A Review of the Technologies for Mapping Within-field Variability

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Abstract

Techniques for mapping soil physical and chemical condition, topography and the weed status of fields, are reviewed from a practical and economic perspective. The conclusions are that it is possible to target sample the soil physical and chemical status of fields and locate areas of high weed density following the use of inexpensive, non-invasive techniques (EMI, aerial digital photography (ADP) and radiometry). Semi-automated field reconnaissance systems on all terrain vehicles and combines also assist in locating the position of weed patches. P and K fertiliser can be replenished by using the "off-take" values determined from yield maps, whilst crop density in the spring period shows potential for the management of nitrogen fertiliser in cereal crops using ADP and could also be a benefit in the application of agrochemicals. Currently the most economically viable method to determine field topography is to use very simple surveying techniques, there is potential to automate this.

1 Introduction

The field factors influencing yield variation are given in Table 1, these are represented from an operational perspective in two major groups, namely: those over which the farmer has little control and those over which he may be able to influence the final yield. Neither these groupings or the solutions are new; farmers have been addressing these problems for centuries.

These factors can be regrouped into 4 major categories for the purpose of determining both the level and extend of the variability, see Table 2, which also indicates the most promising methods. Each of the Groups in Table 2 will be reviewed for those with the greatest practical significance and have seen a substantial research input for temperate agriculture.

2 Soil-Water factors

The correlation between the variation in yield and the variation in available water content has been well documented (Forbes & Watson, 1992; Braum *et al.*, 1999). Available water content is a function of soil texture (Hall *et al.*, 1977), therefore, an understanding of soil textural distribution is an essential when considering precision farming.

A field with a large range of soil texture may warrant management based upon that variation, whereas a more uniform textural variation may not. This is illustrated in *Fig.*1 which shows the semi-variogram of yield for 3 fields in the United Kingdom where Shagsby shows a significant variation in yield (2 t/Ha) over a 70 m distance, Twelve Acre (1.2 t/Ha) over 25 m distance and Holly Field effectively no variation other than the random error of measurement (Lark *et al.*, 1998).

One of the limiting factors linking the commercial application of precision farming is the cost of sampling data at sufficient intensities to provide accurate mapped information (Fogbrook, 1999). Whilst mapping soil-water features may only need to be a one-off operation, current prices (£25/sample, US$38/sample) for manual sampling limit the sampling intensity to one 1 m deep auger sample per hectare (100 m grid) of which *Fig.*2 is typical. This shows three principal soil series; the Wickham series (clay loam over stoneless clay) is a poorly drained stagnogley whilst the Ludford (clay loam) and Maplestead series (sandy loam) are more freely draining brown earths. Soil sampling at this intensity gives a reasonable overview of the major soil types/textures and enables targeted profile pit excavation at (1-2/series) to enable farmers to adjust to the practical significance of the variability in their fields. However, this sampling density is inadequate for varying seed rate and nutrients.

In arable soils where salinity is not a significant factor, measurements of electrical conductivity are primarily a function of soil moisture and clay contents. Recent studies into the use of electrical-magnetic induction (EMI) have shown strong correlation with soil texture when the survey is conducted with the soils at field capacity, see Figs.3 and 4 for two different fields (Waine *et al.*, 2000). This is based upon the unique relationship for both the volumetric moisture content at

(1) field capacity (FC), i.e. when the macropores have drained 2-3 days after rainfall or irrigation, and

(2) permanent wilting point (PWP), i.e. the moisture content at which plants are permanently wilted and will die if water is not added

and soil texture as suggested by the USDA in 1955 and given in Brady (1990) using the USDA soil textural classification.

The data in Figs. 3 and 4 show the equivalent UK data from Hall *et al.* (1977) namely the UK FC and UK PWP lines. The abissa for these figures was based upon a textural fineness class for the soils using the weighted index given below by Waine (1999):

$$\text{Fineness class} = -0.898\,(T_w^{\,2}) + 3.8704\,(T_w) + 1.9686 \qquad (1)$$

$$\text{where: } T_w = 0.03\,(\%\text{ clay}) - 0.004\,(\%\text{ sand})$$

These figures show that for the representative soils that the sandy soils will be at field capacity and permanent wilting point at much lower moisture content values than the loam and clay soils. Fortunately, the slope of the UK relationships for the FC line whilst becoming less steep at the clay end of the textural band does not exhibit the same plateau effect as the US line. Hence this relationship is a valuable indicator of soil texture for a given volumetric moisture content at field capacity. UK soils are typically at field capacity during the period from mid-November to April. The data collected at field capacity in February and March respectively show a close relationship with the conceptual relationships using the data from Hall *et al.* (1977).

Studies conducted at other times in the growing season, as shown for July and August, are valuable in estimating soil moisture deficits to indicate levels of crop moisture stress which could then form the basis for variable irrigation purposes. The studies by Waine *et al.*, (2000) concluded that it would be possible to determine soil texture to within one textural group, but would required targeted field soil data collection for total confidence.

The results of a detailed study by James *et al.*, (2000), using an EMI scanner along 24 m spaced field tramlines at intervals of 10 m for the field shown in *Fig.*2 is given in *Fig.* 5. This shows higher electrical conductivity values corresponding with the clay loam over clay soil with lower values corresponding to the sandy loam soils. The results of detailed studies of soil texture of 168 cores collected using a tractor-mounted soil coring device at a grid spacing of 50 m for the perimeter of the field and 24 m in the central zone are shown in *Fig.* 6. Comparing the revised textural boundaries with the EMI results in *Fig.*6 show a close correlation between EMI conductivity readings and the textural boundaries of the detailed soil survey. This method has been improved by using an objective technique, cluster analysis, which, when applied to EMI data, provides a method to zone fields into classes reflecting underlying variations in soil texture and other physical properties, Taylor *et al.* (2001).

Currently EMI surveys cost £14/ha, (US$20ha) (Smith, 2001) from which it can be concluded that EMI surveying provides a cost-effective method to compliment traditional soil survey practices by providing rapid, non-invasive information on the variation in soil texture and available water. The traditional survey methods could then be focussed upon the transects XX^1 and YY^1 in *Fig.*5. The yield map in *Fig.* 7 shows an average of 1 t/ha difference in the average yield between the major soil groups.

There is now from commercial sources, evidence that EMI will also distinguish between different levels of soil compaction (Smith, 2001) as shown in *Fig.* 8 (left). The patterns running across the map result from compaction caused by farm traffic travelling between the gates on the left and right of the field. The effect of subsequent targeted soil loosening of those traffic lanes only is shown in *Fig.* 8 (right).

Following surveys of this nature the authors would recommend excavating a number of profile pits and photograph them for the farmer/agronomist to study and file for future use. It is worthy of note that none of the good farmers whose fields were used in the HGCA funded project, had any knowledge of the overall variability of the sub-soils in the selected fields and expressed benefit from observing the detailed analysis of the profile pits.

Studies by Yule *et al.* (1999) using a fully instrumented tractor with GPS to map field performance demonstrated that the effects of compaction almost doubled tillage costs at the headlands and gateways. Noticing the relatively low average engine power utilization (47%) in their first test field, they subsequently operated the tractor in the highest gear possible at less than the rated engine speed in a second field and increased the engine power utilization to 56%, saving £4.70/ha (US$7.00/ha) in cultivation costs.

Detailed draught force maps produced by Richards (2000) using both the inboard tractor-linkage draught force sensing pins and additional extended octagonal ring force transducers (Godwin, 1975 & Kirisci *et al.*, 1994) show variation in subsoiler draught forces operating at a depth of 0.35 m, see *Fig.*9. This shows the higher forces appear to coincide with the compaction associated with the previous seasons tramlines. To achieve the results the draught control system has to be immobilised which unfortunately, from an operational perspective, reduces workrate, increases slip and consumes more fuel per unit area. Given these drawbacks, the method is not recommended for commercial use.

Richards (2000) also used the tractor based GPS system to map all vehicle movements within a field throughout a complete growing season. The primary conclusion was that for routine blanket field operations there was no major benefit but the system has potential for identifying areas of a field where concentrated wheelings are a problem, eg. collecting and transporting both harvested arable and forage crops, see *Fig.* 10 a & b which shows the pathways taken by the trailer when both unloaded and loaded respectively.

A recent example of the benefits of precise information on the charges in soil type is the work of Maguire (2000) where the known variation in soil texture in Shagsby Field, were used to modify the seed rate of onion seeds to improve the size uniformity of the onion crop. The farmer reporting that he had satisfied his target marketable crop from 70 of the planted 100 acres, effectively increasing his marketable yield by 43% from improvements in yield and quality (size).

There is evidence that the size or the "clodiness" of the tilth in the seed bed can effect crop establishment (Malik, 1985 and Marchanko, 1989) and that increasing the seed rate in the rougher conditions and reducing the rate in finer seed beds should be considered. This is particularly critical as the effects of lower seed rates become the agronomic norm. The fundamental method to determine clod size is to conduct a sieve analysis of the diameter of the aggregates as used by Spoor & Godwin (1984).

Data from Bogrekci (2001) given in *Fig.* 11 shows clod size maps drawn from 30 sieve analyses following mouldboard ploughing of two experimental areas with a range of clod mean weight diameters from 20 to 95 mm and 50 to 100 mm in a clay loam and sandy loam soil respectively. The larger clods to the right of the clay soil are an old headland area where there has been more compaction.

Sieving soil tilths and constructing a clod size distribution curve is time consuming and difficult under wet conditions, photographic images such as those developed by Campbell, (1979), however, are quick and simple but is difficult to put into practice. Real-time vision systems using a video camera mounted behind a cultivator recording the seed bed (Stafford & Ambler, 1990) have automated the procedure. Subsequent work by Stafford & Ambler (1994) combined tilth quality and in-field position.

Whilst optical solutions can be used objectively to assess the surface roughness of the seedbed the subsequent analysis is complex. Alternative systems would be to have a non-contact method to record the surface roughness either using a laser profile meter, Sandri *et al.* (1998) or an ultrasonic displacement transducer, Scarlett *et al.* (1997). Both show good correlations with the mean clod size of the soil aggregates determined by sieve analysis. The ultrasonic method has a significantly lower cost and the ability to directly calculate the arithmetic mean size (AMS) of the distribution with a simpler analysis. Application of the ultrasonic technique by Bentley (2000) showed that there was no significant difference at the 95% confidence level between the AMS from the ultrasonic sensor and sieve analysis.

Using mechanical methods, Bogrekci (2001) has shown a near linear relationship between sensor output and the mean weight diameter (MWD) determined by sieve analysis over a range of three aggregate size distributions. The work covered MWD's of 93 mm, 32 mm and 14 mm, for tilths produced by mouldboard ploughing alone, and ploughing followed by a spring tine cultivator and a rotary harrow, as shown in *Fig.* 12.

3 Topographic Factors

Topography is one of the most obvious causes of variation found in field crops both from its direct effect on micro-climate and related soil factors such as soil temperature, which influences germination, tiller production and crop growth. It is for the majority of practical farming purposes unchangeable and as a result can only be used to explain variation.

The amount of solar radiation received by a crop in temperate regions is directly affected by the topography of a field. Experiments conducted by Fiez *et.al*. (1994) found that in two successive years yield varied by 55% and 35% respectively depending upon slope, position and aspect. The results of theoretical studies using the CERES wheat model (Ritchie, *et al.*, 1988) by Geary (2001) show a possible loss in wheat grain yield of 1 t/ha on northern slopes at approximately 10% slope. They also show a small improvement in the total biomass yield on southern slopes with no significant improvement in grain yield.

Although major topographic features are obvious to the naked eye these need to be quantified to enable comparison and understanding of slope processes. A study undertaken by Geary, (2001) reviews the alternative methods for assessing topography showing that they vary greatly in cost, speed and accuracy, see Table 3. The study was conducted on a known circuit of farm tracks around a field with given bench mark positions to enable repeatable comparisons to be made. The study was conducted before "selective availability" had been switched off and current figures are now marginally more accurate. This is illustrated by the fact that the vertical plane accuracy for a quasi-static DGPS with a 60 second residence time improved from 2.78 m to 2.57 m.

The results show that the cost generally increases with the level of accuracy required. Therefore the desired level of accuracy needs to be known before a method of assessment can be chosen. The level of accuracy depends upon what the information is required for and whether "real time" or "post processed" data is required. For most of these applications post processed data is adequate. If, for instance, the slope of the land is relatively flat and is required for surface irrigation then the accuracy needs to be very high (±10 mm). However, if the data is required to assess the variation of the surface undulation in understanding yield variation to manage agricultural inputs, then the accuracy required is by no means as great and estimation of field slope to ±1° should suffice.

Whilst the Total Station is the benchmark surveying system with an accuracy of ±5 mm, a minimum of two surveyors are required and it is relatively time consuming with the added complication of locating the survey with a recognised national grid system. It is, however, significantly faster than the traditional theodolite, with less potential for human error and the added advantage of computerised data handling, calculations and map production.

Simple Differential Global Positioning Systems (DGPS) systems are accurate to within 1 m in a horizontal plane, however, the errors are significantly greater in the vertical plane for a mobile unit, eg. 4.67 m. The simultaneous recording of a second fixed point and post processing can reduce these as can a longer residence time at a given point. This needs to be 30 minutes to reduce the error to 0.56 m.

Following earlier work to improve upon the accuracy of the DGPS in the vertical dimension by Yang *et al.*, (1997) and Yule *et al.*, (1999) two inclinometers were mounted on a vehicle at right angles to each other. One inclinometer was used to measure the pitch of the vehicle (combine or tractor) and the other to measure the roll. This system had the potential to correct the vertical dimension data for minimal cost over the DGPS System (£500). Table 3 shows that the system performed marginally better than the DGPS system but was not sufficiently accurate.

Carrier Phase GPS works by using a base station to measure phase variation over the logging period. By doing this the DGPS signal can be greatly enhanced giving a typical accuracy of ±20 mm. Carrier phase data has to be post processed so the data can not be used in real time. The system gives good accuracy combined with a relatively low capital cost and single person operation.

Real-Time Kinematic GPS is similar in design to Carrier Phase GPS, however, due to a real-time radio link between base station and the rover, the position can be given in real time. Although real time positioning may be desirable if a point needs to be relocated when it comes to assessing topography in most agricultural situations this is not necessary. Table 3:

Comparison of topographic assessment methods: their accuracy (prior to switching off selective availability), residence time and cost (after Geary, 2001)

The costs per hectare are compared by Nugteren & Robert (1999) who estimate a cost for the Total Station to range between £24/ha (US$36/ha) and £13/ha (US$20/ha) for areas between 1000 ha and 25,000 ha. For the same range the high resolution Real-Time Kinematic GPS systems the estimated cost ranges between £33/ha (US$50/ha) and £2.64/ha (US$4/ha). The break-even point being 1900 ha at approximately £18/ha (US$27/ha).

Following the results of the comparison above, an experiment was conducted by Hann (2001) to compare the relative speed and accuracy of a handheld Abney Level and a handheld Clinometer (Bannister and Raymond, 1972) to make quick, relatively accurate, estimates of topography at modest cost, as used in soil and water engineering practice. The results showed that both methods could measure the slope to within ±0.3%. Hence a 100 m long section would give a vertical error of 0.3 m. Changing the effect of section length from 50 m to 200 m and the accuracy had no significant effect upon the accuracy. Each reading required approximately 1 minute and the additional cost of the equipment was £100. The cost/ha of this system is almost independent of area and is estimated at £2-3/ha (US$3-5/ha) depending upon topography.

The mapping procedure would be:

(1) Split the field into zones of similar slope placing poles on the ridge line and grade break lines using an All Terrain Vehicle equipped with a GPS (for horizontal positioning),

(2) Read the percentage slope from the Abney Level or Clinometer,

(3) Adjust the plan for slope in the office using the above data to produce aspect and slope maps.

This system is inexpensive, simple and of sufficient accuracy for precision farming and would, therefore, be the current recommended method.

4 Soil Nutrition

It is in this area that the greatest difficulties and expense can develop. Table 4 reports typical costs for soil nutritional analysis as quoted to the farmer and include collection and laboratory analysis. From this it can be seen that if a field can be considered homogenous and a number of samples collected from walking a typical W pattern in the field and bulked together as one sample, the costs for a 10 ha field are affordable. However, if this analysis is conducted on a 1 ha grid basis then the costs escalate by a factor of 10 to an unaffordable level for grain crops, when estimates of the benefits of improved nutrient management by Earl *et al.* (1996) and Godwin *et al.* (1999) are in the order of £17/ha (US$25/ha).

The solution to this problem therefore lies in targeting the sampling regime based on maps of crop performance (historic yield or real time crop density either from satellite or airborne platforms) or soil texture maps (EMI). A valuable comparison of targeted and grid sampling methods is reported by Thomas *et al.* (1999) who compare a targeting strategy based upon the Normalised Difference Vegetation Index (NDVI) with a 100 m grid as shown in *Fig.* 13.

The NDVI data was derived from the red and near-infrared data from a SPOT satellite image and its near linear relationship to crop yield (Zmuda & Taylor (1990). *Fig.* 13 shows 8 sampling zones where 16 random sub-samples (Oliver *et al.*, 1997) were extracted and bulked together in comparison to 26 grid point samples, where 16 sub-samples were extracted in a 1 m grid pattern around the sampling point and bulked together. All samples were sent for laboratory measurement of phosphorous (P), potassium (K) and Magnesium (Mg).

A comparison of the statistics of the two methods is presented in Table 5 which shows the average values are similar, especially when their indices are compared. The index values show a deficiency (Index value of 1) of both K and Mg and maintenance level (Index value of 3) for P. The minimum values for all nutrients are different for the two sampling procedures but both indicate soil nutritional deficiencies. The maximum values are different for P and K with the targeted values indicating lower values.

Further spatial analysis of the grid results showed that both phosphorous (*Fig.* 14) and potassium were lower in the Northern part of the field and higher in the Southern part. There was no consistent spatial pattern for magnesium. In comparison the targeted samples indicated a deficient level (Index 1) for zones B and C for phosphorous and all zones deficient in potassium. The targeted method indicating 2 zones at Index 0 and 6 zones at Index 1 for magnesium, in comparison the grid data showed 5 points at Index 0 and 21 at Index 1.

The above comparison would result in some differences in field management practice: where:

(1) Grid sampling would result in higher phosphorous and potassium application rates in the Northern part of the field and in a uniform application rate of magnesium (due to no clear spatial pattern) and

(2) Targeted sampling would result in uniform application rates of potassium and magnesium with additional phosphorous applied to the deficient zones B and C.

The targeted soil sampling technique whilst not producing an exact correspondence with the grid samples provides a sensible fertiliser strategy at approximately one third of the cost of collecting and processing the grid samples. As a result given the excellent spatial resolution of soil textural boundaries given by the EMI systems, practical field agronomists are now considering how best to collect targeted soil samples, Rigley & Gould (2000).

With the base line nutritional conditions mapped and at a satisfactory level, the prudent management practice would be to adopt a replenishment strategy to compensate for the P and K removed at harvest as suggested by Moore (1997). Table 6 gives the rates removed from a typical crop of wheat and *Fig.* 15 an application map derived from the yield map assuming that the mass of the straw removed at any point is approximately equivalent to 665% of the mass of grain.

Airborne platforms (Taylor *et al..*, 2000) have proved to have a significant advantage over satellite systems as

(1) Flights can be arranged to suit weather conditions, to avoid the problems of coincidence of cloud cover and satellite availability, and

(2) A vast improvement in resolution with pixel sizes representing a field area of 0.5 m × 0.5 m as opposed to 20 m × 20 m for example, from SPOT imagery.

The NDVI data from the Airborne Digital Photography (ADP) has correlated well with both plant shoot numbers (early in the growing season) and Green Area Index (GAI) (later in the growing season), and as such is proving to be valuable in managing the spatial application of nitrogen (Wood *et al.*, 1998 and Taylor *et al.*, 2000). One of a series of shoot density images through the winter period are shown in *Fig.* 16, for a field where the canopy has been deliberately modified by sowing wheat at different seed rates. This technique can now be applied to a wider group of fields where the same or similar varieties have been sown at approximately the same date. Only 8 field samples are needed to give a good correlation with NDVI data.

5 Crop Weeds, Pests and Diseases

There is now substantial evidence to show that in many circumstances the distribution of some weed species in cereal crops is non-uniform (patchy) including the major grass weeds and that these patches are relatively stable within a season and from season to season. The control of a grass weed in a grass crop requires the use of a herbicide with a high degree of selectivity and often a relatively high cost. There is therefore, the potential to make substantial savings in spray input costs by spatially targeting herbicide applications. Lutman *et al.*, 1998 estimate that savings in the range £5-15/ha could be achieved depending upon the cost of implementing a spatially variable application strategy.

One approach to the spatial treatment of weeds and weed patches is to control a spray delivery system in direct response to the outputs from a sensing system mounted on the treatment vehicle (e.g. Felton, 1995). While this approach is very appropriate for the control of weeds in fallow or on roadsides/pavements, it is much less relevant to the control of weeds in a crop situation because:

(1) Weeds are often difficult to detect at the optimum time for spray treatment particularly in the presence of a growing crop - it may also be appropriate to use a single weed patch map for applications over more than one crop and one season;

(2) There needs to be the opportunity to determine an appropriate dose rate and tank mix to give optimum control;

(3) In many circumstances it is not appropriate to carry a wide range of chemicals on the sprayer that may not then be used.

An alternative approach that has therefore been developed (Miller & Paice, 1998) is the use of a treatment map that is derived from a weed/weed patch map with elements to account for:

(1) Likely movements of weed patches between mapping and treatment due for example to seed dispersal and movement during cultivation and harvesting.

(2) The selection of products and product mixtures to give control.

(3) The dose response characteristics of the products to be applied.

(4) The characteristics of the weed patch detection system - the greater the reliability and resolution of the detection system the greater the opportunity to reduce dose rates or not treat some parts of the field.

Such an approach does require a useable and cost effective method of generating weed patch maps. Although there has been some progress with the development of automated detection systems based on either spectral reflectance characteristics and/or image analysis methods (e.g. see Christiansen, 1999), it is unlikely that such systems will be available particularly to detect grass weeds in cereal crops, within the foreseeable future. Differences in spectral reflectance between weeds and cereal crops can be measured but such differences have been shown not to be a sound basis for weed patch detection because of the effects of growing conditions, varieties, nutrition and lighting conditions at the time of detection. Image analysis-based techniques are being developed for weed detection in widely spaced crops such as sugar beet and vegetables but the complexity of images and the computing power needed for weed/crop discrimination means that any such systems are currently a long way from commercial development.

For this reason approaches to weed patch mapping based on manual detection and GPS location are being developed. Manually walking the whole of a field area is slow and expensive although such an approach can usefully assess changes to weed patch boundaries between seasons. Mapping from tractors, combines or an ATV is a more practical option, as shown in *Fig.* 17, providing that there is:

(1) An adequate field of view with the ability to see the weed patches – this depends on the vehicle and the state of the weed/crop combination;

(2) An appropriate means of recording combinations of weed species and density.

Practical experience has shown that, particularly when field surveying from an ATV, activating switches or panels on a touch screen while driving across a field or down tramlines is difficult. A logging system based on voice recognition has therefore been constructed and validated against maps generated from detailed field surveys, as shown in *Fig.* 18. These approaches are the subject of continuing research and development and should lead to practical systems within a two to three year horizon.

An alternative approach to direct weed patch mapping is to use targeted field walking to examine areas that can be identified as having a high vegetative index either from ADP or measurements from vehicle mounted radiometers, as shown in *Fig.* 19. The vegetative index map can then be used to define patch boundaries with information from the field walking relating to weed species and density. The potential for making weed maps using this method is currently being assessed in a series of field trials.

For foliar diseases in arable, many of the fungicide treatments that are used have a mode of action that relates primarily to the surface of a leaf with either curative or protectant modes of action or a combination of both. A potential method of reducing the use of such materials is therefore to match the delivered dose/volume of fungicide to the leaf area of the crop canopy to be treated. The development of patch spraying systems such as that described by Miller *et al.*, (1998) provide systems that could deliver a variable rate volume application with a 5:1 range but with no change in spray quality. The challenge is to develop sensing systems that will enable a map of leaf area index to be generated that can then be used as a basis for controlling such applications. Work has been conducted using measurements of spectral reflectance from vehicle mounted sensors (and potentially ADP could be used in the same way) as the basis for varying fungicide doses within a field with variable results. Results reported by Secher (1997) suggested that significant increases in yield of a winter cereal crop could be achieved by distributing the dose of a fungicide in relation to crop canopy characteristics as measured using boom-mounted radiometers. This conclusion was not supported by Bjerre (1999) with an indication that penetration of spray into areas of high foliage density may have been a limiting factor in the work. While results from field experiments reported by Miller *et al.*, (2000) did not show differences in deposit levels in plots in areas identified as having high or low crop canopy density based on measurements with boom-mounted radiometers, the work did show significant differences in deposit levels and distribution at different growth stages in a winter wheat crop. The implications from this work relate to the potential to improve application of crop protection chemicals with a predominately leaf surface mode of action by accounting initially for the mean level of canopy development and subsequently for spatial variability across a field. There is strong evidence to show that sensing systems such as boom-mounted radiometers and ADP are an effective method of determining crop canopy density parameters such as leaf area index at early stages of cereal crop growth providing that:

(1) The crop is in a healthy and weed-free state.

(2) There is a calibration to take account of effects due to variety and growing conditions.

At later stages of growth such methods loose discrimination and there is probably a need to link the outputs from more than one sensing approach. The use of multiple sensors would also enable an improved interpretation of the measurements from a radiometer where effects due to colour and canopy structure inter-relate. Methods of characterising canopy structure at later stages of growth using more than one sensing system are now being investigated in research funded by the Home Grown Cereals Authority in the UK. Objectives of the work are the creation of mapped data for the control of chemical application equipment and also links to conventional agronomy via a description of crop growth stage.

For insect pests, in most cases the mobility of the pest prevents an effective control strategy based on the generation of a map. The exception to this is soil-based pests such as potato cyst nematodes where mapping approaches based on soil sample counts have been used to generate maps of nematode eggs/gram of soil and these used as a basis of control treatment application (Evans *et al.*, 2000).

6 Conclusions

Recent technological advances have permitted rapid non-invasive methods to map:

(1) soil texture, structure and moisture content (EMI and tilth sensors),

(2) heavy traffic (GPS),

(3) crop density (NDVI from ADP) and

(4) weed patches (NDVI from airborne (ADP) and ground based radiometers).

These permit:

(1) Targeted sampling of soil physical and chemical status together with areas with a high weed population.

(2) Nutrient application on a replenishment basis for P and K and a crop density basis for N, and

(3) Seed rate variation depending upon the available water of the soil to control crop quality (size).

Further work needs to be conducted to automate the simple topographic surveys as the currently available more accurate methods are not economically viable.

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