ASSESSMENT OF FIELD SATELLITE-BASED POSITIONING SYSTEMS FOR REDUCED, MORE PRECISE USE OF CROP INPUTS

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SUMMARY

The mapping of within-field crop yield variations offers a basis for the adjustment of input application rates to match yield potential. The aim of this project was to examine available yield mapping components and systems, and to assess the benefits that could accrue from yield mapping. The work also included site investigations of possible causes of yield reduction, and an evaluation of the potential increase in profitability from variable-rate N application.

Yield mapping requires the continuous measurement of harvester position and grain yield. Accurate positioning was achieved with systems which received a remote correction signal via communications satellite. A grain flow meter in the clean grain elevator gave low errors in conditions where the deflector plate could be kept clean. The production of useful yield maps was sometimes limited by rainy weather leading to wet crops, lodging, and big variations in harvest conditions within the field. Difficulties are also presented by small, irregularly-shaped fields.

The level of within-field variation in cereal yields (25% of the field area at least 21% below the mean) suggests that there is scope for identifying low-yielding areas and either taking corrective action or applying reduced inputs.

An analysis of the results of N fertiliser trials suggests a potential gain from about £20/ha in sugar beet to less than £10/ha in spring barley if N application rate could be varied to apply the optimum amount to each area within a field. All the costs of application map development and variable-rate application would need to fall below these gains to justify the use of the technology.

To allow further use to be made of yield maps, it is desirable that the factors responsible for yield reduction be identified, in particular those which recur each year. In the present study, soil chemical analysis and compaction affected yield in only a small proportion of cases. Differences between maps from successive years have been small.

It is concluded that the immediate financial benefits from the use of this technology will be small. However, in a future where the recording, justification and minimisation of inputs such as pesticides and fertiliser will grow in significance, and where the cost of the equipment and software will continue to fall, yield mapping and variable-rate input application will find a useful role.

INTRODUCTION

The precision farming concept entails the measurement and mapping of crop yield variations throughout a field, followed by treatment of the low-yielding areas to remove the yield-limiting factors, or variation of inputs (seed, fertilisers, pesticides) to match yield potential.

For the measurement of within-field yield variations, on-board grain yield monitors for combine harvesters have been developed. Global positioning systems (GPS) developed primarily for navigation can provide matching location data. This information can be used to produce a yield map showing yield variations in the field. Successful yield mapping requires the following components to work together (Fig.1):

- An on-board GPS system for approximate positioning with a correction signal from a reference station to improve positioning accuracy and undo the effects of selective scrambling of the GPS signal (DGPS). The correction signal can be transmitted from local or remote reference stations, directly or via satellite.
- An on-board grain yield monitor.
- A data transfer system from combine to computer.
- A data analysis system (computer hardware and software) to produce a yield map from the collected data.

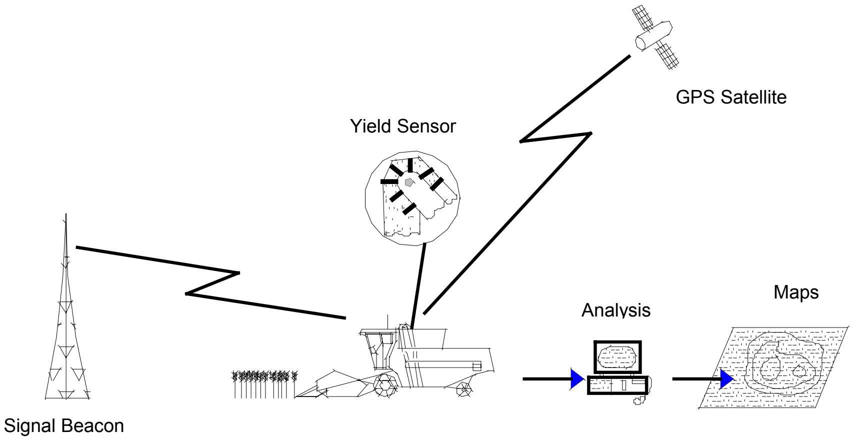

Fig. 1: Schematic of a yield mapping system

The aim of this project was to examine commercially available yield mapping components and systems, and to begin an assessment of the benefits of precision farming techniques in cereal production. The work was divided as follows:

1. Evaluation of yield-mapping components (positioning systems, grain flow-meters, mapping software).

2. Comparison of yield maps from the same sites in successive years.

3. Site investigations of possible causes of yield reduction, in particular nutrient deficiencies and soil compaction.

4. Evaluation of some potential benefits of precision farming, in particular the potential increase in profitability from variable-rate N application in sugar beet and spring barley.

METHODS

Yield mapping systems

Harvest 1996

The following positioning systems were given a preliminary evaluation prior to the 1996 harvest:

1. *Ashtec:* This local base-station system used the same receivers for base station and mobile reception. The co-ordinates for a base station were established at Oak Park House. Tests were carried out with a tractor-mounted mobile receiver travelling on pre-mapped routes within 5 km of the base station. Position accuracies of 1 to 3 metres were obtained. While this was considered adequate, the price of the system was felt to be too high for agricultural applications.

2. *RDS/Sercel:* This system used a remotely transmitted radio signal for differential correction. This signal provided reasonably accurate position values when the differential correction signal was maintained; however, signal reception was intermittent. The system was rejected on this basis.

3. *Navstar:* This was another local base-station system using a 12-channel receiver as base station, and a 6-channel unit as mobile receiver. Tests indicated a typical position accuracy of 5 to 7 metres, which was not considered adequate for agricultural applications.

4. *AGCO:* This system consisted of a local base station with a 10W transmitter, and a mobile receiver. Position accuracy was at least as good as with the Ashtec system.

Following this evaluation, the AGCO system was selected for use in the 1996 harvest.

For grain yield monitoring, an RDS Ceres 2 meter was fitted to a Deutz Fahr 2780 combine harvester. This used through-beam photoelectric sensors to measure the volume of grain passing through the clean-grain elevator. For conversion to weight and correction for moisture content, grain density and moisture content were measured separately and entered via a keyboard.

The SURFER program was used to generate yield maps. This is a widely-used package for the production of contour maps from sample point data. It offers a wide range of data processing and mapping options. In the present case, a 25x16 grid matrix was imposed on the position data set. The analytical method selected was triangulation with linear interpolation.

Harvest 1997

In 1997, a yield mapping system with the following components was installed on the combine harvester of a cereal grower adjacent to Oak Park:

1. *On-board positioning system:* Trimble SV6 mobile receiver, including modem, and VHF radio receiver with VHF and UHF antennae.

2. *Base station:* Navsymm XR5M 12-channel GPS receiver with modem and 10W VHF transmitter. This was located in Oak Park at a point of known co-ordinates. This location was central to the fields to be harvested.

3. *Grain yield meter:* LH Agro LH565 Yield-logger, which measures the force with which the grain strikes a deflector plate in the chute as an indicator of the mass of grain leaving the grain elevator.

4. *Yield mapping software:* Farm Works Site Combo: Farm Trac and Farm Site are part of the Farm Works suite of farm management programs. Farm Site has a facility to plot point data to form a yield map, as well as storing other input and output data for the harvested field.

The system was installed on a new Ford-New Holland TX66 combine harvester with a 5.9 m header and a 6-tonne grain tank.

Harvest 1998

In 1998, a modified positioning system was installed and monitored on the Ford-New Holland TX66 combine harvester. This consisted of a RACAL LandStar Mk4 integrated differential GPS with 12-channel GPS receiver; the correction signal was received from a reference station network via communications satellite (Fig. 2).

The same yield meter (LH565) and mapping software (Farm Trac and Farm Site) were used as in 1997.

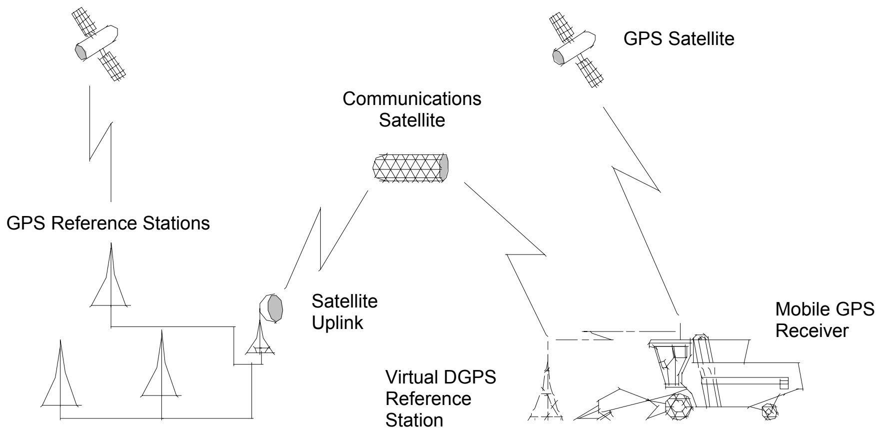

Fig. 2: Schematic of 1998 yield mapping system using communications satellite for reference signal

Harvest 1999

In 1999, the above system was again operated and monitored in the Carlow area. A second system was operated using the same yield monitor, but with a Trimble AgGPS 122 12-channel GPS and beacon receiver, and the correction signal supplied from the coastguard beacon service of the Commissioners of Irish Lights (Fig. 3). This system was fitted on a Deutz Fahr Topliner combine harvester, and operated in Cappoquin, Co. Waterford. For yield mapping, the Ag Leader Precision Map 2000 program was used. This is a dedicated program that plots classified point source data to form a yield map.

Site investigations

In eight yield-mapped fields where it was considered that yield differences might be related to soil pH, P or K levels, these were measured in high- and low-yielding areas. In nine fields where it was considered that soil compaction might be reducing yields, e.g. low-yielding areas near headlands, soil strength was measured with a Bush recording cone penetrometer. The cone had a 12.83 mm base diameter and a 30^{o} angle. At each location, readings were made at 15 depth intervals with 35 mm spacing. This was replicated five times at each location.

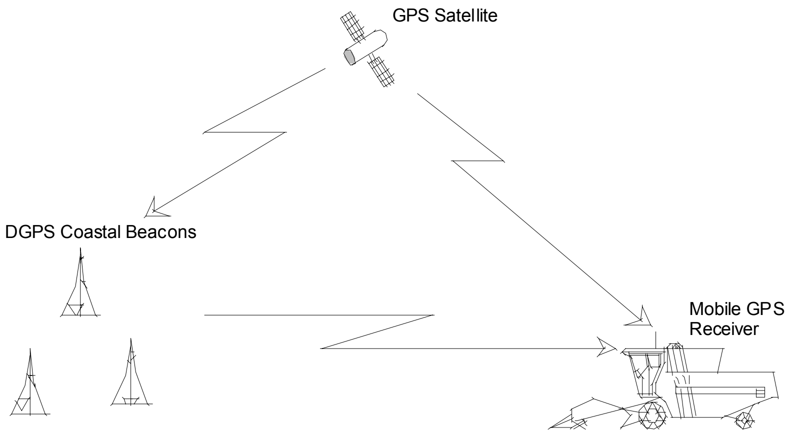

Fig. 3: Schematic of 1998 yield mapping system using coastguard beacon for reference signal

Potential benefits from variable-rate N application

The potential increase in returns from variable-rate N application to sugar beet and spring barley was evaluated as follows:

- N response curves for several sites and years were obtained from published results of fertiliser trials. The assumption was made that the variability in response within these results was similar to that which might occur within a field.

- These response curves were converted from yield to monetary value by taking fertiliser costs and crop values into consideration. Sugar was valued at £250/t, cereals at £88/t and N fertiliser at £0.31/kg.

- The point of maximum monetary benefit was identified on each response curve. The mean monetary return from the application of these optimum rates was compared with a fixed-rate application of the mean optimum rate for each group of response curves. This comparison was made with curves grouped by year, and in the case of sugar beet, by soil N availability.

For sugar beet, 67 yield response curves were generated from the field trial data of Herlihy (1992), on sites with a range of N availability from low (Index 1, continuous tillage) to very high (Index 4, 1 to 2 years from ley). The trials included a zero-N treatment, and the maximum N rate was from 160 to 240 kg/ha. Polynomial functions with either squared ($y=a+bx-cx^2$) or square root ($y=a+bx-cx^{0.5}$) terms were fitted. Those where the predicted maximum y value occurred at x values higher than the maximum N rate in the field trials were excluded from the analysis.

For spring barley, the results of Conry (1997) from five long-term tillage sites for 1990-3 were used to generate 70 response curves. Application rate in these trials was from 75 to 137.5 kg/ha of N in 1990, and from 75 to 175 kg/ha in 1991-3. Quadratic functions were generated. Response curves were excluded from the analysis if the P value associated with the F statistic was under 0.10 and R^2 was higher than 0.8, and if they predicted optimum input levels higher than 200 kg per ha of N.

RESULTS

Yield mapping

Harvest 1996

The yield of winter wheat was mapped in one 10.1-ha field in which variations in crop development were clearly visible. The total yield measured by weighing all loads at a grain intake weighbridge was 90.34 tonnes at moisture contents from 17 to 19%, or 86.5 tonnes corrected to 15% moisture content. The prescribed forward speed calibration was completed beforehand, and moisture contents and hectolitre weights were measured and entered every two hours. In spite of this, yield estimated by the Ceres monitor came to 116.5 tonnes fresh weight, or 108.7 tonnes after moisture correction, an over-estimate of more than 20%. Tests elsewhere with this meter have shown it to give accurate yield estimates (Deutsche Landwirtschafts-Gesellschaft, 1997). The poor results in this case may have arisen from difficulties in mounting the meter on this harvester. In spite of the yield estimate error, the main features of the pattern of yield variation shown on the yield map were reflected in an aerial photograph of an earlier crop (Fig. 8).

Harvest 1997

The TX66 combine was operated between July 18 and Sept. 8, to harvest crops of wheat, barley, oats and rye. The yield sensor was calibrated by weighing four trailer-loads of grain and entering these values for comparison with the meter weights. This procedure was carried out once for each type of cereal. The crops were in 80 fields, which varied in size from 0.5 to 29.9 ha, with an average size of 6.5 ha. High rainfall throughout the harvest period made for very difficult working conditions (Fig. 4).

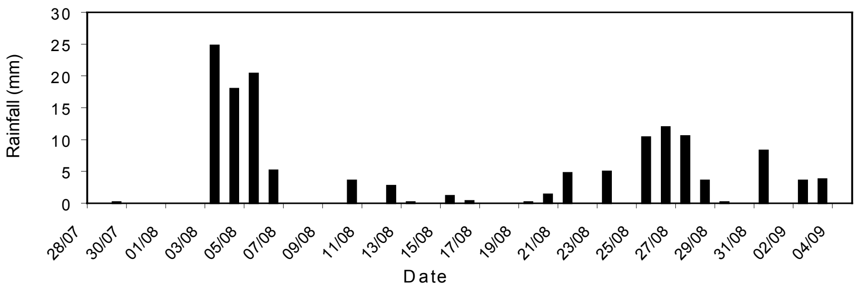

Fig. 4: Rainfall during harvest period, 1997

The grain was transported from each field to a weighbridge, using two 17-tonne and one 15-tonne trailers. The fields were distributed over an area within a 30-km radius of the base station transmitter. Recording of useful yield-map data was limited to about 30 fields throughout which a base station correction signal could be received.

Calibration weighings were carried out in one field each of wheat and barley, and the meter weights in 18 fields were compared with the weighbridge figures (Table 1). Errors were less than 1.5% in five fields of barley harvested before the end of July in good conditions. Of 13 wheat fields, three that were harvested in wet conditions had errors greater than 10%.

Table 1: LH565 yield meter errors in 18 fields in 1997

Cereal	No. of fields	Mean error (%)	Range (%)
Barley	5	-0.09	-2.2 to +2.4
Wheat	13	-1.48	-14.6 to 10.9

The small size, irregular shape and wide dispersion of the fields led to several yield-mapping difficulties:

- Errors at the margins between headland and lengthwise cuts were a particular problem in irregularly-shaped fields.

- When cutting less than a full header width, it was difficult to match accurately the actual and indicated width.

- Practical difficulties with calibration arose in small fields with big trailers remote from the weighbridge. About half of the yield-mapped fields were too small to fill four trailer-loads (as recommended in calibration procedure) after the field had been opened.

- Very big variations were encountered in harvesting conditions, from field to field and within field, due to unsettled weather, in particular high rainfall (Fig. 4). Errors arose due to rapid changes in grain moisture and screenings. Lodged patches were also a problem.

In spite of these difficulties, the yield maps clearly defined areas of reduced yield. In some cases the causes of the yield loss were easily identifiable, e.g. rabbit damage, soil type changes, headland compaction, earlier earth-moving operations.

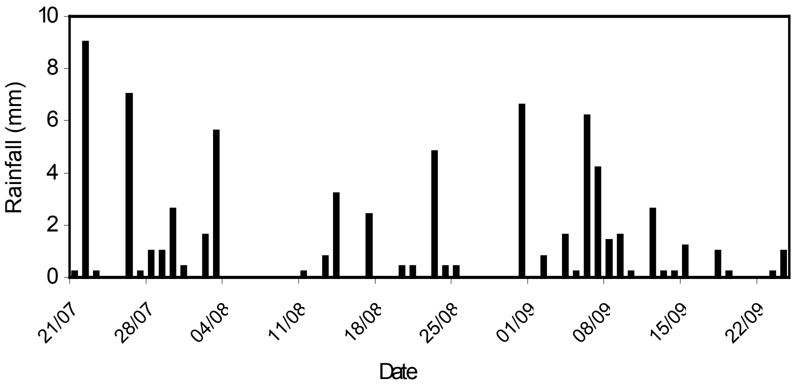

Fig. 5: Rainfall during harvest period, 1998

Harvest 1998

The combine was operated between July 24 and Sept. 21, to harvest crops of wheat, barley, oats, rape and rye. Rainfall was again a problem, with very few dry periods throughout the harvest period (Fig. 5). The crops were in 63 fields with a total area of 392 ha, which varied in size from 0.4 to 16.1 ha, with an average size of 6.2 ha (Table 2).

Table 2: Details of yield-mapped crops, 1998

Crop	No. of fields	Total area (ha)	Meter wt (t)	Meter yield (t/ha)
Barley	18	116.1	724.9	6.2
Wheat	28	163.2	1530.0	9.4
Rye	8	52.0	456.6	8.8
Rape	4	37.0	80.7	2.2
Oats	5	23.9	209.2	8.8
Total	63	392.2	3001.4	7.1

After calibration, meter errors measured in five fields including barley, wheat, rye and rapeseed were all less than 3% (Table 3). These results were obtained in reasonably dry, standing crops.

Table 3: Yield meter errors in five fields, 1998

Crop	Mean error (%)
Barley	-0.2
Wheat 1	-2.5
Wheat 2	+2.3
Rye	0
Rape-seed	+0.3

In the wet conditions that occurred frequently during the season, some additional yield-mapping difficulties arose:

- Fouling of the deflector plate by wet straw in cereal crops.
- Oil deposits on the deflector plate in oil-seed rape crops, leading to adhering deposits of seed and dust particles.
- Changes in grain moisture within fields during harvesting as crops dried out.

Harvest 1999

Fifty-seven fields with a total area of 425 ha (average size 7.5 ha) were yield-mapped in Carlow using the communications-satellite correction signal as in 1998 (Table 4). In Cappoquin, 18 fields with an area of 154 ha (average 8.6 ha) were yield-mapped using the coastguard beacon correction signal (Table 5). Most crops were cut in dry periods in late July and early September (Fig. 6).

Table 4: Details of yield-mapped crops, Carlow, 1999

Crop	No. of fields	Total area (ha)	Meter weight (t)	Meter yield (t/ha)
Barley	6	63.0	415	6.6
Oats	10	41.5	379	9.1
Wheat	41	320.3	2389	7.5
Total	57	424.8	3183	

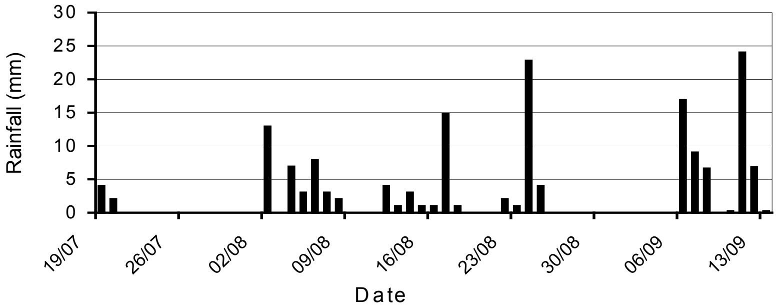

Fig. 6: Rainfall during harvest period, 1999

Table 5: Details of yield-mapped crops, Cappoquin, 1999

Crop	No. of fields	Total area (ha)	Meter weight (t)	Meter yield (t/ha)
Barley	3	29.6	244.9	8.3
Oats	6	38.3	301.3	7.9
Wheat	9	86.2	886.3	10.3
Total	18	154.1	1432.5	

In Cappoquin, calibration was carried out in three crops: barley, oats and wheat (Table 6). After calibration, errors were generally in the order of 1 to 2%. The only errors higher than this were measured in wheat crops towards the end of the season, when harvesting conditions became more difficult.

Table 6: Yield meter errors in five fields, Cappoquin, 1999

Cereal	No. of fields	Mean error (%)	Range (%)
Barley	2	+0.21	-0.6 to +1.0
Wheat	7	+0.96	-5.2 to +6.2
Oats	1	+1.54	

Yield variation within fields

The distribution of yield within each field was expressed as the coefficient of variation (CV) of all the yield readings collected within the field. In 1998-9, the mean CV for yield-mapped cereal crops was 31.5% (range 18-37%), with little difference between cereal types or years. If the yield readings were normally distributed, 25% of the field area would be expected to have a yield at least 21% below the mean, and 5% would have a yield less than 50% of the mean. Although the typical pattern of yield variation was skewed, these estimates of the low-yielding areas were still found to be reasonably accurate (Fig. 7).

For four fields of yield-mapped rape harvested in 1998, the mean CV was 57.3%, with a range from 54 to 61%. This would suggest that 50% of the field area would have a yield differing from the mean by more than 38%. Again the distribution was skewed, with a long tail on the low-yield side.

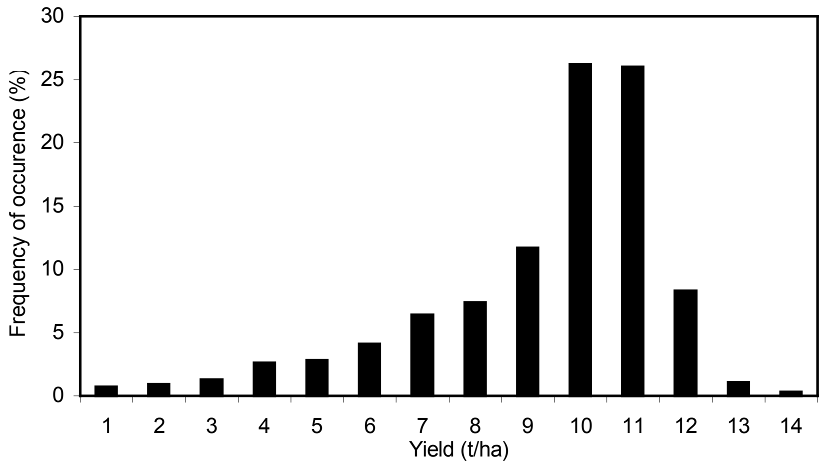

Fig. 7: Yield distribution within a yield-mapped field of winter wheat

Comparison of maps from successive years

In six cases where yield maps for successive years could be compared, the variation in the maps between years was small (e.g. Figs. 8 and 9). In one field where yield maps for two years could be compared with an aerial photograph of an earlier crop, all three showed the same features (Fig. 8). Most of the comparisons were between 1998 and 1999, seasons in which rainfall was adequate but not excessive during the growing season. Bigger differences might have been expected in more extreme conditions.

Comparison of positioning systems

Positioning systems based on local base stations with low-power transmitters are cumbersome to operate and cannot provide a reliable correction signal over a sufficiently wide range. The correction signal transmitted by communications satellite has given accurate, reliable positioning over three harvest seasons. More experience is required with the coastguard beacon service.

Comparison of yield meters

The LH565 yield meter gave low meter errors in conditions where the deflector plate could be kept clean. In the one field in which the Ceres meter was used, the large error may have arisen from difficulties in fitting the meter to the combine.

Comparison of mapping software

The difference between yield maps generated by contouring and simple plotting of classified yield data is illustrated by the two yield maps in Fig. 8. Contouring smoothes the effects of local blips, many of which arise from measurement errors. This smoothing would facilitate an analysis of overlaid maps from successive years. However, a direct plot as produced by Ag Leader or Farm Trac software would be adequate for most purposes.

Site investigations

In a total of eight fields, soil pH and nutrient status was assessed in areas of high and low yield. Differences were small; in only two cases (Fields 1 and 4, Table 7) was there a possibility that reduced yields could be explained by differences in pH or nutrient level.

Of five fields where penetrometer measurements were made in Carlow in 1997, only one had indications of compaction in low-yielding areas at a level that would be likely to reduce yields (Fig. 10).

Table 7: Lime and fertiliser status of soils in high- and low-yielding field areas

Field no.	Yield	pH	P (mg/l)	K (mg/l)	Mg (mg/l)
1	High	7.3	8.0	50	136
	Low	6.4	4.3	147	199
2	High	6.8	6.2	52	208
	Low	6.8	3.9	48	217
3	High	7.1	9.8	43	67
	Low	7.2	13.4	43	81
4	High	6.4	4.0	52	148
	Low	6.1	2.8	64	175
5	High	6.9	2.6	58	62
	Low	6.6	2.1	85	67
6	High	6.7	5.3	15	229
	Low	6.7	10.5	43	239
7	High	6.8	7.7	135	108
	Low	6.8	6.4	109	111
8	High	6.8	11.9	147	156
	Low	7.0	7.8	87	171

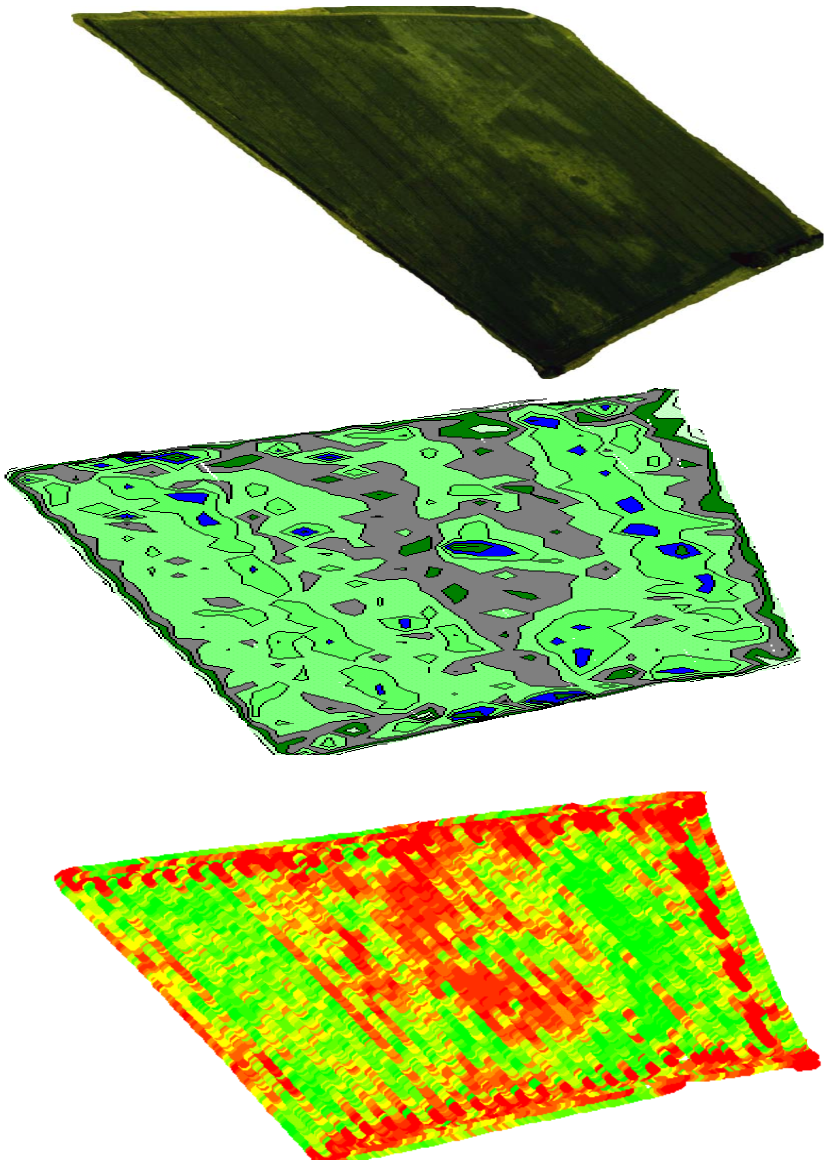

Fig. 8: Comparison of contoured (middle, 1996) with direct plotted (bottom, 1999) winter wheat yield maps and aerial photograph of earlier crop, all in the same field

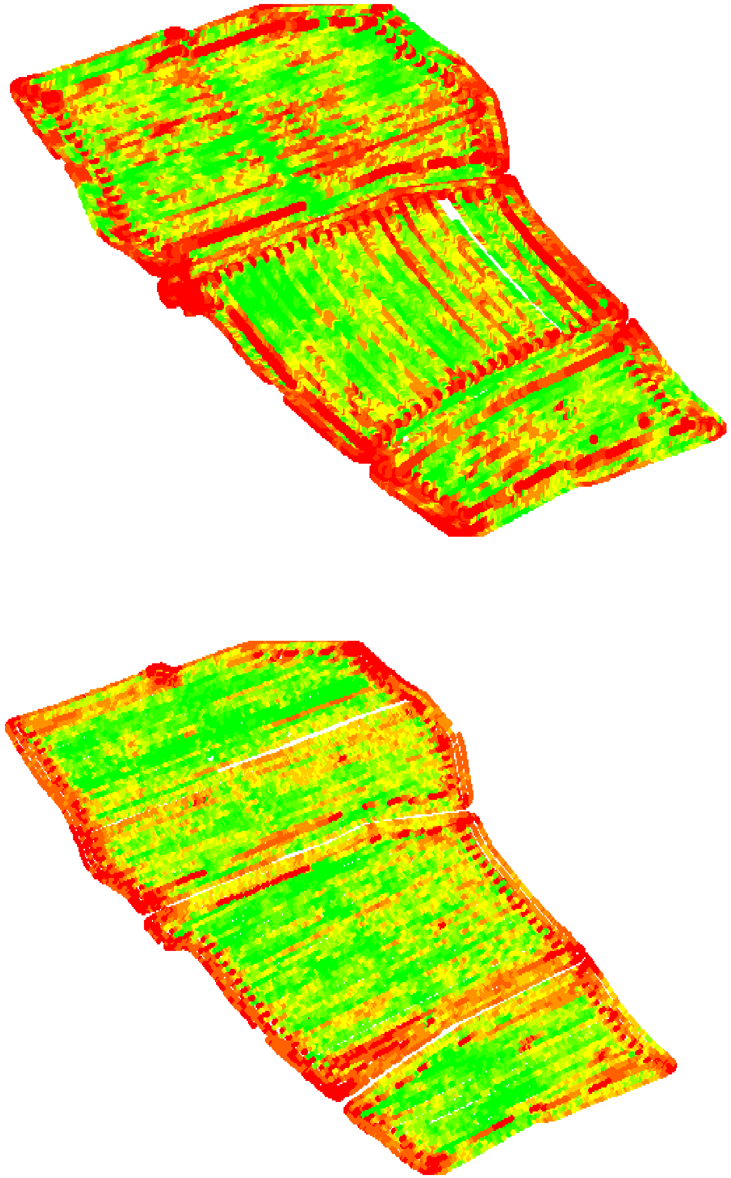

Fig. 9: Yield maps of wheat crops in the same fields in 1998 (below) and 1999 (above). Areas of low yield are red, intermediate yellow, and high green

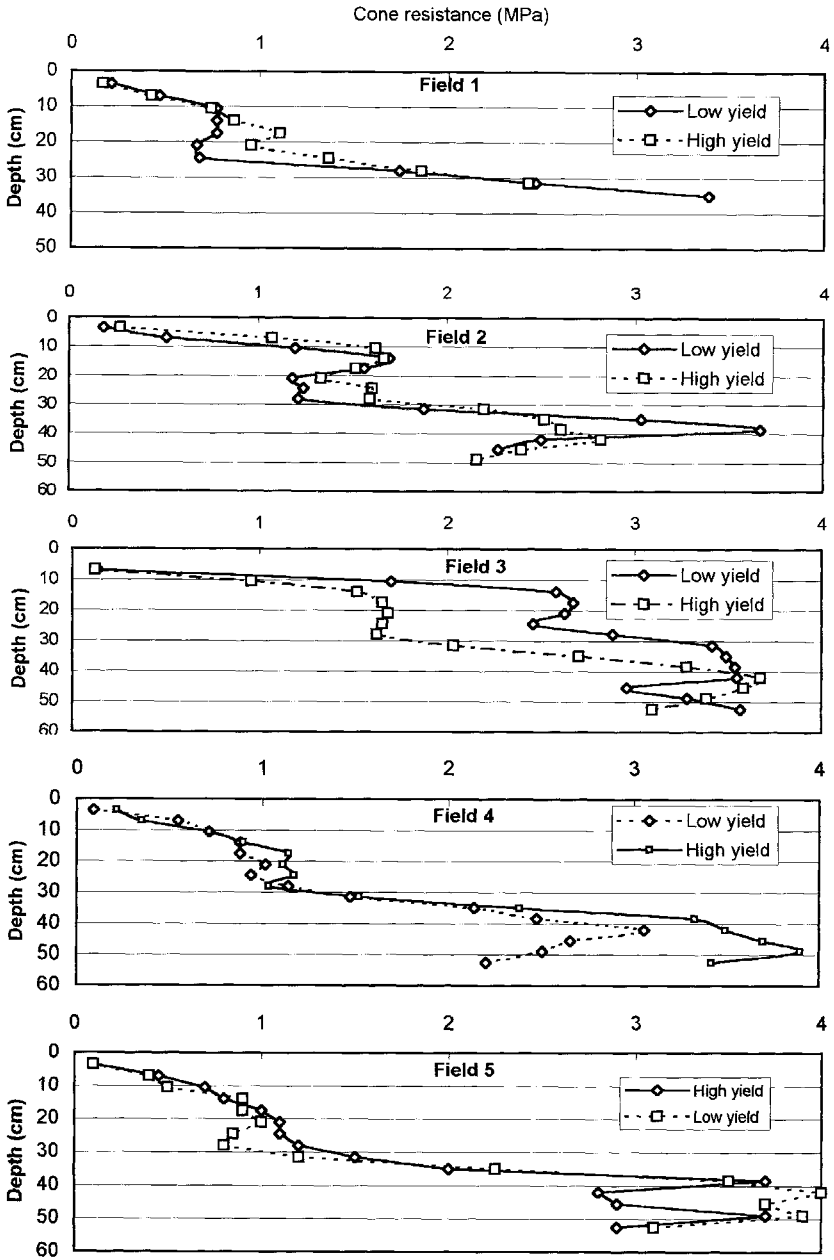

Fig. 10: Results of soil compaction tests in five yield-mapped fields, Carlow, 1999

In one 20-ha field, readings were taken in high- and low-yielding areas in the main body of the field, as well as on a low-yielding headland (Figs. 11 and 12). There was severe compaction on the headland, and an indication of higher compaction in the central low-yielding area, which may have contributed to a yield reduction.

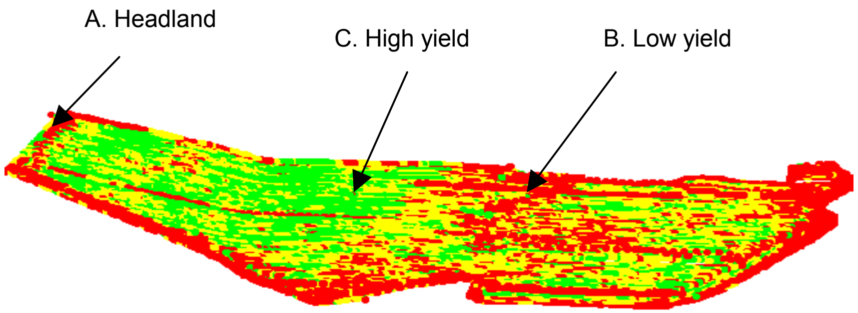

Fig. 11: Areas in yield-mapped field selected for penetrometer tests, Cappoquin, 1999

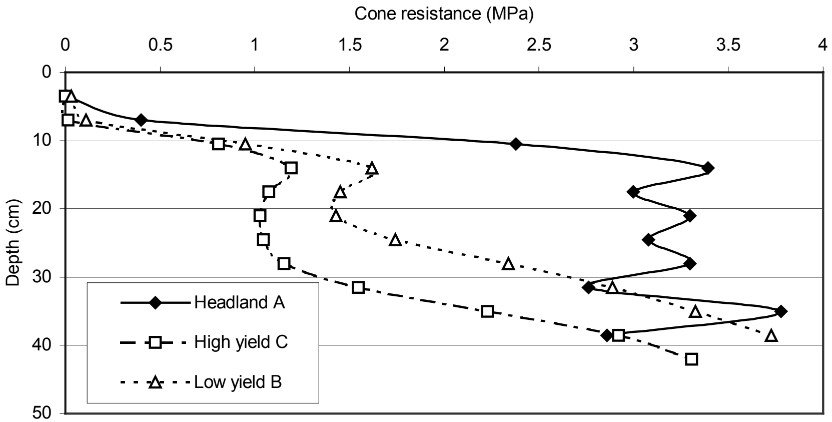

Fig. 12: Penetrometer readings in high- and low-yielding areas, Cappoquin, 1999

Potential benefits of yield mapping

In the sugar beet trials, the mean optimum rate of N was about 100 kg/ha, and the mean optimum sugar yield was 8.6 t/ha (Table 8). When the results were analysed on an annual basis, the gain from variable-rate application was from £19.6 to £50.0/ha, with a mean of £32.6/ha. However, analysis based on N index would be expected to give a more realistic estimate of the gain that could be achieved in practice. Analysis on this basis indicated a mean potential benefit of £18.9/ha (Table 9).

Table 8: Potential gain from variable-rate over fixed-rate application (sugar beet, grouped by year)

Year (no. of curves)	Mean optimum N rate (kg/ha)	Optimum yield (t/ha)	Optimum return (£/ha)	Gain over fixed N rate (£/ha)
1980 (11)	84.9	8.3	2065.1	23.1
1981 (11)	83.8	8.3	2064.3	50.0
1982 (11)	99.8	9.8	2460.1	34.7
1983 (27)	88.2	8.5	2117.7	32.1
1984 (5)	120.9	10.4	2601.9	25.0
1985 (2)	177.9	8.2	2039.8	19.6
Mean (yearly)	109.3	8.6	2152.0	32.6
Mean (all curves)	94.6	8.6	2147.0	37.6

Table 9: Potential gain from variable-rate over fixed-rate application (sugar beet, grouped by N index)

N index (no. of curves)	Mean optimum N rate (kg/ha)	Optimum yield (t/ha)	Optimum return (£/ha)	Gain over fixed N rate (£/ha)
1 (12)	137.2	9.5	2368.7	13.4
2 (28)	102.9	8.9	2227.8	17.8
3 (11)	82.3	8.4	2110.7	19.2
4 (16)	69.9	8.3	2072.3	23.9
Mean	98.1	8.6	2149.0	18.9

With spring barley, the mean optimum N rate was about 140 kg/ha, and the mean optimum yield was 7 t/ha (Table 10). On an annual basis, the gain from variable-rate application varied from £2.4 to £7.8/ha, with a mean of £5.5/ha. In a combined analysis over all years and sites, the gain from variable rate application was £9.5/ha.

Table 10: Potential gain from variable-rate over fixed-rate application (spring barley, grouped by year)

Year (no. of curves)	Mean optimum N rate (kg/ha)	Optimum yield (t/ha)	Optimum return (£/ha)	Gain over fixed N rate (£/ha)
1990 (11)	125.3	6.4	562.8	4.4
1991 (18)	137.1	7.1	625.4	2.4
1992 (20)	146.2	7.1	623.5	6.3
1993 (21)	160.8	7.2	635.7	7.8
Mean (yearly)	142.3	7.0	612.5	5.5
Mean (all curves)	145.1	6.9	608.5	9.5

In a similar type of analysis in the UK, Yule *et al.* (1996) estimated potential gains from £10 to £17/ha from variable-rate N application to winter barley.

The sugar beet analysis suggests a potential gain of about £20/ha if N application rate could be varied to apply the optimum amount to each area within a field. With spring barley, on the other hand, the potential gain would be less than £10/ha. Values for winter cereals are likely to lie between these extremes. All the costs of application map development and variable-rate application would need to fall below these gains to justify the use of the technology.

CONCLUSIONS

Yield mapping is the first step in what is now widely known as precision farming. The technology for yield mapping is now largely in place. Global positioning systems using either beacon- or satellite-based correction signals are freely available; the satellite-based system has proven accurate and reliable, but more experience is required with the beacon service. Recent removal of selective availability from the GPS signal will improve accuracy still further, but will not affect equipment selection. Several makes of on-board grain yield monitors are also available; in good harvesting conditions and with appropriate calibration their accuracy is adequate for yield mapping. The level of within-field variation in cereal yields measured in this project (25% of the field area at least 21% below the mean) suggests that there is some scope for identifying low-yielding areas and either taking corrective action or applying reduced inputs.

In Ireland, the production of useful yield maps is sometimes limited by rainy weather leading to wet crops, lodging, diminished yield meter performance and big variations in harvest conditions within the field. Difficulties are also presented by small, irregularly-shaped fields.

Yield maps should be used in the first instance to inform land use decisions. The yield data collected could also be added directly to the crop record-keeping system.

To allow further use to be made of yield maps, it is desirable that the factors responsible for yield reduction be identified, in particular those which recur each year. In the present study, soil chemical analysis and compaction affected yield in only a small proportion of cases. Differences between maps from successive years have been small.

In areas within the field where the causes of yield reduction cannot be removed, application of reduced inputs in those areas comes into consideration. Adjustment of nitrogen fertiliser rate in relation to potential yield would have the additional bonus of reduced leaching losses. If N application rate could be varied to apply the optimum amount to each area within a field, the potential gain is likely to vary between about £20/ha for sugar-beet and less than £10/ha for spring barley.

As a next step in the development of precision farming, technology for mapped variable-rate application of inputs needs to be evaluated. This includes methodologies for application map development as well as the on-board control of application machinery. The immediate financial benefits from the use of this technology will be small. However, in a future where the recording, justification and minimisation of inputs such as pesticides and fertiliser will grow in significance, and where the cost of the equipment and software will continue to fall, precision farming will eventually find a useful role.

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