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An Economic Analysis of the Potential for Precision Farming in UK Cereal Production

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Abstract.

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

1 Introduction

The potential benefits of managing crops using precision farming techniques include:

(1) The economic benefit of an increase in crop yield, and/or a reduction in inputs i.e. seed, fertiliser and agrochemicals, and

(2) The environmental benefit from a more precise targeting of agricultural chemicals.

Over the past decade the technology has become commercially available to enable the farmer to both spatially record the yield from a field (Murphy *et al.*, 1995; Birrell *et al.*, 1996; Stafford *et al.*, 1996) and vary both seed and fertiliser rates on a site-specific basis. Significant advances have also been made (Miller & Paice, 1998) to permit the spatial

control of weeds on a site specific basis by varying the dose rate of herbicides depending upon the weed density. However, the benefits of either an increase in yield and/or a reduction in fertilisers and agrochemicals have to be offset against the costs of investing in specialist equipment to enable yield maps to be produced and variable applications to be implemented. The aim of this paper is to address these issues.

A range of potential benefits have been reported, from various combinations of different variable application rate practices. Earl *et al.* (1996) postulated a potential benefit of £33.68 ha^{-1} could be possible combining variable nitrogen application and targeting subsoiling to headlands for a crop of wheat in the UK, when wheat prices were £125 t^{-1}. Increases in returns exceeding £57 ha^{-1} ($80 ha^{-1}), when maize seed rates were varied according to soil depth, were reported by Barnhisel *et al.* (1996). Measured benefits in the range of - £11.14 to £74.09 ha^{-1} (-$6.37 to $42.38 ac^{-1}) were reported by Snyder *et al.* (1998) on irrigated maize in the USA. Schmerler & Basten (1999) measured an average benefit of £38.60 ha^{-1} (60 DM ha^{-1}) when growing wheat on a farm scale trial where both seed and agrochemical rates were varied.

Studies conducted by James *et al.* (2000) investigated the benefits of using historic yield data as a guide to varying nitrogen application, for winter barley on a field with both clay loam and sandy loam soil types. Data from the first years results, i.e. 1997 harvest reported by Godwin *et al.* (1999), indicated that an economic benefit of £27.60 ha^{-1} could be possible. This analysis was based upon spot measurements of the yield rather than those for the complete zone in either soil type, however, it is generally indicative of the potential benefits. A further part of the experiment applied nitrogen based upon the calculated value of the most economic rate of nitrogen (MERN) and nitrogen rate for

maximum yield (NMAX) in the previous year, after the principles developed by Kachanososki *et al.* (1996). The main conclusions of this research were that:

(1) the maximum yield of the response curve for each soil type (NMAX), occurred at the same application rate in each growing season,

(2) the MERN for each soil type were not significantly different, and

(3) based on yield information from previous yield maps, there was no simple variable rate application strategy that provided a yield or economic benefit compared to a uniform application of nitrogen fertiliser.

The work reported in Godwin *et al.* (1999) also demonstrated the effect of the nitrogen/grain price ratio on the economic return to variable application of nitrogen and that at 1999 prices of £80 t^{-1} for grain and £0.30 kg^{-1} for nitrogen the MERN rates were 15 to 30 kg ha^{-1} lower than NMAX.

The costs of implementing precision farming practices have been reported by a number of researchers. Earl *et al.* (1996) estimated the costs of yield map production and the ability to apply fertiliser on a site-specific basis to be £10.46 ha^{-1} for an arable area of 250 ha, at 7% interest rate amortised over a 5 year period in the UK. A later estimate of £7.81 ha^{-1} was made by James (1998), for a similar system, the difference in cost being the reduction in hardware and software cost over the 2 year period and the removal of the DGPS costs. In the same year studies, in the USA, by Snyder *et al.* (1998) estimated the cost of yield mapping and variable rate equipment, for nitrogen application, for two fields of 49 and 64 ha as £8.50 ha^{-1} ($11.88 ha^{-1}). Studies by Schmerler and Basten (1999) reported costs of £15.46 ha^{-1} (49 DM ha^{-1}) for a 7,100 ha German farm, of which 3,900 ha was suitable for site-specific management. The major reason for the higher figures

reported by Schmerler and Basten (1999) was the cost of the equipment to variably apply herbicides in addition to the seed rate and fertiliser.

This paper:

(1) examines the increase in revenues that have been achieved through the use of precision farming practices during a three-year study of 5 fields in cereal production in Southern England, where:

   (a) the effect of variable nitrogen application to both barley (Welsh *et al.*, 2001a) and wheat (Welsh *et al.*, 2001b) using historic yield map and real time shoot density data have been investigated,

   (b) significant yield improvements have been made using "real time" nitrogen management in the wheat crop based upon variations in crop canopy (Wood *et al.*, 2001a), and

   (c) improvements to common crop management problems (e.g. waterlogging, rabbit damage and fertiliser application error, Wood *et al.* (2000a)) can be identified and corrected.

(2) estimates of the costs of upgrading farm equipment, at the time of purchase, to a level that enables precision farming techniques to be practised, and

(3) compares the costs/benefits and analyses the potential returns from adopting precision farming technology for given farm sizes and levels of variability.

2 Potential benefits from adopting precision farming

The potential benefits considered in this paper arise from:

(1) studies to determine the spatially optimum nitrogen application rate using

   a) historic yield, and shoot density (Welsh *et al.*, 2001a & b for barley and wheat respectively), and

b) canopy structure (Wood *et al.*, 2001a for the wheat crop), and

(2) identifying and correcting common site-specific problems associated with crop management.

2.1 *Historic yield*

Variation of nitrogen according to historic yield trials were conducted over a period of three years in three fields, Trent Field, Twelve Acres and Far Sweetbrier, using both variable and uniform application rate strategies (Welsh *et al.*, 2001a & b). The variable rate strategies were divided up to give the following treatments:

2.1.1 Historic yield 1 (HY1).

Where the high yield zone received 25 - 30% more nitrogen; the average yield zone received the standard nitrogen rate; and the low yield zone received 25 - 30% less nitrogen.

2.1.2 Historic yield 2 (HY2).

Where the high yield zone received 25 - 30% less nitrogen; the average yield zone received the standard nitrogen rate; and the low yield zone received 25 - 30% more nitrogen.

A further two alternative strategies, HY3 and HY4, could be extracted from the data. HY3 received 25 - 30% more nitrogen on the high yielding zone whilst the remainder of the field received the standard application rate and HY4 received 25 - 30% more nitrogen on the low yielding zone with the standard application rate applied on the other areas.

The economic consequences, excluding the costs of variable application equipment, achieved from the HY1, 2, 3 and 4 management strategies, with grain at £65 t^{-1} and nitrogen at £0.30 kg^{-1}, are presented in Table 1. It can be seen from Table 1 that HY1 and HY2 produced negative returns in 8 and 6 of the 9 trials respectively. Twelve Acres was particularly unresponsive to variable rate application of nitrogen with only the 1998/99 HY4 strategy producing a positive benefit of £4.55 ha^{-1}.

The mean benefit recorded in Trent field for HY3 and HY4 strategies of £9.67 and £14.15 ha^{1} respectively were a consequence of the crop being grown for malting in 1997/98 and 1998/99. Therefore, to retain the malting quality premium of £10 t^{-1} the applied nitrogen rate was below that required to produce maximum yield.

The mean benefit for each strategy over all fields and all years is presented in Table 2.

The following conclusions can be drawn from the data:

(1) varying nitrogen fertiliser application according to historic yield strategies HY1 and HY2 has not, in these field trials, produced a positive benefit,

(2) the HY3 strategy, of feeding only the higher yielding area, produced a small positive benefit, and

(3) feeding the low yielding areas HY4 produced an overall benefit of £7.59 ha-1.

2.2 *Shoot density approach*

Nitrogen application rate was varied according to the density of shoots (i.e. number of shoots m^{-2}) in parallel with the historic yield studies described above (Welsh *et al.*, 2001a and b). The shoot densities being determined in near real time using NDVI data for the

field from airborne digital photography calibrated against a number of spot measurements of shoot density (Wood et al, 2001b). Two application strategies were adopted:

(1) Shoot density 1 (SD1). Where the areas of high shoot density received 30% more nitrogen; the areas of average shoot density received the standard nitrogen rate; and the areas of low shoot density received 30% less nitrogen.

(2) Shoot density 2 (SD2). Where the areas of high shoot density received 30% less nitrogen; the areas of average shoot density received the standard nitrogen rate; and the areas of low shoot density received 30% more nitrogen.

At the outset of the experiment high and low shoot densities were terms used to express relative shoot densities compared with the field average, which changed from one season to the next. In the second and third years, however, there was little variation in the shoot density along the experimental strip in Twelve Acre, hence a uniform application was made and in Far Sweetbrier there were no relatively high shoot density zones. This naturally led into the more objective approach to nitrogen management based upon absolute values of shoot density using crop canopy management reported in the next section. The economic consequences of managing nitrogen using the shoot density approach are summarised in Table 3, which shows that both SD1 and SD2 strategies produced an overall small positive benefit over the three year period in Trent field.

The apparent reversal of crop response to SD1 and SD2 strategies between the 97/98 and both 98/99 and 1999/2000 seasons, in Trent Field, may be explained by the method used to determine the thresholds between high and low shoot densities. The average shoot densities were c. 1400 shoots m^{-2}, c. 950 shoots m^{-2} and c. 1070 shoots m^{-2} in the

1997/98, 1998/99 and 1999/2000 seasons respectively. If the criteria for defining shoot density in 1997/98 had been applied to 1998/99 and 1999/2000 seasons the high density zone in both seasons would have been re-classified as low and the SD2 strategy would have been the most effective. The variation in establishment was probably due to adverse weather conditions in the 1998/99 season.

Far Sweetbrier performed marginally above standard farm practice in 1997/98 and below standard for the remaining two years for the SD1 regime and significantly better than the standard farm practice for the SD2 regime in the final two years, with a small reduction in 1997/98. There were no high shoot density areas in the 1998/99 and 1999/2000 seasons, therefore, the SD1 strategy only consisted of removing nitrogen from the low shoot density areas, and hence the poor return in these two seasons. Whereas the SD2 strategy added nitrogen to the low shoot dentistry areas improving their response.

The average return of £29.90 ha^{-1} recorded in Far Sweetbrier for the SD2 strategy implies that this method of management could have advantages. This was true especially in the final 2 years of the experiment when due to the absence of a relatively high shoot density zone, the fertiliser management regime consisted of only applying nitrogen to the relatively low shoot density areas.

2.3 *Crop canopy approach*

Two fields, growing winter wheat, were used to conduct variable nitrogen application trials to investigate potential benefits that may be gained from managing the crop canopy in real time by varying nitrogen application (Wood *et al.*, 2001a). Each field plot comprised a series of either 20 m or 24 m wide field length strips with differing seed rates

in alternate strips. Nitrogen was applied uniformly to a 10 m or 12 m wide longitudinal split of the strip at a rate representative of the standard farm practice whilst the remaining 10 m to 12 m strip section received nitrogen at varying rates depending on crop canopy structure. Canopy structure was determined using aerial digital photography (ADP) techniques to measure shoot density and green area index (GAI) as discussed in Wood *et al.* (2000b). Nitrogen application rate was determined according to whether the canopy was observed to be "on-target", "below-target" or "above-target" according to benchmark figures set out in the Wheat Growth Guide (HGCA 1998). The difference in the economic performance of variable and standard nitrogen application for all seed rates are summarised in Table 4.

It can be seen from Table 4 that benefits of variably applying nitrogen in comparison with uniform application, based on the standard farm practise, range from -£1 ha^{-1} (Far Highlands @ 195 plants m^{-2}) up to £60 ha^{-1} (Onion Field @ 200 plants m^{-2}). The mean benefit over all seed rates in Onion Field was £36.50 ha^{-1}. This benefit is marginally more than the mean benefit obtained from SD2 in Far Sweetbrier which over a period of 3 seasons averaged a £33.58 ha^{-1} improvement over the uniform rate of N application for wheat. The overall mean improvement in Onion Field and Far Highlands was £22 ha^{-1}.

3 Estimation of the costs of precision farming systems

3.1 *Precision farming monitoring and control systems*

A full precision farming (PF) system comprises hardware and software to enable variations in crop yield to be mapped and crop related treatments to be variably applied on a site-specific basis. In reviewing the literature it is apparent the cost of practising precision farming techniques is dependent on:

(1) the level of technology purchased, i.e. a full or partial system,

(2) depreciation and current interest rates, and

(3) the area of crops managed.

To determine the realistic cost for UK conditions an analysis was conducted, based on prices quoted by main suppliers of precision farming equipment, in January 2001. It was apparent that precision farming systems can be split into four main classes, as shown in Table 5.

Where:

Class 1. Comprises a fully integrated system from an original equipment manufacturer (OEM).

Class 2. Comprises a full system from a specialist manufacturer.

Class 3. Comprises a full system, which is a combination of OEM and specialist manufacturer.

Class 4. Comprises a basic system – from an OEM comprising the basic elements of a system.

Most new combine harvesters sold in the UK can be fitted with yield mapping hardware, however, the degree of integration between the yield mapping system and other components of the combine operating and performance monitoring system varies between manufacturers. The systems range in functionality from fully integrated yield mapping and combine performance monitoring systems, that can be removed from the combine and fitted to tractors or sprayers and include sub-metre DGPS (Class 1 at £11,363) through to low cost partial systems that provide full yield mapping functionality but reduced application rate control functions (Class 4 at £4,500). The remaining two classes

comprise, Class 2 (at £14,100) is a full precision farming system produced by specialist manufacturers, and Class 3 (at £16,150) is an addition of parts of Classes 1 and 2 which comprise an OEM integrated yield and combine performance monitor with components from specialist manufacturers to be mounted in either tractors or spray vehicles for variable application rate control. This has the added advantage that the parallel systems enable both harvesting and application control to be undertaken at the same time.

The basic system (Class 4 at £4,500), the least cost option, uses a non-differential GPS to provide position information to $\pm$10 m. This provides the operator with the capability to produce yield maps of a slightly lower resolution than those produced using full precision farming systems, but probably sufficiently accurate for most management tasks. Variable application rates are achieved through changing the tractor forward speed whilst maintaining a constant material flow from the applicator in use. The speed control is achieved by the operator manually attempting to match a target speed displayed on the on board vehicular computer screen. This provides a limited range over which the application rate can be varied, dependant on the tractor transmission type, but does permit farmers to make initial ventures into precision farming management without a large capital outlay.

3.2 *Assumptions used and the basis of the cost calculations*

The costs are based on the following assumptions:

(1) one set of variable-application crop treatment equipment, i.e. PF-system, can 'farm' an identical area to that harvested by the combine,

(2) operations involving variable application equipment are not conducted at the same time as combine harvesting (with the exception of class 3),

(3) when multiple PF-systems are used the total area would be divided equally between units, and

(4) the farm office would contain a PC, capable of running yield and application mapping software, therefore, no allowance has been made in the following sections, for the purchase of a new PC.

and comprise of both the capital and associated cost components shown in Table 6.

3.2.1 Combine hardware costs

These reflect the cost of upgrading a new machine, at the time of purchase, from standard specification to a level where yield mapping can be conducted. This includes the yield mapping system, a DGPS unit and software to enable the production of yield maps using the farm PC.

3.2.2 *Tractor hardware costs*

Costs include the extra hardware required to upgrade a tractor to allow the fitting of either the reprogrammed combine unit or a separate platform, from a specialist manufacturer. Generally the tractor hardware consists of mounting brackets and wiring harnesses to connect the on board vehicular computer to the systems and sensors on the tractor i.e. a radar unit for measuring true speed.

3.2.3 *Implement hardware costs*

Implement hardware covers the control systems required to enable application rates to be varied on a site-specific basis according to some predetermined strategy i.e. an application map. In the case of integrated removable and reprogrammable yield mapping systems the implement hardware generally consists of the implement-mounted

control units i.e. motors, metering mechanisms and connecting cables. When non-reprogrammable yield mapping systems are fitted to the combine, this cost also includes those parts of a control platform required to enable application rates to be varied. Implement costs, used in this research, have been calculated using the extra cost incurred when purchasing a new precision farming equipped model of a particular machine compared to the cost of purchasing the same model in standard configuration.

3.2.4 Software

Software is used on the farm PC to process the raw yield data to produce both yield maps and application maps for controlling the application of seed and chemicals on a site-specific basis. Software is usually included in the price of the hardware supplied for yield or application mapping operations and, therefore, is not quoted as a separate cost item in this report. There are, however, a number of companies that supply different types of software, for producing and analysing yield and application maps and typically range in cost from being supplied free of charge for determining fertiliser application rates up to £2,400 for a complete precision farming management package compatible with a wide range of commercially available systems. The latter would have a cost of £1.37 ha^{-1} based upon an area of 500 ha and depreciated over 5 years at an interest rate of 8.5%.

3.2.5 Depreciation of the capital cost

Depreciation of the specialist precision farming components has been assumed to be equal to the rate of depreciation of the host machine, using those rates given in the Farm Management Pocketbook (Nix, 2000).

3.2.6 Maintenance costs

Cost of maintenance of the equipment associated with precision farming is difficult to establish as the equipment is mostly solid state i.e. electronic circuit boards with no moving parts, these components should, therefore, be more reliable than components with many moving parts for instance metering mechanisms. However, they are mounted in a hostile environment that is subjected to vibration, dust, moisture and temperature change, which increases the risk of failure. To allow for this a maintenance cost for the precision farming accessories has been calculated using the same percentage of the initial capital cost as quoted by Nix (2000) for the regular maintenance of the machine to which the equipment is fitted.

3.2.7 Training costs

These have been based on a figure of £300, to cover the salary of the trainee during the time of training and the cost course, provided by a leading agricultural machinery manufacturer, amortised over a period of 5 years.

3.2.8 ***Cost of capital***

Capital has been calculated at a rate of 8.5 % pa, i.e. base + 2.5% (Nix, 2000) and reflects the cost of the initial investment in the precision farming equipment.

3.3 *Precision farming equipment costs*

The basis of the additional costs associated with purchasing new precision farming equipped machinery over the cost of purchasing new non precision farming equipped machinery are summarised in Table 7 for all systems. From which the annual cost per PF-system is then calculated which can then be directly compared to the benefits.

3.3.1 *Annual cost per unit area*

This has been calculated for a range of arable areas that could be managed using a single PF-system i.e. the vehicle mounted computer used to record yield when fitted to the combine harvester and control application rate when fitted to the tractor. The results of the analysis for a Class 1 system, based upon a total cost of £11,363, is presented in Fig. 1 for the depreciation of the initial capital cost, the other associated costs are presented in Fig. 2.

These figures show very clearly the effect of the area per PF-system on the annual cost of the operation, with the costs becoming asymptotic to the horizontal axis. The figures show that the other associated costs are greater than the cost of depreciation of the capital equipment.

The two data sets have been combined in Fig. 3 to show the total annual cost £ ha^{-1} for the range of systems. Fig. 3 shows that the basic system (Class 4) which is significantly cheaper than the full systems is less than £5 ha^{-1} for areas above 250 ha, where corresponding values for the full systems range between £12 ha^{-1} and £18 ha^{-1}. Obviously doubling the area to 500 ha reduces the cost to £2.50 ha^{-1} and £6 - £9 ha^{-1} respectively. These figures are higher than those quoted by Earl *et al.* (1996) and James (1998), for an area of 250 ha, as they include the additional expense of maintenance and training, but are lower than those suggested by Schmerler and Basten, (1999) when the economies of scale are considered.

3.4 *Other costs*

A number of other costs can be associated with the management system for precision farming by providing information on which to base application plans. These are as follows:

3.4.1 Soil texture and soil series

Texture and soil series can be determined by traditional manual surveying techniques from auger samples on an approximate 100 m grid basis or the more recently developed electromagnetic induction techniques (Waine, 2000). These are generally based upon a cost per hectare as given in Table 8, and should be viewed as a "one-off" non-recurrent investment.

3.4.2 Soil nutritional (chemical) status

Status is determined upon a cost per sample, current sampling and analysis costs for a range of nutrients are also given in Table 8. This indicates that nitrogen analysis is expensive if undertaken annually, with one sample per hectare, and explains why there is great interest in targeting the samples needed for this and similar analyses as outlined in Thomas *et al.* (1999).

3.4.3 Crop canopy status

Crop canopy status covers the costs to assist in the management of the crop canopy in near real time using crop reflectance data. This can be determined using either aerial digital photography (ADP) or tractor mounted radiometers (TMR).

The hardware required for obtaining remotely sensed data comprises a pair of digital cameras for use in ADP mounted in a light aircraft (Wood et al, 2001b) or a tractor

mounted radiometer (Boissard *et al.*, 2001) for collecting near-ground crop reflectance data. The annual depreciation and maintenance costs, associated with ADP and TMR equipment, have been calculated using the same assumptions as used for calculating the costs of other precision farming system hardware in the earlier sections, these costs are summarised in Table 9. The TMR may also be hired for a season as indicated in Table 9.

For the farm scales in the UK it is most likely that a service provider, agronomy consulting group or a syndicate of farmers would make the substantial investment (c £15,000) in the digital camera system for ADP. The annual cost of £3,750 would, therefore, be spread over a much larger area than a single farm.

In order to estimate the cost per hectare of acquiring the crop reflectance data using ADP it has been assumed that:

(i) each 3 hour flight could cover up to 3,650 ha and that each field would need to be photographed prior to each application of nitrogen at the 3 growth stages in the January – May period,

(ii) it is possible to make 2 flights per day, and

(iii) weather conditions limit the number of days when images may be obtained.

From the experience of this project, the most difficult period for flying was during the phase in late April early May. Taking the worst-case scenario weather conditions during this period may permit only 2 days of data collection, however, during this period it would be possible to collect up to 15,000 ha of crop data.

The cost of data collected, per flight as a function of the area per flight is presented in Fig. 4, this includes the cost of the plane, pilot, cameras and the technicians to perform the image calibration in the field. It can be seen that the cost is almost independent of the area flown above 1000 ha, and at 1500 ha (a typical day's work for collecting the ground calibration data) would cost £7 ha^{-1}.

The cost of the tractor-mounted radiometer (TMR) is more likely to be borne by an individual farmer or a small syndicate of farmers. The TMR could provide similar, but lower resolution, data to ADP for use in producing fertiliser application plans. However, certain models of TMR can be interfaced with the fertiliser distributor to effect real time adjustment of nitrogen application rate according to crop reflectance. The cost per ha has been calculated, as a function of the area managed per radiometer, using the data in Table 9, and is presented in Fig. 5.

From Fig. 5 it can be seen that the rented TMR and the farmer-owned TMR used for real time control of nitrogen application rate have respectively the highest and lowest cost per unit area. The lower cost per unit area of the TMR used for real time control is due to the lower labour requirement for in-field calibration of the radiometer data with the crop canopy in comparison to that required when application maps are to be produced.

The difference between owning (£10.75 ha^{-1}) and renting (£13.75 ha^{-1}) a TMR being £3 ha^{-1} at 500 ha, however, to be competitive with ADP it would be necessary to manage an area in excess of 1500 ha. The cost of using a TMR for real time control of nitrogen application rate is £5 ha^{-1} for an area of 500 ha.

4 Breakeven analysis

The breakeven analysis has been based on a benefit of £15 ha^{-1}. This has been calculated by subtracting the £7 ha^{-1} cost of acquiring ADP data from the £22 ha^{-1} benefit achieved by varying nitrogen application according to crop needs assessed using real time monitoring of the canopy in Onion Field and Far Highlands. In order to estimate the area per PF-system required to break even the mean benefit of £15 ha^{-1} has been compared with the cost of the four different classes of PF-system shown in Fig. 6.

It can be seen from Fig. 6 how the increase in system cost increases the area per PF-system required for breakeven at an economic return of £15 ha^{-1}, with the exact areas shown in Table 10. The cost of sampling for soil mineral nitrogen has not been factored into this analysis as it is envisaged that it would be conducted as part of an improved uniform application strategy, the cost would be prohibitive for a sampling density greater than that accounted for good field practise (MAFF, 2000).

This shows for a low cost basic system precision farming can be economically viable for areas in excess of 78 ha, rising to 308 ha for the most expensive system for fields responding in a similar way to Onion Field and Far Highlands. These areas would have to be increased if the TMR was used to collect reflectance data, similar to that from ADP, and lower if the TMR was used for "real-time control".

The average benefits obtained from managing Far Highlands on a site-specific basis (namely £7.75 ha^{-1}) are too low to justify the investment in precision farming equipment for nitrogen management alone, however, combined with other benefits listed in Table 9 could prove worthwhile.

4.1 *Other economic benefits*

Benefits of up to £60 ha^{-1} have been achieved in these field trials (Onion Field) when varying nitrogen application rate according to crop requirements determined through the use of ADP to measure the crop canopy. However, there are a number of other factors, which need to be considered. These factors and their possible economic implications are summarised in Table 11.

During the course of this project three examples of the above additional benefits of precision farming were recorded. The cost of water logging, shown as up to £195 ha^{-1}, was calculated using a potential yield reduction of 3 t ha^{-1}, experienced at one of the trial sites following a wet period in the winter of 1998/99 (Wood *et al.*, 2000a). This could have been rectified for a one off cost of £50 ha^{-1} (Nix, 2000) for re-moling the site and clearing blocked drain outlets which could have an economic life in excess of 5 years.

Uneven distribution of fertiliser, which had absorbed moisture during transport and storage, resulted in uneven application and a yield penalty of up to 1 t ha^{-1} during the blanket application phase. This could be corrected by using an alternative source of fertiliser and spreader calibration.

The cost of failing to rectify problems involving pH levels was estimated to be up to £7 ha^{-1}, calculated using yield data from one of the trial sites that was affected by sub-optimal pH levels. The collection of these data using yield mapping techniques enables simple cost/benefit analyses to be conducted to ascertain the scale and extent of the

problem(s), from which estimates of the cost of correction can be made to compare with the potential long term benefits.

Economic benefits resulting from the site-specific control of herbicide (Rew *et al.*, 1997 and Perry *et al.*, 2001) and fungicide (Secher, 1997) application have been included in Table 11. The reported cost savings for herbicides range between £0.50 and £20.70 ha^{-1}, and were achieved by targeted application using patch-spraying techniques. A statistically significant yield increase of 0.3 t ha^{-1}, equivalent to an increase in revenue of £21.67 ha^{-1}, has been achieved by varying fungicide application rate according to crop canopy density.

It can be seen from Table 11 that the potential economic penalties of problems including water-logging due to poor drainage, and poor calibration of fertiliser application equipment, can outweigh the highest increase in benefit achieved, during this research, from spatially varying nitrogen fertiliser. It is, therefore, imperative that the areas affected and the potential economic consequences of these problems are addressed prior to considering the use of spatially varying nitrogen.

4.2 *Sensitivity analysis of field variability*

The scale of any benefit obtained from adopting precision farming practices will ultimately depend on the magnitude of the response and the proportion of the field (%) that will respond positively to variable management. The increase in yield required to break even for different levels of field variability has been calculated using the costs based on Class 1 and Class 4 systems and grain at £65 t^{-1} is shown in Figs 7a and 7b. The proportion of the field (%) responding positively to variable nitrogen management is

based upon data from the shoot density and crop canopy studies, which varied between 12% and 52% of the strip areas and could be estimated for a particular farm using yield maps.

It can be seen from Fig. 7 that for:

(1) areas per PF-system greater than approximately 250 ha, and

(2) areas of the field likely to produce a positive response to site specific management, greater than 30%

the response curves are asymptotic to the horizontal axis. Using these figures as an example shows that minimum yield increases of 1.0 t ha^{-1} and 0.25 t ha^{-1} are required for breakeven for the Class 3 (most expensive) and Class 4 (least expensive) systems respectively, larger potential yield benefits would then be profitable.

5 Conclusions

These conclusions are based upon nitrogen and cereal prices at £0.30 kg^{-1} and £65 t^{-1} respectively, and for equipment prices in the UK in January 2001.

(1) At the above prices the benefits of the variable rate application of nitrogen, based upon crop canopy management using aerial digital photography compared to a standard uniform rate provided an average improvement of £22 ha^{-1}. This was based upon the results of 8 experimental strips in 2 fields of wheat, with a range of seed rates. The fields were located in Southern and South Eastern England and represented soils similar to 30% of the arable growing area of England and Wales.

(2) Applying nitrogen fertiliser based upon the variations in historic yield is not economically justified.

(3) The capital cost of yield mapping and variable application equipment varies from:

(a) a basic PF-system (£4,500) which uses a non-differential GPS system with the yield monitor to produce a yield map and a forward speed indicator to advise the operator of the target speed needed to achieve the required application rate, to

(b) a DGPS equipped unit with greater spatial accuracy and automatically controlled variable application systems ranging in cost from £11,500 to £16,000, depending upon the level of integration and compatibility with existing farm machinery. The most expensive system permitting both yield mapping and spatially variable application to be undertaken concurrently.

(4) The annual cost per hectare of the above equipment over a 5 year depreciation period, at an interest rate of 8.5% together with maintenance and training vary between £4.67 ha^{-1} and £18.46 ha^{-1} for the basic and most expensive system respectively for an area managed per PF-system of 250 ha. These costs will change in inverse proportion to the area managed per unit.

(5) The benefits outweigh the additional costs of the investment in precision farming systems and services for cereal farms greater than 80 ha for basic low cost systems and 200 - 300 ha for the range of the more sophisticated systems. These figures also assume a £7 ha^{-1} charge for crop canopy images either from aerial or ground based systems.

(6) The costs of detailed soil analysis prohibit collection from a dense grid of data points and targeted sampling based upon significant variations in yield or soil type is recommended.

(7) Common problems, such as water logging and fertiliser application errors, can result in significant crop yield penalties. Precision Farming can enable these problems to be identified, the lost revenue to be calculated and the resultant impact

on the cost/benefit to be determined. This provides a basis from which informed management decisions can be taken.

(8) Work carried out by other researchers indicates that savings in herbicide use of the order of £0.50 to £20.70 ha^{-1} can be made.

(9) Currently ADP appears to be less expensive than TMR for collecting NDVI data, however, "real time control" of nitrogen based on a TMR system offers the least cost option.

(10) The scale of the benefits obtained from precision farming practices depends upon the magnitude of the response to the corrective/variable treatments and the proportion of the field, which will respond. Typically a farmed area of 250 ha of cereals, where 30% of the area will respond to corrective/variable treatment requires an increase in yield on the responsive areas of between 0.25 t ha^{-1} and 1.0 t ha^{-1} for the basic and the most expensive system respectively. These figures will change in inverse proportion to (i) the size of the area managed with each PF-system and (ii) the percentage of the field that will respond to treatment.

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Tables and Figures for

An Economic Analysis of the Potential for Precision Farming in UK Cereal Production

R. J. Godwin[1]; T.E. Richards[1]; G.A. Wood[1]; J. P. Welsh[1]; S.M. Knight[2]

Table 1
Economic consequences of the alternative strategies in comparison with the standard farm practice

		1997/98 £ ha^{-1}	*1998/99* £ ha^{-1}	*1999/2000* £ ha^{-1}	*Mean* £ ha^{-1}
1	**Far Sweetbrier** (Wheat)				
	HY1	11.70	-1.95	-26.65	-5.63
	HY2	37.05	41.60	-14.95	21.23
	HY3	7.15	0.65	-5.85	0.65
	HY4	7.80	24.70	-0.65	10.62
2	**Trent Field (**Barley)				
	HY1	-7.15	-8.45	-17.55	-11.05
	HY2	-17.55	0.00	-29.25	-15.60
	HY3	9.10	1.30	11.70	7.37
	HY4	11.70	9.10	14.95	11.92
3	**Twelve Acres (**Wheat)				
	HY1	-20.15	-2.60	-0.46	-7.74
	HY2	-10.40	-3.25	-31.20	-14.95
	HY3	-1.30	-2.60	-3.25	-2.38
	HY4	-0.65	7.15	-5.85	0.22

Table 2
Mean economic consequences, from using historic yield approach all fields all years

Strategy	*£ ha^{-1}*
HY1	-8.14
HY2	-3.11
HY3	1.88
HY4	7.59

Table 3
Economic consequences over standard farm practice achieved using shoot density approach to determine nitrogen application rate

	1997/98 £ ha^{-1}	*1998/99* £ ha^{-1}	*1999/2000* £ ha^{-1}	*Mean* £ ha^{-1}
Far Sweetbrier (Wheat)	4	5		
SD1	7.80	-12.35	-23.40	-9.32
SD2	-3.25	57.85	35.10	29.90
Trent Field (Barley)				
SD1	-29.25	20.80	23.40	4.98
SD2	13.65	-5.85	-6.50	0.43

Table 4
Economic comparisons of variable and uniform nitrogen application rates

	Target Seed Rate (seeds m^{-2})			
	150	250	350	450
	Establishment (plants m^{-2})			
Onion Field	100	143	177	200
	Gross margin £ ha^{-1}			
Variable N	366	432	434	441
Uniform N	349	394	403	381
Difference	17	38	31	60
	Establishment (plants m^{-2})			
Far Highlands	120	195	240	320
	Gross margin £ ha^{-1}			
Variable N	437	397	406	391
Uniform N	417	398	404	381
Difference	20	-1	2	10

Table 5
Precision farming system cost

PF System type	*Hardware cost (£)*
Class 1	11,363
Class 2	14,100
Class 3	16,150
Class 4	4,500

Table 6
Cost component of precision farming

Cost – capital depreciation	*Other - associated costs*
Combine mounted hardware	Maintenance
Tractor mounted hardware	Training
Implement mounted hardware	Cost of capital
Software	Bought in services

Table 7.
Summary of the cost of precision farming equipment

6 PF equipment Cost	*7 Full system*			*8 Basic system*
	Class 1	*Class 2*	*Class 3*	*Class 4*
Initial capital cost	£ 11 363	£14 100	£ 16 150	£ 4 500
Cost of capital	8.5 %			8.5 %
Depreciation all equipment	13% for 5 yr replacement			13% for 5 yr replacement
Maintenance				
Combine	3.5% for 150 hrs use pa			3.5% for 150 hrs use pa
Tractor	8% for 1000 hrs use pa			0
Seed drill	7.5% for 150 hrs use pa			0
Fertiliser distributor	7.5% for 150 hrs use pa			0
Training	£60 pa (£300 over 5 yr)			£60 pa (£300 over 5 yr)

Table 8
Typical fixed area costs

One-off cost	*£ ha^{-1}*	*Annual cost*	*£ sample^{-1}*
Soil surveying (manual)	25	P, K, pH, Mg	9
Soil surveying (electromagnetic induction)	14	P, K, pH, Mg + Cu, B	20
		Available N	
		a) upper, middle and lower samples from 0.9 m deep core	100
		b) 0.9 m core bulked together	40

Table 9
Cost associated with acquiring crop reflectance data

	TMR Purchased	*TMR Hired*	*ADP Cameras*
Hardware cost (£)	10,000	-	15,000
Annual costs (£)			
Depreciation @ 13%	1,300	-	1,950
Maintenance @ 3.5%	350	-	525
Cost of capital @ 8.5%	850	-	1,275
Rental charges	-	4,000	-
Total annual cost (£ pa)	2,500	4,000	3,750
Cost of ground calibration (£ ha^{-1})	4.85	4.85	4.85

Table 10
Breakeven area per PF-system for the average returns
In Onion Field and Far Highlands in 1999/2000

System type	*Breakeven areas (ha) mean benefit £15 ha^{-1}*
Class 3	308
Class 2	240
Class 1	206
Class 4	78

Table 11
Other economic considerations

Factor	*Implication*	*Penalty or Benefit*
Water-logging	Economic penalty	Up to £195 ha-1
Fertiliser application errors	Economic penalty	Up to £65 ha-1
.pH	Economic advantage	Up to £7 ha–1
Herbicide application[1]	Economic advantage	Up to £20 ha-1 [1]
Fungicide application[2]	Economic advantage	Up to £22 ha-1 [2]

[1] after Rew *et al.* (1997), [2] after Secher (1997)

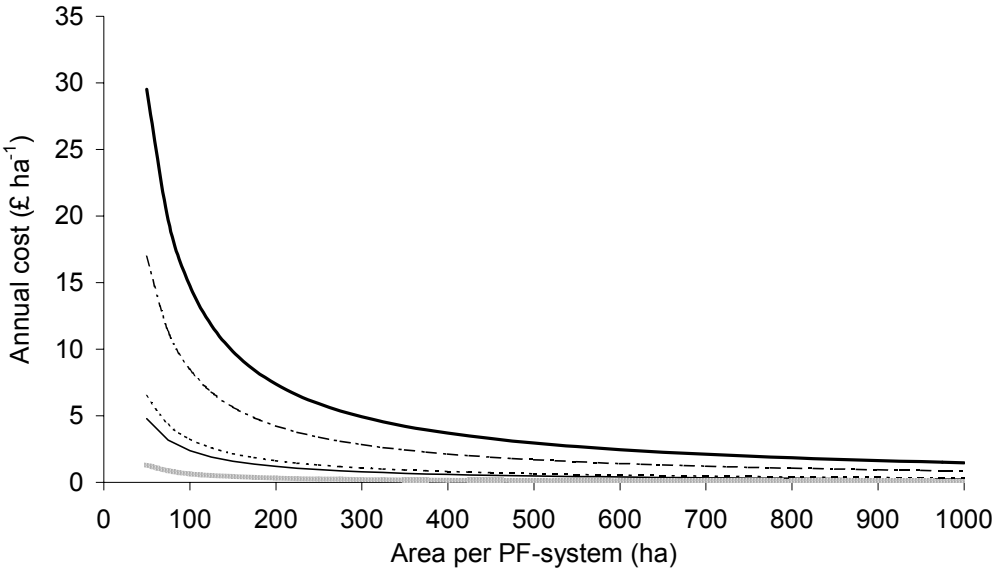

Fig 1. Depreciation of the initial capital cost of precision farming equipment hardware for a Class 1 system for a range of areas per PF-system: ——,Total hardware cost; ·····, Combine; - - - -, Seed drill; ——, Fertilizer distributor; ——,Tractor

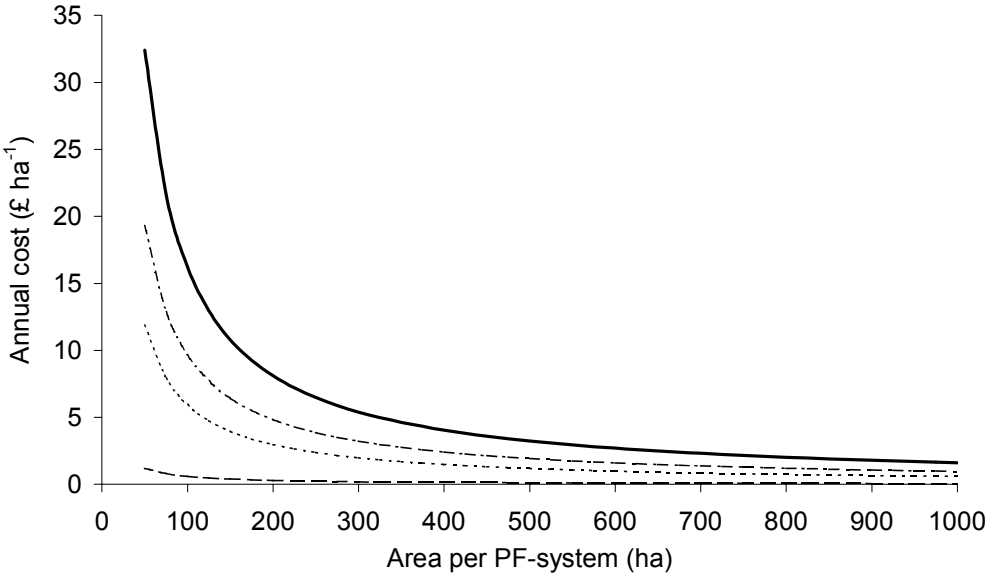

Fig 2. Other associated costs of precision farming equipment for a Class 1 system for a range of areas per PF-system: ——,Total associated cost; - - - -, Cost of capital; ·····, Maintenance; – – –, Training

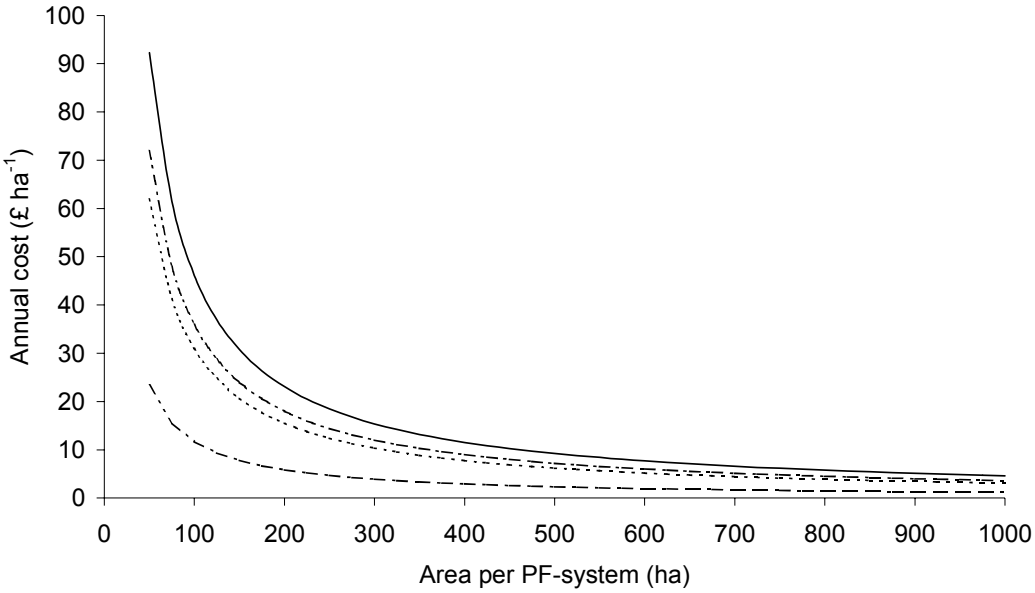

Fig 3 Total cost of four different Precision farming systems compared to area managed per PF-system: ----, Class 1; ·····, Class 2; ——,Class 3; – – –, Class 4

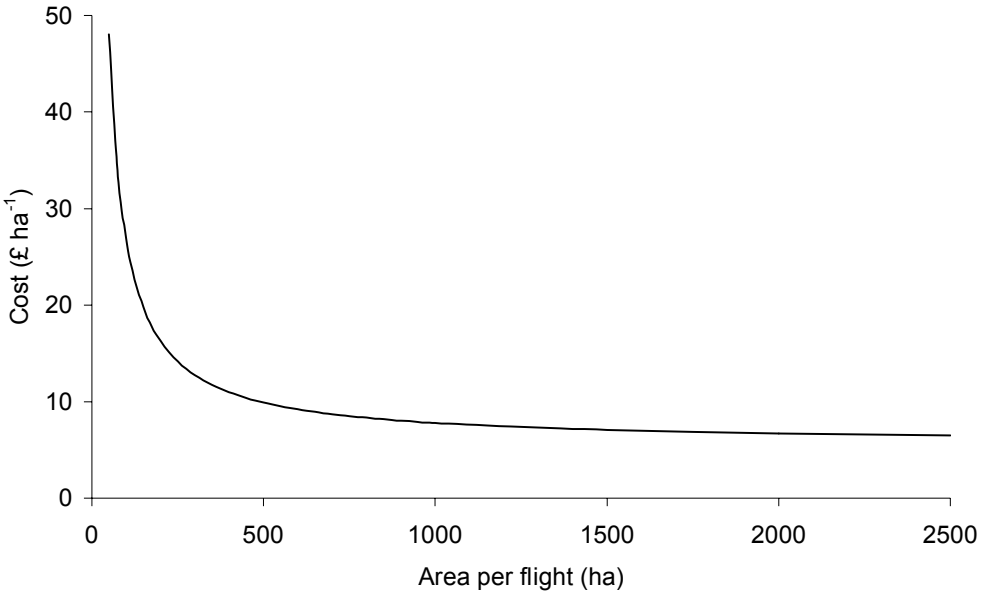

Fig .4 Cost of acquiring crop reflectance data using aerial digital photography

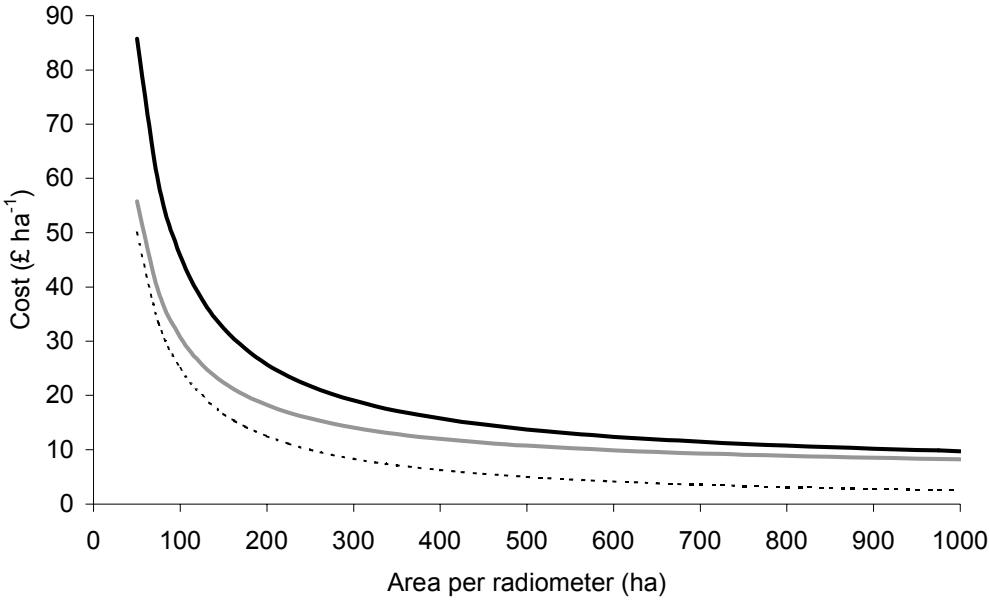

Fig 5 Cost of acquiring crop reflectance data using a tractor mounted radiometer (TMR): ——, TMR rented; ——, TMR farmer owned; - - - - -,TMR real time control

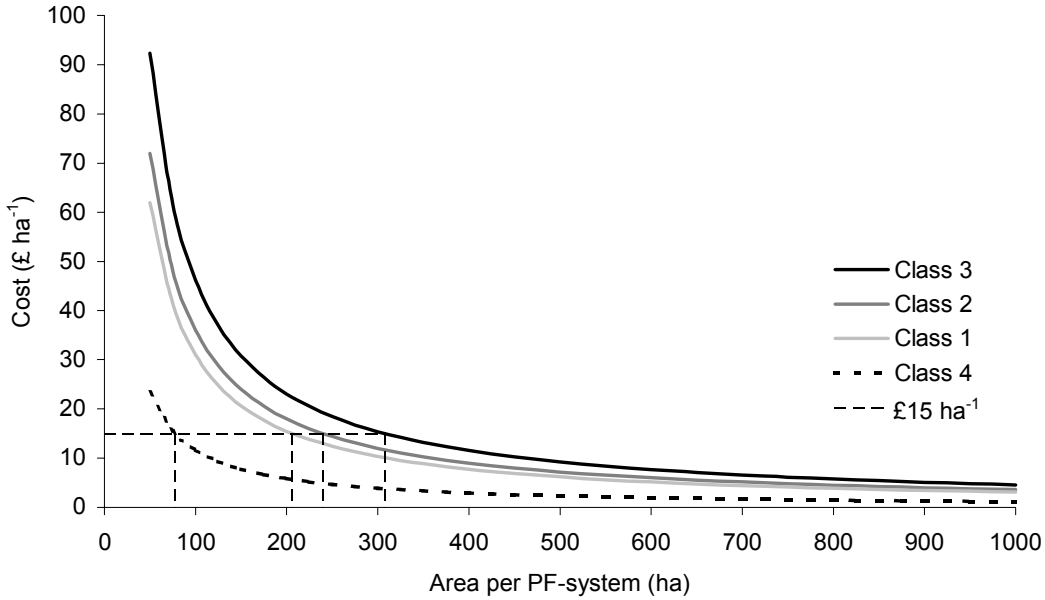

Fig 6. Breakeven area per PF-system for each of the 4 classes of precision farming systems for a return of £15 ha^{-1} : ——, Class 1;——, Class 2; ——,Class 3; ·····, Class 4; – – –,£15 ha^{-1}

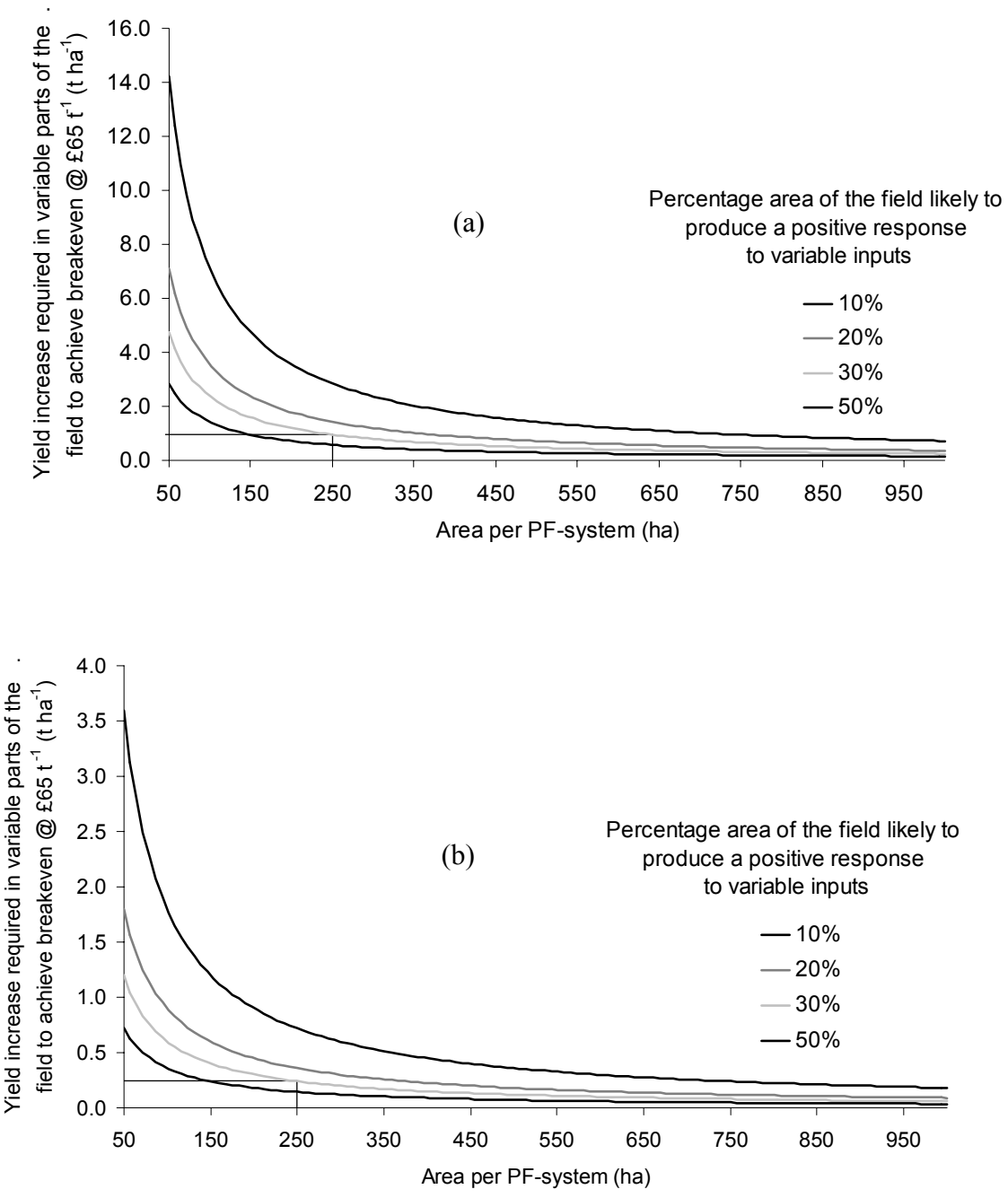

Fig 7 Field variability sensitivity analysis a) Class 3, and b) Class 4 systems: —, 10%;— , 20%; —,30%; —,50%[1]

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An Economic analysis of the potential for precision farming in UK cereal production

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