA, London.

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