GPS in Agriculture – A Growing Market!

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In conventional arable agriculture, position within the field was usually irrelevant! However, the advent of precision agriculture, wherein inputs are targeted according to locally-determined requirements within the field, has opened up a potentially large market for GPS. Indeed, it was the availability of GPS which permitted the development and implementation of precision agriculture – a concept which holds the promise of significant economic and environmental benefits to the farmer. This paper indicates the technical requirements for GPS and presents three case studies where a positioning system is required.

1. introduction. GPS has played a pivotal role in the implementation of a key concept in agriculture: precision farming. This concept has developed because of the spatial variability in soil, crop and environmental factors found in all agricultural fields. Conventionally, in arable agriculture and horticulture, fields are assumed to be uniform with regard to the application of inputs such as agro-chemicals and fertilisers. Thus, uniform rates are applied to what is a highly variable system – the soil/plant/environment system. This paradox has been appreciated by some for centuries. The advent of a low-cost, universal positioning system that can be transparent to the user, i.e. GPS, has provided the potential to take account of the inherent spatial variability within fields by varying the crop management action according to position in the field. Thus, precision agriculture may be defined as the targeting of inputs to crops according to very locally-determined requirements.

The implementation of precision agriculture requires a positioning/navigation system for two areas; sensing/mapping and application equipment. Mapping of soil, crop and environment factors requires robust, reliable and low-cost sensing systems linked to GPS. Variable rate application of inputs is usually based on a 'treatment map' that provides control signals to the application system dependent on the position of the vehicle in the field. The requirements for the positioning system for the two areas are quite different in terms of position resolution, reliability and dynamic performance.

The first commercial application of GPS was for yield-mapping on combine harvesters. However, as the precision agriculture concept is increasingly put into practice in production agriculture, GPS positioning is being used on application equipment, soil sampling equipment and field surveying. The components of precision agriculture are illustrated in Figure 1.

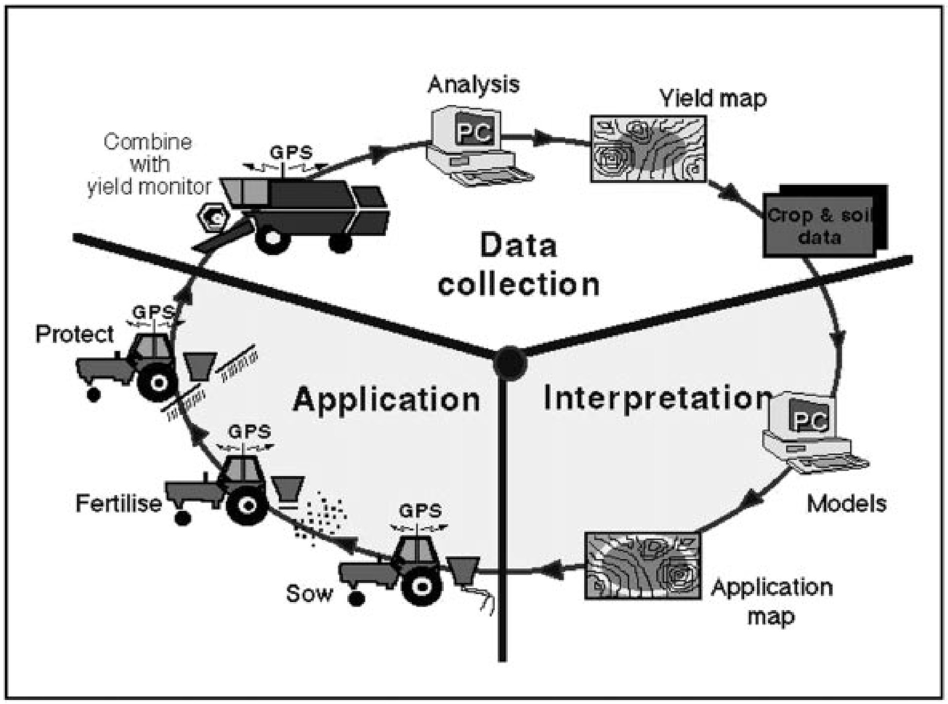

Figure 1. The 'spatial variability' circle.

Table 1. Position Resolution Requirements

Operation	Position resolution, metres
Variable Fertiliser Application	30
Yield mapping	10
Variable Application of Herbicide	1
Spray Overlap Avoidance	0·1
Row Crop Planting	0·1
Seed Bed Structure	0·05

2. technical requirements. In-field positioning is required in order to map the sensed soil and crop factors and for the control of application equipment. The position resolution required depends on the operation under consideration, perhaps being as shown in Table 1.

These figures are open to considerable debate, but they illustrate the large range of position resolution required. For spot sensing and establishment of a sampling grid within a field, GPS position can be computed in static mode repeatedly to reduce the error. However, positioning of field vehicles requires reliable positioning resolution in dynamic mode with, perhaps, 0·5s updates. As the application rate of the input is determined from a treatment map that is dependent on GPS to provide a precise instantaneous position, the position error distribution must be narrow to ensure that the correct rate is identified from the map.

Although GPS is now the *de facto* location system for precision agriculture, other positioning technologies such as radio systems (Scorer, 1991; Palmer, 1995), microwave systems and laser (Gorham and MacLeod, 1991) have been advocated. Some of these systems depend on locally-installed reference points. The attraction of GPS to agriculture is the establishment of global reference points (the constellation of satellites) providing positioning signals at (apparently) no cost.

GPS pseudo-range position computation with differential correction attains a position resolution of the order of 2–5 metres. The problem with such position computations is that they are subject to an error distribution with tails extending from sub-metre accuracy to ten or more metres. The 2 × rms value of 2–5 m assumes that the GPS receiver is locked into a constellation of satellites well positioned across the sky (giving low Dilution of Precision – DOP). In practice, satellite switch-over as satellites move below the elevation mask of the receiver, obscuration of satellites by trees and buildings (Lachapelle and Henriksen, 1995) and multi-path reflections lead to significant degradation in position resolution. The resolution is, of course, also dependent on the availability of dependable differential corrections. Thus the method of transmitting correction signals to the mobile receiver is a consideration for agricultural applications. The lack of reliability in positioning resolution has serious implications for real-time dynamic positioning of application equipment within the field. Serious positional error will lead to the treatment map that controls the applicator providing positionally-misplaced information.

During a field operation where GPS positioning is used, position resolution varies both spatially and temporally. Temporal dependence is due primarily to the fact that the satellite constellation is not geostationary; the geometry of the constellation is changing continuously. Spatial dependency is due to signal obstruction by obstacles such as trees, buildings and powerline towers, and to multi-path signal reception which may vary from one point of a field to another. The result of this variation in position resolution is that, although the overall accuracy over the field is acceptable, the instantaneous position fix may be excessively in error.

In order to improve the reliability and accuracy of positioning for precision agriculture, both enhancement of GPS with other positioning information and the use of on-the-fly kinematic GPS may be considered. Enhanced GPS requires the integration of other positioning information available on the field vehicle such as speed and heading, using techniques such as Kalman filtering and forward error estimation (e.g. Stafford and Bolam, 1996). However, for accurate and reliable positioning, kinematic GPS may have more potential, provided that pseudo-range computation is incorporated to take over positioning when cycle slip occurs. For most field operations, it would be unacceptable for the vehicle to stop in the middle of an operation whilst position was re-initialized after momentary loss of satellite signal. Even with the back-up of pseudo-range computation during cycle slip, the reliability of positioning is questionable.

3. industry uptake.

Although there is continuing scepticism in some areas of the farming community towards GPS and precision agriculture (as a glance through farming periodicals will show), the steady growth in combine harvesters fitted with GPS yield-mapping equipment has introduced more and more farmers to the technology. Yield mapping was first introduced commercially in the UK by Massey Ferguson (now AGCO Ltd.) followed closely by RDS Technology some four years ago. It was recently stated that 400 combines with GPS yield mapping were operating in the UK in the 1997 harvest, with double that number expected in 1998. The same article (*Farmers Weekly*, 10 April 1998) reported 10000 combines fitted with yield monitors in the USA. The uptake in other European countries is mixed with, perhaps, most GPS yield-mapping systems in Germany, Denmark and Sweden. Within the last year, all major combine manufacturers have introduced yield-mapping systems and so uptake should grow significantly – indeed, it has been stated that yield mapping (and, hence, GPS) will become standard equipment on combine harvesters within a year or two.

As variable rate application equipment from implement manufacturers such as Amazone, Greenland and Hardi (mainly for fertilisers and pesticides) are introduced, so the market for GPS grows. Farmers are also appreciating the need to sample their field soils for analyses and undertake more intensive field investigation as a result of the information provided by yield maps. Sampling equipment is now routinely supplied with GPS so that within-field measurements can be position-tagged. Farmers, being very cost-conscious, do not readily accept that GPS (which they perceive to be expensive) should be tied to just one field machine, and so the introduction of systems such as the MF Datavision GPS/intelligent terminal, which can be moved between combine and other field machines, is welcomed.

Differential GPS operation is essential for on-farm applications. The early yield-mapping systems relied on local base stations sited on the farm or at the local agricultural dealer with short range MF/UHF data transmission. Early experience with differential corrections transmitted on the sidebands of commercial FM broadcasts was variable because of signal fading in areas of undulating farm land. Satellite-based differential services do not suffer from that problem, but farmers do not appreciate having to pay a licence fee for a service that they may only use for a few weeks in the year, during harvest. The prospect of the free differential service to be provided by the General Lighthouse Authorities in 1998 is therefore attractive, although its range and effectiveness for agricultural applications is yet to be tested.

4. yield mapping. Much of the interest in precision agriculture, and thus in GPS, in the farming community has been generated by the commercial availability of yield mapping on combine harvesters. In essence, this comprises a continuous grain-flow sensor and a position sensing system, as typified by a design developed at Silsoe Research Institute (Stafford *et al*., 1994). Yield mapping is illustrative of the mapping systems that are required for other soil and crop parameters, i.e. two relatively low-cost and reliable sensors forming a sensing system operating in a routine field operation with little or no intervention by the operator. Grain-flow sensors may measure mass or volumetric flow rate; examples of both are commercially available in Europe, e.g. the Massey Ferguson gamma absorption and the John Deere curved plate (change of momentum) mass flow sensing systems and the RDS 'Ceres' light beam interruption volumetric system, also fitted to Claas combines. The advantage of mass flow sensing systems is that they are not dependent on variation in grain-specific weight across the field and thus are potentially more accurate than volumetric systems (Stafford *et al*., 1996). A typical yield map is shown in Figure 2.

Whilst most yield-mapping systems appear to be accurate in terms of equating total grain flow to that measured over a weighbridge, the instantaneous accuracy of flow sensors has not been reported. A more important limitation on the spatial resolution achievable by combine-mounted yield-mapping systems is the effect of the grain flow path through the combine on the instantaneous measured throughput. Work by Lark *et al*. (1997) indicated that a yield-mapping system can only resolve yield variation over spatial intervals of around 15 metres, although 20–25 metres may be a more

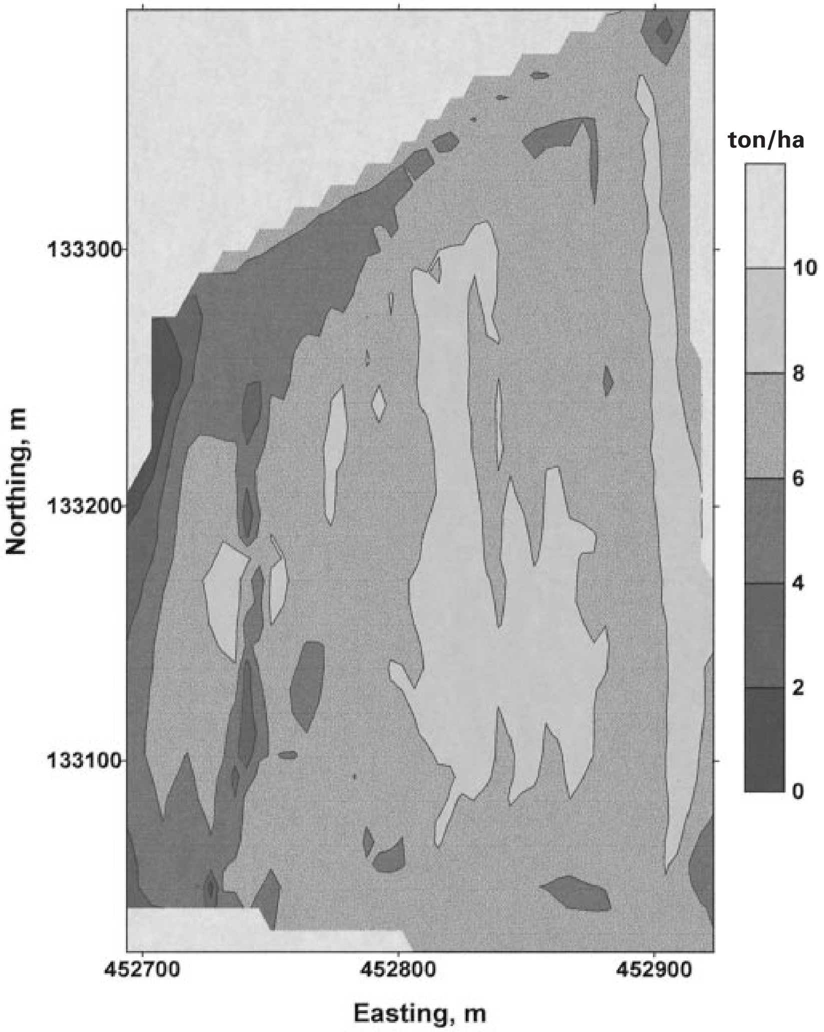

Figure 2. Yield map of winter wheat.

realistic scale of resolution. Thus the requirements for GPS on a combine are not exacting, with a position resolution of 5 metres being sufficient. Yield-mapping systems typically sample data every metre of forward travel, and so a fairly dense data set is generated from which a yield map is interpolated. Occasional GPS position degradation has an insignificant effect on the yield map. In any case, such positions will be excluded from the interpolation set, with sufficient data screening in the software package.

With the GPS antenna mounted at a height of three metres or more on the combine cab, good signal reception is generally assured and signal obscuration by trees is minimized. Problems do arise in some areas with terrestrial transmission of correction signals; the author has observed yield-map data sets where significant areas of a field suffered from unacceptable positioning due to loss of correction signal.

Knowledge of the variability of yield at harvest can be used in two important ways: it enables the farmer to make more informed management decisions regarding the succeeding crop, and it may provide a basis for automatically varying inputs such as fertiliser according to a defined strategy. Variable rate application equipment will then require GPS to provide dynamic, real-time positioning. The variation in final yield integrates the effects of spatial variability in soil, above-ground environment and crop variables. The magnitude of the effect is different for each factor. For the potential of yield maps to be realized, the effects of different factors must be 'disentangled'. Interpretation of yield maps is thus a major research challenge for their practical use (Lark and Stafford, 1997).

5. plant scale husbandry. In contrast to the low positional resolution required of GPS for yield mapping (5 metres), or variable rate fertiliser application (24 metres), a concept being developed at Silsoe Research Institute, called 'plant scale husbandry', requires dynamic position resolution to a few centimetres (Tillett *et al.*, 1996). Although the concept, which is briefly described below, does not currently use GPS for positioning, further development dictates that high accuracy GPS will have to be incorporated.

An alternative approach to mapping variables in a field and treating sub-areas of the field is to sense crop or weed targets on-line and treat accordingly. This allows a much finer resolution, down to individual plants, and requires little prior knowledge of the field except an estimate of planting geometry. This concept, called plant scale husbandry, might range from mechanical hoe guidance in cereals to the targeting of parts of vegetable plants – such as the base of stems – with insecticide.

Commercially, such more highly-targeted, individual, plant-scale operations are likely to be too slow for manned vehicles. An autonomous vehicle has therefore been developed as a platform for experimental plant scale operation. The vehicle is based on a lightweight toolframe with two independent, hydrostatically-driven wheels which control both speed and vehicle orientation. The treatment device consists of a linear array of solenoid operated nozzles at 50 mm intervals across the width of the vehicle. Selective treatment is achieved by switching each individual nozzle on or off as the vehicle progresses through the crop.

The vehicle is fitted with a number of sensors, in particular an odometric device on each front wheel and a monochrome TV camera which grabs near-infra-red images. Images are fed at a rate of 10 Hz to a module (the Hough tracker) that derives the vehicle lateral offset and heading angle with respect to the crop row structure (Marchant and Brivot, 1995). It uses a special Hough transform to find the row structure in an image, fusing features from three rows at once. This fusion results in a very robust tracker that can deal with typical natural variability – for example, missing or misplaced plants in the structure and the presence of weeds. The vehicle controller (Hague and Tillet, 1996), uses a model of the vehicle kinematics and a Kalman filter to fuse the output of the Hough tracker with the odometric data. The controller runs at 50 Hz and receives an update from the vision system every five cycles. Ultimately, the controller produces actuation signals for the wheel drives but, as an intermediate step, its Kalman filter produces an optimal estimate of the vehicle heading and offset by combining both sensing sources. This estimate is used to seed the tracker at each time-step and means that the likelihood of losing track of the row structure is small. The segmentation module differentiates between crop, weeds, and soil in the image (Brivot and Marchant, 1996). As the images are grabbed from an area in front of the vehicle, motion must be tracked from the time the images are grabbed until the same area is treated. This is done by forming a local map of the area between the image field of view and the nozzles. As each image is loaded into the map, it is registered with the existing images using the output of the Kalman filter in the controller. A processed camera image with computed row direction vectors is shown in Figure 3.

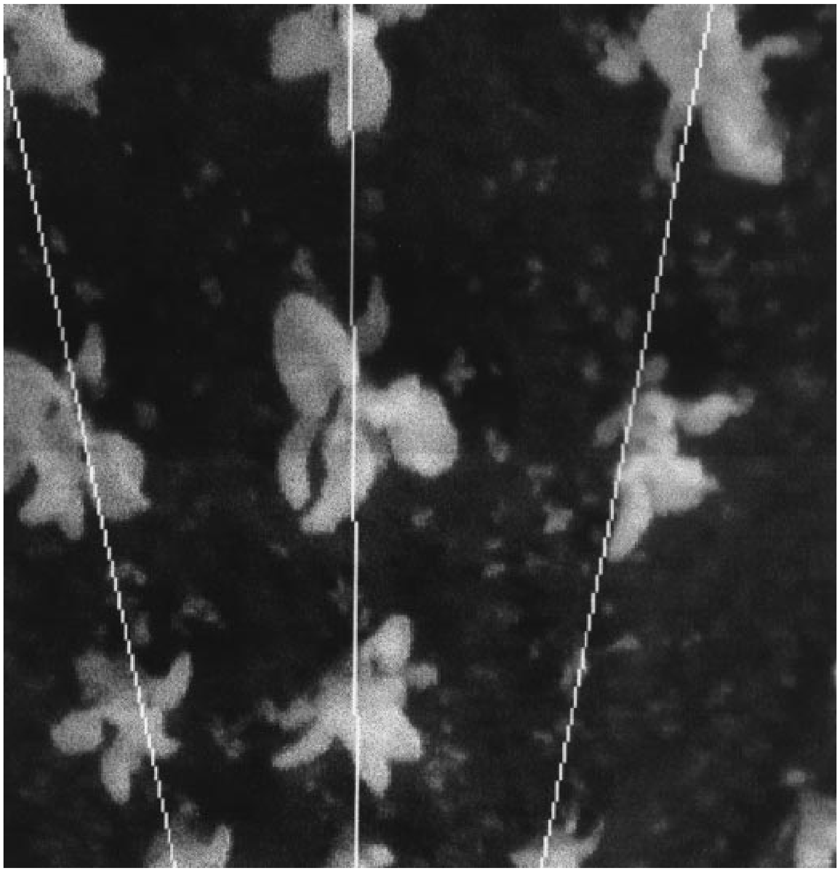

Figure 3. Tracking camera image of 3 crop rows with computed row vectors.

Although the concept, as a real-time, on-line treatment system, does not currently use GPS for positioning, the integration of other mapped data, collected at different times, will require an absolute positioning system. Supermarkets are applying ever more stringent requirements on produce quality and the recording of treatments, even down to single plant scale. Mapping treatments including harvesting requires absolute, accurate and repeatable positioning of row crops. On-the-fly kinematic GPS is clearly a contender for the autonomous system described above which travels at relatively low speeds across the field but works 24 hours in each day. Loss of position information through cycle slip is not the serious problem that it is with manned field machines travelling at up to four metres per second.

6. patch spraying. In an era of increasing concern over the environmental impact of farming operations and appreciation of the need to optimize use of inputs,

the uniform application of agro-chemicals is no longer acceptable. The technologies developed within precision agriculture using GPS provide scope to target herbicide more accurately and thus achieve a significant degree of optimization of the use of herbicide. Weed control is essential for the successful production of arable crops with, typically, two or three applications being made to winter-grown, small, grain cereal crops. These weed control measures range in cost from £13 to £75 per hectare. Thus, if targeted application reduces herbicide input by 50%, a significant saving in input costs could be made whilst reducing the environmental impact significantly in terms of residues on crops and leached agro-chemicals.

The basis of the Silsoe Patch Spraying System is the use of a digital field weed-map showing the distribution of weed patches, together with GPS position data, to control the application of herbicide by a precision agricultural sprayer (Stafford and Miller, 1996). Significant weed species tend to grow in patches that remain reasonably static in size and location from season to season. Hence, an 'historical' weed map of the distribution can be used for spraying in the current season. A treatment map is generated from the weed-map together with a herbicide application strategy. This is held in a PC in the tractor cab and is used to generate, together with GPS position information, control signals to drive the sprayer controller.

The field weed-map approach is amenable to the use of various manual, semi-automatic and automatic methods of weed patch detection including near-ground imaging, aerial imaging and interpretation, assisted manual surveying using high clearance survey vehicles, assisted manual surveying from field operations and assisted manual surveying by field walking. The ability to combine field location with manual weed recognition provides the basis for a number of approaches to weed-map generation (e.g. Rew *et al.*, 1996).

A backpack GPS system and palmtop PC have been developed for logging weed patch positions during field walking (Stafford and Le Bars, 1996). The PC screen displays a field map showing boundaries and weed patches logged so far, together with a cursor indicating operator position derived from the GPS receiver. For recording weed patches, options are provided to input geometrically-shaped patches or to walk irregular patches to define their position. Weed type and patch density are entered from a menu-based system. A combine harvester, fitted with a GPS system for yield mapping purposes, also provides an opportunity to log weed patch positions particularly for those weeds which are easily seen at harvest time. An initial study, where couch grass in a wheat crop was mapped, showed good agreement between a weed map generated by the combine harvester and one generated by the backpack system (Stafford and Le Bars, 1996).

The experimental sprayer developed at Silsoe Research Institute is based on a 12 metre boom with two parallel spray lines each with nozzles in groups of four at 0·5 metre spacing. A direct injection system is used in which water from the spray tank is mixed with herbicide concentrate measured from a cylinder according to demand. The output from each boom section is separately controlled from a central control system via solenoid valves. With the two lines, four levels of control (including off) were available depending on the spray strategy implemented. For example, a base concentration could be supplied on one line, with a different concentration on the second line. Thus, three levels of concentration could be applied. Alternatively, two pesticide formulations could be used and the proportion applied to different areas of the field varied. As spray nozzles are commonly at 0·5 metre spacing, a basic spatial resolution for the system was set at 1 m. Thus, the GPS system was required to provide 1 m position resolution reliably for dynamic, real-time control. This proved too exacting for pseudo-range differential GPS, and enhancement was sought in various ways from carrier phase enhanced DGPS to the system described earlier (Stafford and Bolam, 1996).

The experimental spraying system has been used to apply a range of herbicide formulations on commercial and experimental holdings mainly aimed at the control of grass weeds in cereal crops. Maps, such as the example shown in Figure 4, generated by a manual survey vehicle, have been used as the basis for the sprayer control. Mapped weed areas have been edited to create a treatment map typically by adding a 4 metre 'guard ring' around each patch. Savings in the use of herbicide have typically been in the range 40–60 % depending upon the weed distribution within the field. Collaboration with Micron Sprayers and Massey Ferguson has led to a commercial prototype which is now being evaluated on commercial farms.

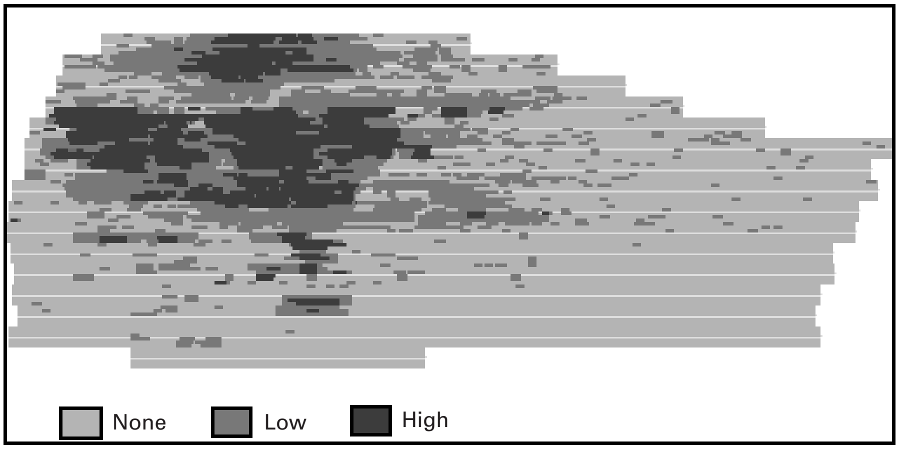

Figure 4. Field weed map – patches of blackgrass at several infestation levels. Tramlines also shown.

7. conclusion. The use of GPS in agriculture is becoming more widespread although mainly restricted to 'technical enthusiasts'. As the system has become more reliable, through completion of the satellite constellation and more sophisticated receiver design and data processing, farmers have gained confidence in its use. Whilst yield mapping provides the main use for GPS, other uses related to precision agriculture are increasing.

The wide range of position resolutions from centimetres to tens of metres required by various aspects of precision agriculture sets a demanding specification for GPS systems. At the centimetre level, other local positioning technologies are being used but 'on-the-fly' kinematic has the potential to meet these needs as well.

As a GPS user, the farmer requires a system which is a transparent and reliable tool. The area that currently does not meet this requirement is the provision of differential correction services at low or no cost with consistent coverage for all arable field situations.

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key words

1. Agriculture. 2. Automation. 3. GPS.