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Spatially variable herbicide application technology; opportunities for herbicide minimisation and protection of beneficial weeds

by

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CONTENTS

Abstract

This review considered changes that have occurred in relation to the patch spraying of weeds since the end of the HGCA/Defra/LINK project in 2002 (Lutman *et al.*, 2002 – Project LK0902: Developing a Weed Patch Spraying System for use in Arable Crops). At the end of that project we demonstrated that it was possible to map weeds and to use the map to control the sprayer and apply herbicides on a spatially selective basis. All the components (mapping procedures, computer controllers, sprayer and appropriate software) were commercially available. However, since then commercial uptake of the technology has been very limited. In the course of the review we talked to a number of the key 'players' in the industry and visited several commercial demonstrations of spraying and precision agriculture technology. We also, in association with the Precision Farming Alliance, held a one day meeting on the future of patch spraying. These discussions, along with searches of current published information, linked to patch spraying, formed the basis of this review.

Location technologies

The technologies associated with 'precision agriculture' have continued to advance over the last five years. The most obvious element of this has been the increase in the use of GPS based navigation systems. In 2002 these were still largely restricted to combine harvesters and could be unreliable. They are now becoming standard items in new tractors and harvesters. This increase is partly attributable to reductions in price but also to the increased precision and reliability of the satellite signals used by the GPS systems. Sub-metre location accuracy can be achieved in most situations. The published information and the discussions we have had all support the conclusion that positional accuracy with DGPS is generally adequately accurate for creation of patch maps and for subsequent treatment.

Sprayer design and control

While basic sprayer design and control principles have changed little since 2002, there have been developments, particularly with control systems, that would aid the implementation of a spatially variable herbicide application strategy. Most sprayer control systems are now computer based with established interfaces to mapping software, inputs from field location systems such as GPS and the ability to implement control decision algorithms. Systems for delivering controlled/variable doses across the whole width of the boom using twin-fluid nozzle or injection metering systems have seen a small amount of further development but have not gained a substantial share of the new sprayer market. The use of multiple boom lines and/or multiple nozzle clusters supplied from a single line have been further developed in association with the potential to vary output from different parts of the boom by switching nozzle sections. The trend towards increasing boom widths has continued and the pressure to use section controls in small increments to

give good matching in variably shaped field areas has also continued. It is concluded that modern sprayers are more readily adapted to making spatially variable applications if all other parts of the system are in place.

Spatial biology of weeds

Publications since 2002 still support the basic conclusion that many agronomically important weeds are spatially aggregated in distribution and consequently are a suitable target for patch treatment. Reviewing the evidence on differences between species suggests that large seeded species, which tend to be the more aggressive weeds, have more aggregated distributions than smaller seeded species. There is more debate as to the stability of patches, with some researchers pointing to stability whilst others highlighting greater mobility, even with the same species. It is certainly true that core patch areas of the large seeded target weeds are quite stable, but patches can expand and contract in relation to the weather conditions and agronomic practices that either enhance or reduce seedling emergence. Some species are more likely to spread single seeds around the field, thus influencing decisions on what to apply to non-patch areas. This issue of patch stability impacts on frequency of remapping. From basic biology it may be adequate to map, for example, every three years for black-grass but more often for wild-oats. In reality, cautious adopters of the technology are likely to want to map every year, to reduce risks. Mapping frequency impacts on the costs of patch spraying and hence on the overall profitability of patch spraying.

Patch detection

The previous project developed a system for visually mapping weeds either from a quad bike or from a combine or tractor. The relevant software to do this is still available and developments in software associated with computer control of sprayers have also incorporated a patch mapping (flagging) capability into modern sprayers. However, there is a great reluctance by farmers to spend time creating maps. They would much prefer automated detection systems. There also appears to be little interest by contractors or advisors to provide a mapping service, in the same way as has been done for spatially variable fertiliser applications. Mapping weeds when doing another farm operation (fertiliser application) is possible and has been done by some users, but there is a real risk that the operator becomes distracted by events associated with the primary activity and so create an inaccurate map.

As of now, automated weed detection systems for arable crops are still in various stages of development. Various techniques could lead to practical detection systems within the next five years. Visual detection is the only practical option that could be used in 2007. The “Gerhards system” in Germany can deliver automatically collected maps created by a combination of bi-spectral cameras (red/far red) and image analysis, but to date this is not in full commercial production and no other technique yet approaches practical implementation.

There are issues over the resolution of the map that still need to be resolved; the finer the scale of map the lower the proportion of the field that will appear to be infested with a given weed infestation. But the finer the scale, the more labour-intensive and costly it will be to create the map and subsequently treat the weeds. Research suggests that an optimum detection grid should be smaller than 7 x 7 m, but this is probably unrealistic in practice, so a compromise is needed.

Some sections of the industry would prefer real time detection and treatment in one operation. Such an approach is already available for industrial weed control, where detectors on the front of the treatment vehicle control the herbicide application. This is not yet commercially developed for arable agriculture, because of the difficulties of achieving good weed identification in the presence of a crop. Additionally, real time treatment has a major flaw. The user has no idea how much product will be needed prior to entering the field to be treated and so disposing of excess product could be a very serious problem.

Treatment plans

The software to transform a weed map into a treatment map was written in the previous project and is still available. There are two approaches to patch treatment, either spray/no spray (where the parts of the field outside the weed patches are not treated) or low dose/high dose (where the non-patch area receives a low dose). If a spray/no spray strategy is adopted the user only has to decide which product to use but if a low dose/high dose strategy is used a decision has also to be made on what dose to use. Information on the dose response of many herbicides is lacking and advisors are reluctant to recommend low rates because of issues of legal liability. This is a clear constraint to adoption of low dose/high dose approaches, which from a biological standpoint are preferred, as they are less risky, because there is less chance of re-infestation from isolated weeds present outside the patches. Variable dose potential requires more complex engineering on the sprayer and hence greater costs. Sprayers capable of spray/no spray treatments are currently being sold but variable dose ability would require the use of engineering that has been developed but not widely taken up.

Economics

As there has been little commercial uptake of patch spraying it has not been possible to collect ‘on farm’ economic data. However, we have updated the calculations made in the previous project as to the costs of treatment of weed patches (mapping and equipment costs) and linked this to predicted reductions in herbicide use, based on the percentage of the field infested and treated, derived from real fields studied in the previous project.

The cost savings depend on the percentage of the field infested and the cost of the products. The calculations done assumed 65% of the field required treatment, which was based on the average infestation levels recorded in the previous project. We explored the use of Atlantis and Crystal for black-grass control and Starane for cleavers, both in winter wheat and also the use of glyphosate for common couch in set-aside. We concluded that in winter cereals cost reductions of £10/ha would be possible with an ‘on/off’ strategy, but less than £5/ha with a ‘low dose/high dose’ approach. Savings with glyphosate were less than £2/ha. The previous project based its calculations on a saving of £6/ha.

The costs of equipment to patch spray were difficult to calculate because many of the elements needed are ‘bundled’ into the control systems used in current sprayers, but we concluded that an added cost of £8,000 was appropriate. This was the same cost as estimated in 2002. This cost could be discounted over five years, giving an annual cost of £1,600. Additionally, there would be a £500/year cost for part of the overall price of the differential signal for the GPS. Assuming the sprayer was used on 500 ha/year the cost would be approximately £4/ha. There was also the cost of mapping and this depended on whether it was done by farm staff or by contractors and could vary from £2.50 and £13/ha. This could also be discounted, depending how often the fields needed mapping. We used a conservative figure of mapping every two years (cost £3/ha) as although the biology studies suggested it could be less frequent, our interpretation of users comments indicated that they would prefer, at least initially, annual mapping. All these values bring together an overall cost of £7/ha (£3/ha for mapping and £4/ha for equipment).

Comparing the two previous paragraphs it is clear the herbicide savings from the biologically less risky approach of low dose/high dose were going to struggle to exceed the costs. There was some profit on the spray/no spray approach. If our figures are reasonably sound the low dose/high dose approach does not look profitable unless the mapping costs could be reduced to zero by using automated detection, which at present is not available for commercial practice.

Environmental benefits of patch spraying

Patch spraying can help meet government targets to reduce pesticide use and to increase the floral diversity of arable fields, with possible consequent benefits for invertebrates and birds. At present, there is little legal or financial incentive for farmers to use the technique for this purpose.

Farmer attitudes

Farmers perceive patch spraying as risky, because of the perceived risks that unsprayed areas could contain weeds that would act as foci for future infestations. They are also concerned about the reliability of lower dose treatments used on non-patch areas. A field research/demonstration project could resolve how risky the technology is. They are also not enthusiastic about a technology that increases the complexity of crop protection, by indicating that individual fields and parts of fields should have different treatments.

Conclusion

The technology required to patch spray weeds has advanced over the last five years, and is now more reliable and more readily available. Despite this, there has been little practical uptake of the technology. The evidence is that the basic biology behind the concept is sound and that weeds are appropriate for spatially variable treatment. But, farmers perceive that the technology is risky and are reluctant to spend time mapping weeds. They are also wary of approaches requiring the choice of herbicide doses lower than those recommended by the manufacturers, as independent data to support these are very limited. Finally, the cost benefit of low dose/high dose approaches seems very marginal, unless the cost of mapping is reduced to zero. The intrinsically more risky spray/no spray approach does seem to deliver a profit to the user, but R&D would be needed to check on the reality of the perceived risks. Automated detection could reduce costs and although receiving a lot of research interest has still not delivered a fully commercial system, though the “Gerhards research project” in Germany does approach it. Future R&D could deliver this target.

The uncertainties relating to cost benefit, field reinvasion for unsprayed weeds and choice of appropriate doses need to be resolved. This could be done with appropriate R&D projects. In our opinion the technology would be much more attractive to potential users if research could deliver functional automated detection.

1. Introduction

1.1 Background

The focus of this review is the current status of spatially variable weed control in the UK. The review aims to provide an update on changes in science and technology and in farmer adoption of patch spraying techniques. The baseline for this update is 2001/02, when the last HGCA supported LINK project (LK0902 – Developing a Weed Patch Spraying System for use in Arable Crops) (Lutman *et al.*, 2002) was completed. Patch spraying weeds is one of the techniques included under the umbrella term of 'precision agriculture' and so development and uptake of this technique is closely linked to the development of generic technologies of computing and geo-location (GPS – global positioning system) used in all precision agriculture approaches. Thus, this review will consider not only the specific components of patch treatment of weeds, such as weed mapping, but also the generic components such as developments in GPS and navigation systems.

There are two main reasons why farmers have adopted (or will adopt) this technique. Firstly, if the cost reductions resulting from the reduction in herbicide use arising from patch spraying clearly exceed the costs of achieving the patch treatment, and thus enhance the profitability of the farm, then the technique will be adopted. The economic aspects of patch spraying are discussed in Chapter 7. The second driver is Government Regulation. Over the last 20 years there has been greater regulation of pesticide use but despite this there has been increasing disquiet over the impact of agricultural activities on the ecological sustainability of arable farming - its impact on 'biodiversity'. In 2006 Defra's Pesticide Safety Directorate published its strategic document on pesticide use 'Pesticides and the Environment: A Strategy for the Sustainable Use of Plant Protection Products' (Defra, 2006) (http://www.pesticides.gov.uk/environment.asp?id=70). Three of its objectives are:

- Reduce water pollution caused by plant protection products to the standards required by the EC Water Framework Directive. This was introduced in December 2000 and requires all inland and coastal waters to reach "good status" by 2015. A number of herbicides, including isoproturon and trifluralin, are identified as 'priority substances' under the WFD (http://ec.europa.eu/environment/water/water-framework/priority_substances.htm). The recent withdrawal of approval for the these two products (March 2007) indicates that environmental concerns related to pesticides are increasing;
- Reverse the loss of biodiversity caused by plant protection products;
- Encourage the introduction of more alternative chemicals and greater use of integrated crop management with a lower plant protection product dependency.

Although the UK has no prescribed limits on pesticide use, unlike some other countries in the EU (e.g. Denmark, The Netherlands) it is possible that pesticide ‘rationing’ could be introduced. The techniques of patch spraying provide a number of tools that could address some of these environmental concerns. For example, the avoidance of application of pesticides to ‘border’ areas of fields, to reduce their presence in surface waters (an extension of the current LERAP scheme) requires the same technologies as patch spraying. Achieving an overall target reduction in herbicide use could also be facilitated by patch spraying. Indeed, if a pesticide tax was introduced (for environmental reasons) it would improve the economic equations in favour of patch spraying.

Even without legislation to ‘encourage’ pesticide reduction, patch spraying does provide a tool to enhance plant biodiversity within fields. Plants provide the base of the biodiversity pyramid, providing food and shelter for invertebrates, birds and mammals (Marshall *et al*., 2003). Reductions in the range of plants in arable areas have contributed to the decline in other species. There is currently some debate as to whether the decline in biodiversity on farm can be halted and even reversed by enhancing diversity in non-cropped areas, or whether changes to in-field management will also be needed. Agri-environment schemes that change the management of field margins have been widely adopted but those requiring changed in-field management, such as conservation headlands and cultivated uncropped strips, have been less popular **(**http//statistics.defra.gov.uk**).** Several recent papers have discussed the role of these schemes in reversing the decline of farmland birds (e.g. Vickery *et al*., 2004, Whittingham *et al*., 2006). Although it is believed they have helped, there is still some uncertainty, particularly in relation to over-winter food, as to whether field margin management will achieve the desired goal for all farmland birds. Enhanced over winter food is most obviously delivered from over winter stubbles that contain appreciable numbers of seeds. These are more effectively created by lower input weed management (Vickery *et al*., 2005) This could be delivered by patch spraying the most severely infested areas, and controlling the aggressive species, whilst leaving the other areas untreated to provide seeds for birds, but without seriously jeopardising crop yields.

1.2 Programme

Over the last six months we have consulted a number of ‘key players’ in the industry and have attended demonstrations of sprayers and precision agriculture equipment. We have also, in association with the Precision Farming Alliance held a meeting last autumn, involving over 30 members of the industry (machinery manufacturers, researchers, farmers, farm advisors, pesticide manufacturers, software engineers) (see Appendix A). These meetings and discussions, along with a thorough search of the published literature since 2002 have formed the basis of this review.

1.3 Objectives

Issues to be covered within the review:

- What equipment and advice is currently available for:
    - Weed patch mapping (manual and automated);
    - Development of a treatment map;
    - Patch spraying of herbicides?
- To what extent is spatially variable herbicide application being adopted (information to be collected through discussions with advisors and equipment manufacturers and not through a detailed national survey)?
- What are the real and perceived barriers to wider adoption?
- What are the real and perceived economic benefits of adoption (to include a re-evaluation of the economic analyses in HGCA Project Report 291)?
- What are the opportunities for delivering environmental benefits through spatially variable herbicide application in terms:
    - of reduced risk of herbicides in water;
    - of leaving populations of beneficial weeds?
- Identify scientific and technical progress overseas with relevance to UK cereal production.
- Recommendations regarding what could be done to realise the potential economic and environmental benefits of spatially variable herbicide application by:
    - HGCA;
    - Other organisations.
- The whole review needs to be put into the context of broader precision farming developments and issues.

The review will highlight the changes in technology that have occurred since 2002; the advances in GPS, changes in sprayer design and the increase in the use of computer technologies in farm machinery. It will also update knowledge on the spatial biology of weeds and of weed detection techniques. The issues associated with how to select appropriate doses for patch and non-patch areas and the associated risks will be contrasted and then the economic costs and benefits will be estimated, as far as possible. Finally the review will reach some conclusions and will make recommendations to HGCA in relation to further action.

2. Location technologies

The technologies associated with ‘precision agriculture’ have continued to advance over the last five years. The most obvious element of this has been the increase in the use of GPS based navigation systems. In 2002 these were still largely restricted to combine harvesters and could be unreliable. They are now becoming standard items in new tractors and harvesters. This increase is partly attributable to reductions in price but also to the increased precision and reliability of the satellite signals used by the GPS systems. There are now more than 50 satellites circulating above the earth providing guidance signals. However, the basic GPS signal provides only relatively coarse location (5-10m) which may be adequate for the increasingly popular in-car navigation systems, but agricultural activities may require considerably greater accuracy. This is being delivered by the availability of a greater range of fixed signals either from remote ground-stations, or from geostationary satellites (e.g. Omnistar, Egnos), or with greatest precision from a local base station using the RTK (Real Time Kinematic) system. So, with appropriate fixed signals, sub-metre location accuracy can be achieved in most situations.

This increased precision is partly attributable to the improvement in the USA’s GPS (Navstar) satellite system, new more advanced satellites continue to be launched, and partly to improvements in the receivers. The latest receivers have the potential to monitor 12 channels simultaneously, whereas old ones were often restricted to 6 or 8. There are now 29 satellites in the American Navstar system and the EU has started to establish its own satellite network (Galileo). Differential signals are now widely available from either land-based sources or from geostationary satellites, providing increased accuracy (DGPS). Real-time kinematic (RTK) signals with a local base station can provide the most precise (centimetre accuracy) location. RTK is probably unnecessarily precise for current arable agricultural uses, but does play an important role in horticulture. It is reported that local area RTK networks are being set up in the USA and Australia (Mark James, pers. comm., 2006) indicating what may happen in the UK in the future.

Robinson & Metternicht (2005) reported on the errors in yield mapping and included GPS errors in their study. The indications were that other errors, such as inappropriate kriging of data, grain time lags and inaccurate crop width during harvest were more significant causes of errors in yield maps than GPS errors. Bogaert and colleagues (2005) explored, in a model system, the accuracy of GPS navigation enhanced with the EGNOS geostationary signal to measure areas of land (0.5 – 5ha), that could equate to weed patches. They found that the errors in the detected areas were only 1-5% (Bogaert *et al.*, 2005). These errors were reduced when the operator travelled at the best speed and when the receiver had a high acquisition rate. In a test of GPS accuracy (without a differential signal) for mapping purposes, Li *et al.*, (2005) reported that mean positional error was about 6m. They also made the point that when the number of satellites is low and/or their geometry is poor, then accuracy declined. An ‘on farm’ evaluation of the accuracy of GPS guidance systems was reported in 2006. Four tractor autosteer packages were compared. All systems used

DGPS signals and their accuracy was compared to an RTK system. Tractors fitted with the four systems were driven up and down a field five times at two speeds, and the degree of ‘wander’ of the tractor from the centre line recorded. All four systems delivered 20-50cm pass-to-pass accuracy (Pearce, 2006 Farmers Wkly 29 Sept 06). These studies all support the conclusion that positional accuracy with DGPS is generally adequately accurate for creation and treatment of patch maps. Any locational ‘drift’ can be accommodated by putting buffers around the patches before treatment. Such buffers to accommodate GPS errors would probably be smaller than those needed to resolve errors in detection of patch limits (see Section 6). However, there are still reports from users of losing signals when adjacent to woods and buildings (when the number of satellites that can be ‘seen’ is reduced), so practical issues with the accuracy of locations may still have to be resolved.

Discussions with sectors of the farm machinery industry have emphasised that GPS receivers are now installed in many tractors, combine harvesters and self-propelled sprayers. The main reason for this has been to take advantage of the advances in GPS guidance systems (manual and automated) to reduce overlap (and underlap) in farm operations. This may be to ensure that the combine header is working at optimum efficiency or to optimise pesticide and fertiliser application. The importance of the ‘driver’ of interest in GPS linked guidance systems is emphasised in a recent survey in the USA of 343 retail agriculture dealerships (Whipker & Akridge, 2006). This shows that in 2006, 67% of dealers were offering services with GPS guidance systems (manual and automated), an increase of over 40% since 2000. The second most important service they provided was field mapping for legal and insurance purposes. Other activities associated with precision agriculture were a relatively minor proportion of their total activities, although there was a significant interest in providing services for recording soil electrical conductivity, soil pH and chlorophyll. All these link primarily to optimising fertiliser application. Although there has been a lot of research in relation to weed detection (see Section 5) the practical uptake of mapping technologies in Europe and USA has been very low.

3. Sprayer design and control

There have been measurable advances over the last five years in the provision of computer systems in tractors and combine harvesters. Those in tractors can control many farm operations, such as pesticide applications, fertiliser, drilling. Many tractors, particularly those at the higher specification end of the market are now fitted with computer-aided control systems as standard equipment. Combinations of these more sophisticated controllers with better sprayer design have led to an increase in boom section control capabilities. Farm software companies (e.g. Farmade, RDS, Patchwork Technology, Muddy Boots) have developed programmes to control the various tasks required by the farmer and record what has been done, for farm records and assurance purposes. These can now be linked to the GPS system to control and record details of spatial location.

There are two main components of sprayer control that relate to spatially variable herbicide application, namely:

- the ability to adjust the delivered dose and potentially the components of a “tank mix” across the whole of the working width of the sprayer;
- adjusting the outputs from different parts of a boom so as to be able to operate with a spatial resolution that is less than the full width of the boom.

Both of these control characteristics have relevance to the conventional operation of a crop sprayer (see below) but are potentially more important when considering spatially variable applications.

3.1 Methods of achieving dose control across the full width of the sprayer

Most agricultural crop sprayers are now fitted with some form of dose control system with the aim of delivering a constant applied dose over, for example, a range of operating speeds in the field. Most commonly, pressure control systems are based on:

- a method of monitoring forward speed – e.g. using wheel sensors, ground radar or GPS;
- the sensing of nozzle pressure or liquid flow to the nozzles;
- a method for controlling the liquid pressure at the nozzles.

Most designs of conventional flat fan nozzles have an operating pressure range of typically 2.0 to 4.0 bar, based on achieving an adequate volume distribution pattern and a droplet size distribution that can be mapped to a defined spray quality over this pressure range. Because of the square root relationship between pressure and flow, this pressure range typically results in a forward speed range of ± 15% of a nominal value over which good control of dose can be achieved. The use of extended range/variable pressure nozzles with an operating pressure range of 1.0 to 5.0 bar enables variations of ± 30% of a nominal speed to be used but with implications for spray quality and the risk of drift. In some circumstances not all of this variation will be used to compensate for changes in speed and some may be available to vary the applied dose. However, the scope for making substantial changes in the applied dose with conventional pressure control systems even using extended range/variable pressure nozzle designs is very limited.

At the time of the earlier HGCA/LINK-funded study (Lutman *et al*., 2002), a control strategy based on the use of multiple nozzles and the switching of different nozzle sizes at individual locations on the boom, or in small sections, (Miller *et al*., 1997) had been developed to the commercial prototype stage. This concept has now been further developed by a number of organisations using:

- multiple boom lines fitted with different nozzle sizes and that can be switched to use one or more lines (e.g. Kee Technologies Ltd);
- multiple nozzle assemblies with switching arrangements to enable one or more nozzles to be operated (e.g. Lechler “VarioSelect” system).

A key performance parameter for such a delivery system that is to be used in a spatially variable application system is the ‘turn-down ratio’ (Paice *et al.*, 1996; Combellack and Miller, 1999). Commercial versions of the nozzle switching principle now claim to be able to operate steplessly with a turn-down ratio of 12:1 (i.e. from 600 down to 50 L/ha), (Lechler product data sheet). This compares with a turn-down ratio of less than 2:1 for a conventional pressure control system fitted with extended range/variable pressure nozzles.

There have been few major developments relating to systems for controlling the delivered dose across the width of the boom for crop sprayers since 2001/02 and only a small increase in activity, if any, in the systems that were available at that time. Options that are now available for use with boom sprayers are as follows:

3.1.1 Twin-fluid nozzles (e.g. Cleanacres “AirTec”; Spraying Systems “AirJet”)

Such nozzles use both air and liquid supplied under pressure to a special nozzle body such that the flow rate and spray quality can be varied independently by adjusting the two supply pressures. Examination of nozzle manufacturers data sheets indicates that current commercial versions of this nozzle design can achieve turn-down ratios in the order 2.5:1 at a given spray quality. A prototype twin-fluid nozzle design capable of achieving higher turn-down ratios (5.0:1) has been demonstrated in the UK and elsewhere but has yet to be developed on a full commercial scale (Combellack *et al.*, 2004). The need and costs associated with providing an air compressor to operate with twin-fluid nozzle systems is often cited as a reason for not using this type of application system, particularly since a number of advantages of the system, other than the flexibility in dose control, can be achieved to a limited extent by using air induction nozzles on a conventional boom arrangement.

3.1.2 Pulsed nozzle systems

These systems, based on the work of Giles and colleagues (Giles & Comino, 1990; Giles, 1997), pulse the output from a conventional pressure nozzle and vary the pulse/spray ratio to adjust the output from the nozzle. Studies have shown that a turn-down ratio of 3:1 can be achieved at a given spray quality with such systems. However, they have not been taken up in the UK except at an experimental scale and this may be because of electrical power and costs considerations for the nozzle based units. It is possible to pulse the supply to a boom section of nozzles but in this case the pulsing frequencies are lower and there is less evidence relating to the effect on both droplet size and spray volume distributions from using such a control strategy. Although systems based on this concept have been demonstrated in the UK, it is likely that the main effects of the pressure pulses are lost due to compressibility in the liquid delivery line and there is little evidence that such a principle can be developed to give a commercially successful system for controlling a crop sprayer.

3.1.3 Variable orifice nozzles

In these designs the size of the delivery orifice is increased as the supply pressure increases such that the flow rate/pressure characteristic is much steeper than for a simple orifice. Again, the commercial development and use of such units in the UK has been very limited to date and designs that have been available in limited quantities have shown considerable hysteresis with higher nozzle outputs recorded when the pressure supply is reducing compared to when it is increasing.

3.1.4 Injection metering systems

Injection metering systems can be configured to operate in a number of ways as follows (Miller, 2003):

i) Injection into the low pressure side of the main pump with the injection pump operating against a low pressure head and hence a lower cost metering pump such as a peristaltic unit can be used: such an arrangement can be operated in two main ways, namely:

    (a) in a constant concentration mode with the output from the boom varied by adjusting the volume delivered as in a conventional pressure control system; or
    (b) in a variable concentration mode operating to deliver a constant application volume.

With the constant concentration option, performance characteristics in terms of response times and turn-down ratios are very similar to those of a conventional pressure control system and the main advantages of the injection metering approach relate to keeping clean water in the main tank. For a variable concentration system, response times are relatively long because of the volume of spray liquid contained in the main pump and the delivery pipework. The response to a step change in demand will also be complex because of the need to recirculate a proportion of the main pump output with diaphragm and piston pumps so that delivery to the nozzles can be controlled.

ii) Injection into the high pressure side of the pump with the metering pump operating against the spray line pressure involves the use of pump designs such as the piston pump. Although systems using high pressure pumps could operate in a constant concentration mode, they more commonly operate with variable concentrations and a constant flow rate through the nozzles. For applications of spatially variable treatments, this gives delay times due to flow in the sprayer pipework that need to be accounted for. While these are less than delays with systems that inject on the input side of the pump, because the flow distances are shorter, delay times of 10 to 20 s are not uncommon. Such delays can be minimised by injecting as close to the boom as possible and by using small bore pipes, providing that any pressure losses due to the use of small pipes are accounted for.

A relatively recent development aimed at addressing the issue of response times and the tapering pattern as the change in concentration is delivered to different parts of the boom, involves the use of a recirculation system within the pipework on the boom (Brian Knight – pers. comm. with data; Richard Price – pers. comm. with patent spec.). Concentrated formulation is then injected into a recirculating line on the boom so as to give:

- relatively rapid response times; and
- a uniform but ramped response along the whole length of the boom.

This approach considerably improves the performance specification of an injection metering system used for spatially variable application and minimises modifications to treatment maps needed to accommodate extended and variable lag times.

While there have been some technical developments relating to injection metering systems for dose control including variable rate applications since 2001/02, the adoption of this technology has been relatively limited. This is in spite of the advantages that the approach gives in terms of ease of washing out a machine after use and the safe disposal of such wash waters - an issue that has attracted considerable attention over the last decade. The relatively limited commercial uptake of such systems probably relates to a combination of factors, including:

- the high added cost (circa £15 to £20 k – see also Section 7.2.2 of this report);
- problems with interfacing containers of formulation with the sprayer, including the need to rinse containers and dispose of the rinsings and containers for single trip systems;
- the need to clean pipe lines delivering concentrated formulation – this can be reduced by keeping such lines as short as possible;
- safety implications relating to the carrying of concentrated formulation on the sprayer and to using pipework with concentrated formulations under pressure particularly when injection on the downstream side of the main pump;

- operation with liquid formulations at a time when much effort has been directed at the development of water dispersible granular formulations, with advantages relating to handling, transport and the management of any spillage. While there are injection metering systems that can handle granular formulations these rely on metered pre-mixing prior to injection and are therefore relatively complex and may have problems due to air becoming entrained in the sprayer pipework.

3.1.5 Conclusions

It is concluded that there are a number of different ways of achieving dose control that would enable spatially variable applications to be made. Those technologies that were established at the time of completion of the previous HGCA- funded project in 2001/02 are still available, have been refined a little but have not seen a large increase in their commercial adoption. This particularly includes the use of twin-fluid nozzles, injection metering systems and multiple nozzle heads at given locations on a boom line. The use of multiple boom lines on a sprayer with the lines controlled independently is probably increasing in popularity because of the flexibility offered by such a system and has implications for the commercial adoption of spatially variable applications.

3.2 Controlling output along the boom

Most of the methods of dose control used commercially vary output across the full width of the boom. Section control is normally achieved by arranging the supply to separate sections via a solenoid valve. The use of a larger number of smaller sections enables improved matching of relatively large boom widths with complex field boundary or weed patch shapes (Figure 3.1).

The output from individual nozzles can be controlled by pneumatically operated valves and the use of “back-to-back” valves effectively enables multiple nozzles to be controlled from the same liquid supply line. This type of arrangement could be operated to give a resolution along the boom equal to the nozzle spacing, although the costs of air solenoid valves and piping to individual valves would then be relatively high. In practice, few machines control to a boom section width of 3.0 m or less and such a resolution is consistent with the use of nozzles that require a “double overlapped” pattern to give a uniform treatment. In relation to spatially variable treatments this means that the resolution proposed by Rew & Cussans (1997) of 4.0 m x 4.0 m would be achievable if treatment map information could be produced at this resolution in a cost effective manner.

If a spatial resolution of treatment of less than the width of a boom is required with a dose resolution of better than on/off, then the use of multiple lines/nozzles on a given line does enable this to be achieved with only small modifications to conventional control arrangements. The use of other dose control strategies such as those using injection metering or twin-fluid nozzles can only be adapted to give different outputs from different boom sections with a substantial increase in capital investment.

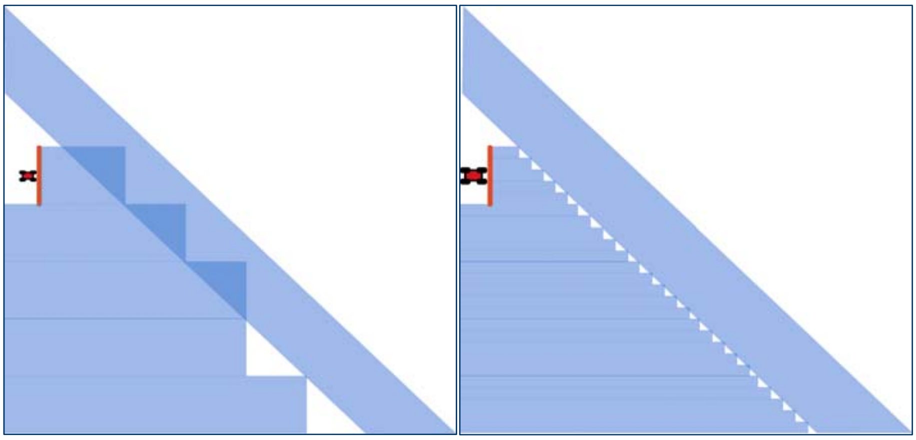

Figure 3.1 Minimising overlaps at field/patch boundaries by using boom control in small sections (from Spraying Systems Ltd)

Figure 3.2 A typical sprayer control system using touch-screen control menus (from John Deere Ltd).

3.3 In-cab control units

Most sprayer controllers are now computer-based with improved facilities for data handling and the processing of control information. The operator interface has been simplified in many designs with the use of touch-screen technologies – see Figure 3.2. This means that control systems can now more easily interface with stored treatment maps and location inputs to implement spatially variable treatment strategies if required. As an example, the Zynx X20 control system from Kee Technologies in Australia is essentially a small computer that uses Windows operating software and can run most farm management software programs. It typically has a 2 GB hard drive and a 800 x 600 colour touch screen and can be used to control a wide range of agricultural implements. As a sprayer controller, such a system can be readily programmed to make spatially variable applications with the ability to accept and interpret treatment maps, location information and implement a range of possible control strategies.

A serious issue inhibiting the uptake of precision agriculture in the past has been the incompatibility of components from different manufacturers. This is now being addressed by the development of *ISOBUS.* This is the common specification of the manufacturers concerning the application of the International Standard ISO 11783 *Serial Control and Communications Data Network*. (see www.isobus.net). The companies involved have agreed to cooperate in the development and introduction of 'bus' systems for the data communication between tractor, implement, virtual terminal and personal computer (PC). This is being driven from Germany but is also impacting on UK manufacturers.

3.4 Prototype patch spraying systems

Gerhards and Oebel (2006) describe an experimental prototype patch spraying system that delivers treatments based on using three separate tanks, delivery lines and control systems on a single machine – see Figure 3.3. The machine had a 21 m boom and was divided into seven 3.0 m sections. At each nozzle location there were nozzles supplied by three separate circuits so that effectively treatment comprising three separate layers could be applied (Figure 3.3). This system used on-line weed detection based on the digital analysis of images as well as GPS location as inputs to an application decision algorithm and field trials over two seasons gave savings in herbicide use of between 6 and 81% in winter cereal crops.

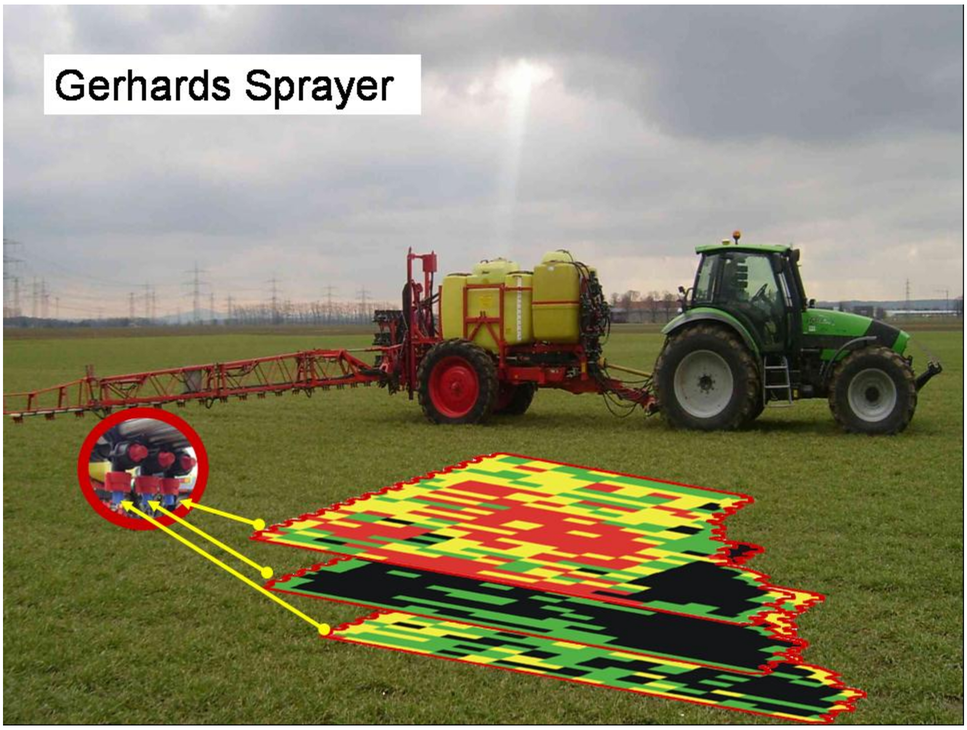

Figure 3.3 The experimental/prototype patch sprayer described by Gerhards and Oebel (2006).

This system is the one that it most advanced in Europe, and is being developed and tested by Rau-Kverneland (Dunn, 2005, Gerhards & Oebel, 2006). Other manufacturers are also exploring patch spraying technology, but to our knowledge no fully automated patch spraying system for arable crops is yet available.

4. Weed biology in relation to spatially variable treatments with herbicides

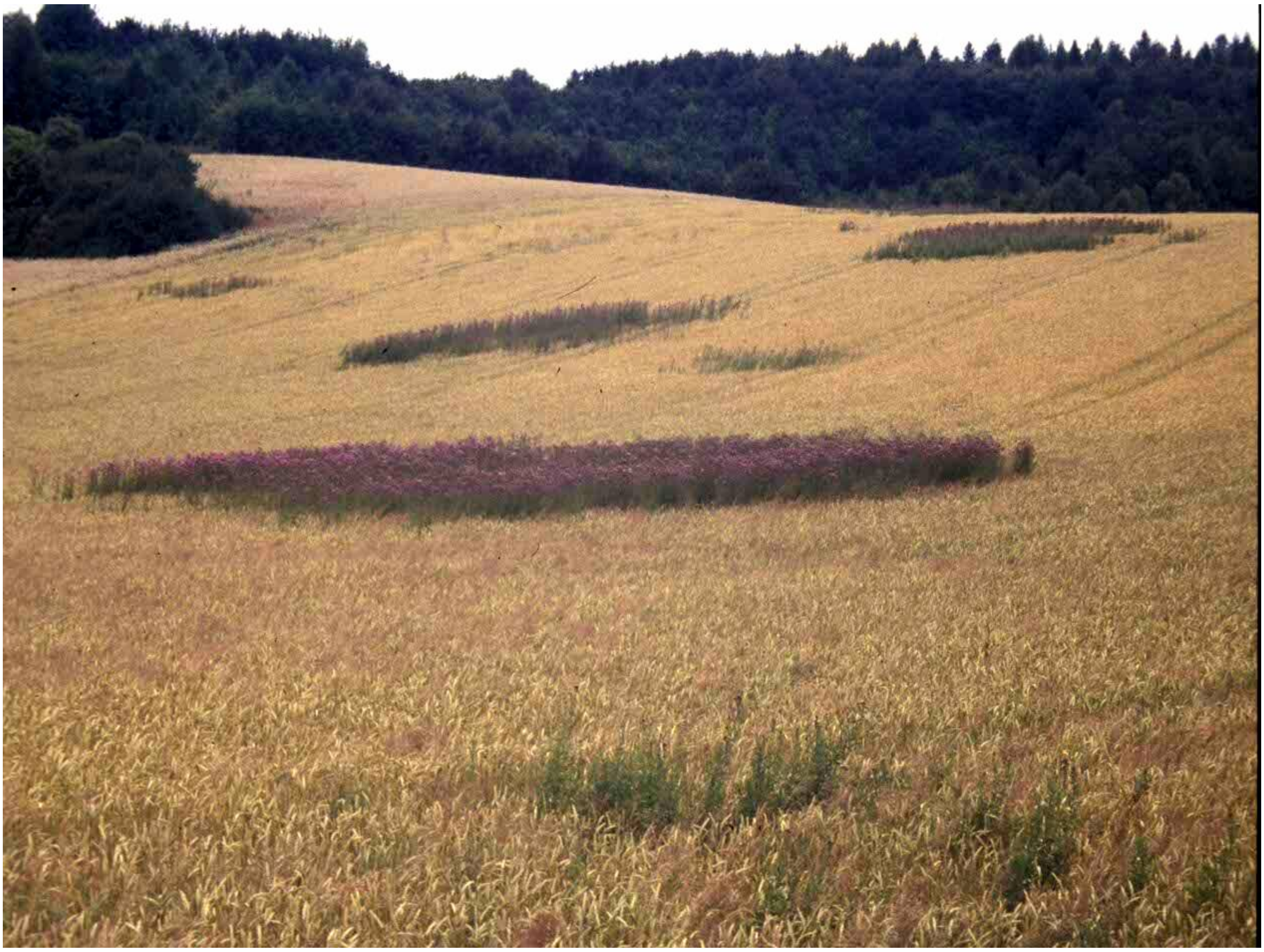

Figure 4.1 Typical patchy distribution of weeds in a maturing cereal crop.

4.1 Weed spatial biology

The whole basis of the technique of spatially variable weed control depends on the aggregated distribution of weeds (Figure 4.1). The previous project concluded that the most aggressive weed species in UK arable crops, such as black-grass (*Alopecurus myosuroides*), wild-oat (*Avena fatua*), barren brome (*Anisantha sterilis*), common couch (*Elymus repens*) and cleavers (G*alium aparine*) are aggregated in distribution and that the patches are reasonably stable (Lutman *et al.*, 2002). This conclusion was based on work undertaken in the project and on other published research. Subsequent work still continues to confirm that this view is correct. As was found in our HGCA project, some species appear to be more heterogeneously distributed than others. For example, Hamouz *et al.* (2004)) have shown that creeping thistle (*Cirsium arvense),* cleavers (*G. aparine)* and scentless mayweed (*Tripleurospermum inodorum)* were more patchy than field pansy (*Viola arvensis).* Similarly, Gonzalez-Andujar & Saavedra (2003) reporting on the distribution of wild-oat (*Avena sterilis)* and ryegrass (*Lolium rigidum*) in 52 fields in Spain, concluded that these species showed a high degree of patchiness. In some situations these weeds tended to form large discrete patches, whilst in others a large numbers of small and variable patches were created. Opportunities for patch treatment are clearly better in the former. There are biotic and abiotic causes of this variation in aggregation, as both site characteristics and intrinsic biology of the species can influence its distribution. This variability is exemplified by studies of 31 fields in Spain infested with wild-oats (*A. sterilis*) (Ruiz *et al*., 2006). Overall, the majority of the infestations in the fields were caused by a few large patches, with a few small and regular patches making up most of the rest of the infested areas. A large number of very small patches made up the remainder. This confirms our view that patch size of wild-oats is very variable.

The apparent degree of heterogeneity of distribution of weeds, as well as being influenced by the ‘real’ distribution of the weed is also affected by the sampling regime and the size of the sample ‘pixel’. Infrequent samples on a large grid size may result in maps that do not reflect the true spatial variation. Sampling intensity is governed by the method used and by time and costs. This is discussed in the section on mapping.

4.2 How patchy are weeds

The basic parameter driving the economic attractiveness of weed patch spraying and hence its commercial viability is the percentage of the field that is infested with the weed. As already stated, patchiness varies between species. It also varies year on year, as cultural and environmental conditions make the ground more or less suitable for seed germination (see below: Section 4.3). Summarising data from weed maps generated in the previous two LINK projects indicates that weed patches vary greatly field to field and that some fields will therefore not merit patch treatment. Table 4.1 summarises previous data. Weed infestations were ‘on average’ affecting less than 50% of the infested fields, although levels on individual fields varied from <10% to >80%. Other data on the percentage infestation levels is hard to obtain. The German researchers Gerhards and Nordmeyer (Gerhards & Oebel, 2006, Nordmeyer, 2006) have reported a lot of work on percentage herbicide reductions achieved in their patch treatment projects, but this is not the same as the percentage of field area infested, especially when variable doses are being used.

4.3 Stability of patches

A second critical issue relating to patch treatment of weeds is the stability of the patches. If the patches are relatively static, mapping needs to be done relatively infrequently. Repeat mapping in the previous LINK project indicated that patch stability varied depending on the species, but for example, black-grass and cleaver patches were quite stable. Work by Gerhards and his colleagues showed that patches of black-grass and annual meadow-grass (*Poa annua*) are relatively stable Gerhards (2002), and Hamouz *et al.*, (2004) confirmed that cleaver patches were also quite stable.

Table 4.1 Percentage of field areas infested with 'target' weeds for patch treatment Data from previous projects ((Lutman *et al.*, 1998, Lutman *et al.*, 2002)

Weed species	No of fields mapped	% infestation	Range
Black-grass	24	41	4-85
Wild-oats	12	17	2-57
Cleavers	2	16	14-18
Creeping thistle	4	23	9-37
Common couch	11	34	3-79

Thus, some of the key target species for patch treatment do appear to have relatively stable patches. However, climatic and cropping variation may cause patches to be more evident in some years (with high weed emergence) than in others, making the patches appear to 'wax and wane'. This annual variability is highlighted in work by Jurado-Exposito (2004) and Nordmeyer (2006). The key issue in relation to the practical use of weed maps as predictions for herbicide application in subsequent years is that patches are **relatively** stable. Colbach working on some USA data for weeds in soybeans concluded that predictions of another grass weed (*Setaria viridis*) could only be used to predict forward into the following season, longer predictions being too inaccurate (Colbach *et al*., 2000). This suggests that predictions for 1-2 years for annual grasses may be the limit. Colbach (2000) also comments that patches of perennial creeping thistle (*C. arvense)* were more stable than the grasses. Much of published work uses correlations between weed infestation data collected at specific locations over a series of years. These correlations are nowhere near 1.0. Correlation values by Nordmeyer (2006) for grass weeds varied from 0.15 to 0.46, which although statistically significant in many cases, do not indicate close links between years. Similarly, Hamouz *et al.* (2004) only report correlations for the 'stable' patchy weed, cleavers, of 0.19-0.38. There are flaws in using correlation techniques for year-to-year comparisons, as for example, if weeds are more abundant in one year the patch appears to expand and thus, although the patch has not moved, the correlation between years will be low. Also correlations based on very low weed infestations are rather suspect, as there are so few plants to assess. Some workers have published stability values for such data.

Thus, published data since 2002 do not conflict with the basic conclusions of the earlier work, that a number of weeds of key agronomic importance are spatially heterogeneous in distribution. These patches can be relatively stable though clearly there is variability between years and stability clearly varies from species to species (Table 4.2). Uncertainty, as to the reliability of historic maps of weed distribution for controlling herbicide treatments can be resolved in two ways. Firstly buffers can be added to the weed patches to ensure that low density infested areas around the core patches are treated. Secondly, a high dose/low dose treatment strategy can be used, instead of a spray/no spray strategy, with the high dose being applied to the patch and a low (partially effective) dose applied to the non-patch area. The same strategy can be used with mixtures of products, with an expensive but highly active product applied only to the patches and a cheaper, less effective product applied to the non-patch area. Alternatively, the cheap product can be applied overall and the expensive product added to treat the patch areas. All options, apart from the spray/no spray approach, require some modification to the sprayer and its control systems.

Table 4.2 Heterogeneity of distribution and stability of patches of common arable weeds

Species	Heterogeneity of distribution	Stability of patches	Sources
Barren brome	high	moderate	(Howard *et al*., 1991)
Black-grass	high	high	(Wilson & Brain, 1991) (Gerhards *et al.*, 2002)
Cleavers	high	high	(Lutman *et al.*, 2002) (Hamouz *et al.*, 2004)
Common chickweed	low	moderate ?	(Hamouz *et al.*, 2004)
Common couch	high	high	(Mortimer, 1990)
Creeping thistle	high	high	(Hamouz *et al.*, 2004) (Bakker, 1960) (Colbach *et al*., 2000)
Wild-oats	high	moderate	(Lutman *et al.*, 2002) (Barroso *et al.*, 2006)

4.4 Conclusion

Research published since the completion of the previous project still continues to support the view that many agronomically important weeds are spatially aggregated in distribution. Data from surveyed fields in the two previous LINK projects (2-24 fields) indicate that mean weed infestations varied from 16-41% of the field area, depending on the species. But the range between infestations in fields of the same weed species was very large. After reviewing the evidence on differences between species it suggests to us that large seeded species, which tend to be the more aggressive weeds, have more aggregated distributions than smaller seeded species. There is more debate as to the stability of patches, with some researchers pointing to stability whilst others highlighting greater mobility, even with the same species. It is certainly true that core patch areas of the large seeded target weeds are quite stable, but patches can expand and contract in relation to the weather conditions and agronomic practices that either enhance or reduce seedling emergence. Some species are also more likely to spread single seeds around the field, thus influencing decisions on what to apply to non-patch areas. Patch spraying is viable but more evidence is needed on how long a map will remain valid and how soon it is necessary to remap. We found some evidence to suggest that weeds should be mapped more often than suggested in the previous project (see Colbach *et al.,* (2000)) but the data are not fully relevant to UK conditions. Consequently, in the absence of further clear data, we continue to support the conclusion of the previous project that cleavers and black-grass patches should be mapped every three years, whilst wild-oats and bromes needed to be mapped more often and perennial weeds less frequently (Lutman *et al.,* 2002).

5. Patch detection

Patch spraying can be achieved in two ways:

1. creation of a map in advance of treatment and then using that map to control the sprayer;
2. real-time weed detection directly controlling the sprayer.

There are advantages and disadvantages to both systems and these will be discussed below.

To use a map based system, a separate operation has to be done to create the map. This could be done by a human operator, with or without the aid of detection technologies, or automatically. With real-time detection and spraying, weed detection has to be automatic. To our knowledge there is little use yet of real time detection and treatment in arable agriculture, although there is some use in industrial weed control. Map-based systems with/without automated detection have been developed into potential user-based approaches for arable crops (e.g. Gerhards & Oebel, 2006, Lutman *et al.*, 2002, Nordmeyer, 2006). However, none of these approaches has yet attracted wide commercial interest. The project that is nearest full commercialisation is based on the German project of Gerhards and colleagues. Their prototype system with automatic weed detection (but not real-time treatment) and triple boom application systems with sub-section control is in development and is being tested (see Section 3.4).

Real-time systems have the advantage that detection and treatment are done in one operation but have the disadvantages that it currently takes a lot of computing power to rapidly translate the image detection information into spraying instructions and secondly it poses application problems. The user does not have detailed information of how much product will be needed to treat a particular field and so there could be a requirement to dispose of surplus pesticide, which is not straightforward. This can be overcome by using direct injection application systems, but adoption of this technique brings is own problems (see section on sprayer design). Map-based systems are more time consuming but, as they are created in advance, provide the user with the opportunity to plan the treatment strategy for the mapped field in advance of actual treatment. There is also much less of a load on the sprayer's computer control system.

5.1 Weed map-based systems

One of the key constraints on the uptake of weed map based patch spraying has been the difficulty and costs associated with creating the weed map. There are many issues relating to patch detection that cause this constraint. Farmers, in our belief, would prefer automated detection systems, either ground-based or remote detection by aircraft or satellite, to an operator controlled detection system. This is mainly because human detection systems take time (and therefore have a cost), unless the detection can be done simultaneously with other operations. As creation of the map can be expensive in terms either of labour to manually record weeds, or in machinery for automated detection, it is important that costs are kept to a minimum. This may mean that the sampling regime will become compromised by being inadequately detailed. The bigger the assessment pixel the less accurate the map is and the greater the percentage of a field that will have to be treated. Conversely, the bigger the pixel the easier it is to treat e.g. application can be across the full boom instead of by boom section. The distribution of the patches in the field will also influence the effect that pixel size has on the treatment area; large pixels are less of a problem when the weeds are in a few large patches but are much more critical if there are many small ones, even where the total infested area is the same. The 'resolution' of the detection system needs to be as fine as it is feasible to achieve. There is a clear relationship between the size of the pixel and the percentage of a field that has to be treated (Wallinga, 1995). Resolution is discussed in more detail below (see Section 5.1.3).

5.1.1 Manual detection

Most research projects use a grid mapping system to record weeds, assessors visiting the same position each season and recording weed density. This is not practical for a commercial system as it is much too time consuming. Research interest in visual mapping has been low but, as demonstrated in the previous project, it is a viable option with both advantages and disadvantages. It is much less dependent on technology than all forms of automated detection (see below) and can be used by farmers now. The human eye can also scan much bigger areas than most ground-based detectors. However, it can really only detect presence/absence or perhaps zero/high/low. The previous project tested several different ways of creating weed maps by human eye. Different species are visible within crops at different times of the year and this constrains techniques that can be used. In autumn-sown arable crops detection from a quad-bike or tractor is possible in autumn and winter but later in the year a tractor has to be used and obviously at harvest mapping from the harvester platform is possible (Lutman *et al.,* 2002). Mapping from a quad-bike can be done on a variable grid, with flexibility of how far apart each pass is made, but when mapping from a tractor the only practical option is to map from the tramlines. Mapping from a combine harvester will produce maps based on the header width of the combine. An alternative to vehicle based mapping using GPS and associated technologies, is to map on foot, walking around patches either with a GPS to geo-reference the map or with a pencil and paper to create a written map that can subsequently be transferred to GPS linked field maps. However, it can be difficult, when at ground level, to see where a patch really ends. Hand written maps can also be created from a tractor, where the extra vision from the higher viewpoint is helpful. These simple approaches will provide less detailed maps than the more mechanised systems but if the weeds occur in isolated large patches this may not be a disadvantage. Hand written maps are less useful where there are a lot of small patches

The most costly option is to employ a contractor to create the weed map by visual means. On the basis of our experiences with mapping from a quad bike, we concluded in 2002 that visual mapping would cost £2/ha on the basis of wages of £6/h and a mapping rate of 3-4 ha/h. Updating labour costs to a current £7.50/h (Nix, 2005) would mean that labour costs of mapping would be about £2.50/ha, if ‘in house’ staff were used for the mapping. If the mapping was done as part of another operation then the cost would be much lower and could be zero. If contractors or consultants were employed for mapping the cost would rise. A recent discussion with those soil sampling for spatially variable fertiliser application indicated that they would charge c. £40/h, so if mapping was at a rate of 3-4 ha/h this would cost c. £10-13/ha. Crop consultants also charge in the region of £10/ha. Interestingly, the recent survey of American contractors indicated that they would charge c. $6/ac (c. £8/ha) for precision agriculture soil sampling (Whipker & Akridge, 2006), a similar figure to that calculated for the UK. Is it feasible for field advisors to provide the weed map? If the farmer was prepared to pay for the map, as discussed above, could an advisor deliver? Consultants would probably advise on 4,000 – 10,000 ha per person. Assuming around 2000 working hours in a year (50 weeks x 5days x 8h) then each hectare would receive a maximum attention of 10-30 mins/yr (this ignores travelling time). Consequently, they would struggle to map more than a small minority of fields in any one year. Maps could be built up over a number of years, but it would require appreciable commitment by the consultants to create the required maps.

Recording information whilst driving a quad-bike is not simple and requires experience and some relevant technology (robust computers, relevant software). The previous project developed a voice recognition system associated with a laptop computer for mapping (Lutman *et al*., 2002). This meant that the operator/recorder did not have to take his/her hands off the handlebars of the bike, to record the data. As discussed above it is feasible for weeds to be mapped whilst doing another operation (combining, fertiliser application, spraying). Recording mapping information on a tractor or harvester, is now simpler, as current GPS linked software often provides a ‘flag’ facility. Flags can be used to map weeds and the information is directly converted to a patch map. There are however several practical issues. When mapping from a sprayer or fertiliser sprayer the tramline width is likely to be 18-24 m, so the information recorded will have a pixel width of 18 or 24 m, which may be rather coarse. It is possible to use the flags to map weeds on the left and right of the tractor and relevant software to do that was written in the previous project and is still available from Patchwork Technology. This requires greater alertness on the part of the person mapping, but is possible. A further practical issue is that mapping whilst combining or spraying is realistic, provided nothing goes wrong! If the operator is distracted by an event associated with the primary task, he may forget to turn on or off the weed mapping flags at the appropriate time, thus creating an inaccurate map. Without more extensive field testing it remains uncertain as to whether adequately accurate maps could be created by operators, for example, applying fertiliser or combining. It can be done but is it really practical?

5.1.2 Automated detection

Research teams around the world have been expending a great deal of effort over the last 10 years on both ground-based and remote sensing techniques to map plants. To date there has only been limited commercial uptake, except for the simplest approaches of detecting green material against a soil or hard surface background. These have been developed for industrial and amenity use and also for wide-row crops (Brown & Noble, 2005, Kempenaar & Leemans, 2005). Other technologies are at various stages of development.

5.1.2.1 Remote sensing

Satellite and aircraft-based detection systems have been explored quite extensively, especially in the USA. The main problems have been that the pixel size tends to be too large for field scale treatment. This applies particularly to satellite based systems. But technology is improving rapidly and this constraint may not be true in the future. Secondly, detection generally depends on a colour difference between patch and non-patch areas. This could be a flowering weed of could be an increase in the intensity of greenness signifying the presence of a weed patch in an otherwise uniform green crop. These detection systems struggle to record low weed infestations in crops, that may be commercially important and also to detect weeds in crops when they are at early growth stages (Brown & Noble, 2005). Cloud cover can also pose problems as maps, especially aircraft-based ones, may not be available when needed. The ability of satellite sensors to image large areas in a short time makes it much more suitable for the mapping of, for example, invasive weeds on rangeland and other semi-natural habitats (Lass *et al.*, 2005, Thorp & Tian, 2004). In the short term, we believe remote sensing is unlikely to deliver commercially appropriate weed mapping in arable crops such as wheat or oilseed rape.

5.1.2.2 Ground based sensing

A wide range of detection techniques has been studied over the last 10 years. These include photographic images, either alone or in combination with shape and texture, hyperspectral or multispectral analyses and chlorophyll fluorescence. Many of these techniques will successfully identify plant material but the major difficulty has been differentiating between species. The bi-spectral cameras (red/near-infra red) developed in Germany, combined with image analysis software that differentiates by shape (Gerhards & Christensen, 2003, Oebel & Gerhards, 2006), are reported to be able to successfully differentiate between cereal and other crops and 25 grass and broad-leaved weeds. Resolution of the images and identification of the species requires a lot of computer power! Spectral reflectance on its own seems not to be able to reliably identify individual weed species. For example, some worked reported by Bossu (2005) explored the use of spectral reflectance enhanced with a controlled light source and with a neural network to assist classification. They concluded that although monocot/dicot discrimination was good, that of individual weeds was not sufficient. They suggested that it was likely to be more successful if it was associated with prior knowledge of crop position. Such an approach has been used by Tillett & Hague in their work on weed detection in wide-spaced cereal crops. They used reflectance in the visible spectrum plus pre-determined data on crop row positions to successfully differentiate between crop and weeds and between monocotyledonous and dicotyledonous weeds in the field (Hague *et al*., 2006). Nordmeyer (2005) had some success in the use of chlorophyll fluorescence to differentiate between 15 weed species, but the time taken to collect the fluorescence information was too long. Similarly, Assemat *et al.* (2004) have been successful in the laboratory with the use of polarised light. Although some of these techniques have potential in the longer term, none is really robust enough to be used in practice except perhaps the techniques of the "Gerhards group". There are still issues that remain to be resolved such as the ability to detect weeds at early growth stages and the impact of variable light conditions and of plant stress on the spectral data. Many of these issues are discussed by Brown and Noble (2005). Reflecting on the attempts to automatically identify weeds in crops, it seems possible that more success could be achieved if row widths of crops such as cereals and oilseed rape could be increased from the current c. 12 cm to c. 25 cm, which would enable detectors to identify weeds between crop rows, removing the complicating factor of separating green crop leaves from green weeds. Evidence from cereal experiments suggests that although some yield losses could ensue, they would not be great.

A further issue with machine-based detection is the field of view of the detector. Some of the test systems are only a few centimetres wide. This in our view is hardly adequate. The "Gerhards system" takes images 0.02 m^2 (Gerhards & Oebel, 2006) and in their test system they took 3000 images per hectare, which means information was collected from less that 1% of the area. Although this seems very low, the practical tests of spraying on the basis of the maps seem to have been successful. However, the map is based on a very small proportion of the land area. Even if reliable detectors with a greater field of view are developed, the distance between passes and, if they are to be mounted on a sprayer or fertiliser spreader, the distance between detectors, to ensure an adequately precise map (see below), still has to be resolved.

5.1.3 Resolution and sampling strategies

There is a clear relationship between the requirements for mapping and the design of the sprayer. From basic spatial mathematics it is clear that with a defined weed patch in a field, the smaller the application pixel size the lower the proportion of the field that needs to be treated (Wallinga, 1995). The reason for this is that the larger the pixel, the greater the area that does not contain the weed patch that has to be treated. Wallinga estimated that with a given weed infestation a 2 fold reduction in herbicide needed to control the patch would be achieved by approximately halving the size of the grid. Taking this to its logical conclusion the greatest saving is achieved when only the weed leaves are treated. This approach is the basis of micro-spraying (Sogaard & Lund, 2005), perhaps a technique for the future – see Section 9.3 of this report. A sampling exercise reported by Backes *et al*. (2005), surveying cleavers in winter wheat, concluded that a grid of 2 x 3 m gave the best accuracy and that sampling at a greater scale than 7 x 7 m was insufficient. Rew & Cussans (1997) suggested that a 4 x 4m grid was most appropriate.

However, the requirement to minimise the pixel size has to be balanced by the engineering cost of achieving the desired spray application pattern. This relates both to the ability to split the boom into separate sections and the response time of the sprayer to instructions to change application (either on/off or change rate). In the previous project the response time of the Micron patch sprayer was fast and it would change application rates within a few metres, but this applied to the whole boom (12 m). Modern sprayers respond quickly and lag times are small. Current sprayers will respond to on/off commands in about 3 m but if the requirement was to change volume rate to reduce dose, then it takes longer and the sprayer could require 9-10 m. Boom section control is now available on a number of commercial sprayers. These will provide on/off responses but not variable dose. So the potential to patch spray from different sections of the boom is there. For example, both the Zynx controller and that in the John Deere 800 sprayers can switch sections on and off but could only change rates across the whole boom. Injection metering systems would deliver variable dose options on sub-sections of booms but the lead and lag times can be longer and may result in asymmetrical changes in dose across the width of the boom sections. Consequently, some modification of the treatment map would be needed to accommodate this lag. Commercial manufacturers indicated that the potential was there to change rates on boom sections on conventional sprayers but the added cost would be appreciable. Thus, for the immediate future, pixel width for variable rate treatment with commercial sprayers is probably the width of the boom. This clearly diminishes the accuracy of the maps and the potential savings in herbicides, especially when the weeds are dispersed in many small patches. The German Rau/Kverneland patch sprayer operates on 3 m sections, greatly reducing the pixel size and enhancing the reduction in product use. These issues have been discussed in more detail in Sections 3 and 4 of this report.

Thus, current technology is available to deliver spray pixel size for on/off spraying of 6 x 3 m or even 3 x 3 m. For variable dose treatments pixel size might have to be 18 x 9 m. If boom section control for patch spraying is not a viable option, then it could be argued that there is less need to map more intensively than the width of the spray boom. However, even with a coarse spray grid, it is important to have a sound map of the weed distribution, which would mean continuing to map in as detailed a way as possible. Manual mapping, even on a 7 x 7 m grid, suggested as being the minimum by Backes *et al.* (2005), could be a labour intensive activity.

Before concluding this section on resolution and precision of maps, the issue of kriging needs to be addressed. Most workers use various forms of kriging to interpolate data. Concern has been expressed as to the potential for kriging to produce sound maps (Cousens *et al.*, 2002, Dille *et al.*, 2003, Rew *et al.*, 2001). Kriging is clearly useful but it will not create an accurate map if the sampling grid is too small. Adequate sampling is of more importance than the kriging method used. Rew *et al.,* (2001) makes the point that continuous sampling such as recording vegetation cover tends to lead to more accurate maps than discrete sampling at specific points. This again emphasises the need for a sound sampling strategy with relatively small pixels.

5.1.4 Frequency of mapping

Biological studies suggest that for many weeds patches are relatively stable (see Section 4). Cultivation and in some cases combine harvesters will move seeds in fields but movement by the former is relatively limited (Rew & Cussans, 1997). Only weeds that retain seeds at the time of harvest, such as wild-oat will be affected by combines and it is clear that some seeds can be moved quite considerable distances (Barroso *et al.*, 2006). The conclusion of the previous LINK project was that black-grass and cleavers should be mapped every three years, whilst wild-oat and bromes should be mapped more often and perennials like common couch and creeping thistle less often. The frequency of mapping has an appreciable effect on the costs of patch spraying, if it is done as a separate operation, and so would not be done more often than necessary. However, in practice, we would expect new adopters to map more often than was really necessary until they became fully familiar with the approach and were confident in the reliability of the maps. It is also true that patches ‘wax and wane’ depending on the weather conditions and crop management at the time of weed emergence. Because of this it would probably be prudent when taking up the technology to map each year, until a sound map of the weeds in the field had been created. Our financial calculations are based on mapping every other year (see Section 7).

5.1.5 Conclusion

As of now, automated weed detection systems for arable crops are still in various stages of development. Various techniques could lead to practical detection systems within the next five years. Visual detection is the only practical option that could be used in 2007. However, the comment by Wiles (2005) in the USA that 'most growers say they will never count weeds or have seedbanks analysed to make maps' rings true for the UK. Although, some farmers are willing to pay for soil sampling to support precision application of fertiliser, there is no evidence that they will pay their consultants to provide detailed weed maps for patch treatment. Research on the precision of maps, emphasises the need for a fine pixel size, which will increase the cost! The 'holy grail' is several automatic detectors mounted on a sprayer or fertiliser spreader (<6 m apart), creating a detailed map, with minimal labour input from the farmer. The "Gerhards project" will deliver this, but no other technique yet approaches it, apart from visual mapping.

5.2 Real time detection and treatment

This approach to patch treatment is superficially very attractive as it links detection and treatment in one operation. At its simplest, an automated detector mounted on the front of the tractor identifies the target and then passes the treatment instruction to the sprayer. Such approaches are already used in industrial and amenity weed control, such as treatment of weeds on pavements (Kempenaar & Leemans, 2005) or railways, but so far are not commercially available for arable crops such as cereals and oilseed rape, although appreciable research is in progress. There is some usage of automated detection/treatment in a single operation, in horticulture, but this is restricted to small acreage, high value crops, where small areas require treatment. There are two issues of concern related to real time treatment. Firstly, the user has no detailed information as to how much product will be needed prior to entering the field and therefore disposal of excess product may be a major and increasing issue, with more rigorous environmental controls on pesticide usage. Secondly, the requirement to detect and control the sprayer in one operation requires high power computers with a very rapid time response. If the detector is on the front of the sprayer there are only a few seconds between detection and treatment. Although the potential to achieve this is available, it is costly and requires a lot of computer power. It is likely that each detector would require its own computer. The final issue, as described under automated detection (Section 5.1.2), is that identification of weeds automatically is not easy and so far few machines have yet reached commercialisation. The only one to approach practical use, is that developed by Gerhards and colleagues (Gerhards & Oebel, 2006). However, from discussions with farmers it seems that they prefer the apparent simplicity of the real time approach, as there is no need for extra visits to the field to create the map. They find the concept more attractive than the map based approach, despite the potential problem of disposal of surplus product. It should be noted that a real time treatment controlled through the sprayer's computer will create a map of where the herbicide has been applied, which could be used in the future in a mapping mode.

6. Treatment plans

Having mapped a field the information has to be turned into a treatment map. This was discussed in some detail in the previous project (Lutman *et al.*, 2002). The data may have to be kriged to create the initial map and then may have to be inflated with buffers. Then decisions have to be made about what treatment to apply to the patch and non-patch areas (if a spray/no spray strategy is not employed). It should be pointed out that patch spraying focuses on the management of a weed in an individual field with the herbicide treatments tailored to the species present in that field. This means that different fields and indeed different parts of one field may require different treatments. This approach conflicts with current attitudes, where farmers, who are now managing much bigger areas, require simple ‘recipes’ for weed management that can be applied to all fields and do not require adjustment to accommodate different weed species and certainly not spatial variability within fields. Patch spraying does not sit comfortably with these wishes and the financial incentives to adopt the technology need to be appreciable.

6.1 Patch maps

The previous project, with the support of Patchwork Technology, created software that would convert a weed map into a treatment map (Lutman *et al.*, 2002). The steps of smoothing and inserting buffers, when needed, were incorporated into the software. Buffers can be needed for a variety of reasons:

a) to account for lead and lag times of the sprayer;
b) to resolve uncertainties as to the full extent of patches;
c) to take account of potential local-scale movement of patches as a result of seed rain and cultivations;
d) to absorb any drift in performance of the location system.

Programmes, such as that from Patchwork Technology, will insert buffers around the mapped patch. The size of the buffers will be influenced by the patchy nature of the weeds and when the map was created. If treatment is based on maps from a previous year it may be necessary to inflate the patches slightly (c. 5m) to account for seed movement by cultivation equipment. Having added buffers, the map then needs to be adjusted according to the requirements of the sprayer, such as its width and lead and lag time, to create a treatment map. The area to be treated will depend on the resolution of the sprayer – how big the spray pixels are. If the sprayer boom can be split into smaller sections for treatment, then the increase in area to be treated to ensure all weed patches are treated will be smaller than where application rates can only be changed across the whole boom. The increase in the proportion of the field that has to be treated, as a result of adding buffers and constraints of the sprayer design depend on the patch distribution, as the inflation of the weed area will be greater when there are many small patches than where there are few big ones.

Assessing the data from the previous project indicates that adding buffers and creating a treatment map will on average add about 15% to the weed infested area.

The final decision that then has to be made is the product(s) and dose(s) to use.

6.2 Treatment decisions

There are two approaches to patch treatment, either spray / no spray (where the field area outside the weed patches is not treated) or low dose/high dose (where the non-patch area receives a low dose). If the sprayer only has the potential to be turned on or off, the only decisions that have to be made is what product to use and what area to treat. If the sprayer is able to vary dose, decisions have also to be made on the doses to use. If the sprayer has the potential to apply more than one product, an added requirement is to decide what product to use, as well as what dose. Much advice is available to farmers as to what products to choose, the difficult problem is 'what dose to use'. This applies particularly to the non-patch area, where lower doses are more likely to be applied. The ideal strategy is to link information on the weed infestation level, to its competitive effects on crop yield and then to choose a product and dose to achieve the economic optimum level of control. This was the theory behind the development of the weed management decision support system, Weed Manager (Collings *et al.*, 2003, Tatnell *et al*., 2006). In practice, although Weed Manager has made great strides, its suggestions are still mainly based on recommended herbicide rates. In the UK, information on the performance of lower rates is not widely available, either from the manufacturers or from the public sector. Crop consultants do recommend low rates, but this is considered to be confidential, partly because of the implications for legal liability. If the manufacturer's recommended dose is not used the legal liability rests with the person giving the advice and consequently there is reluctance to provide general advice on low rates. This lack of information has made choosing a patch treatment for less infested areas difficult. The situation is better in Denmark, as government supported research has resulted in the availability of dose response data through their decision support system PC-Plant Protection (now PVO) (see www.agrsci.org). Advice on what dose to use for a specific weed has been linked to patch treatment to create DAPS (decision algorithm for patch spraying) (Christensen *et al*., 2003)**.** However, as the uptake of patch spraying the Denmark has been limited (P. Kudsk, pers. comm., 2006) the potential of DAPS has not really been tested. The German project of Gerhards used DAPS to assist the selection of doses (Gerhards & Oebel, 2006). Products were selected on the basis of published German data and farmer experience. However DAPS only supported dose reduction of 30%, so the economic savings were small, the main reduction in herbicide use resulting from not spraying areas where the mapping indicated the weeds were absent (or below a threshold density level). Not all products were applied on a spatially selective basis, as the sprayer has the potential to apply three spray solutions on a spatially variable basis at one time (by changing volume rates).

As mentioned in the previous paragraph, information on the response of weeds to doses lower than the recommended rate is very limited. It is known that some products have steeper dose response curves than others. For example, sulfonyl urea herbicides (which include Atlantis, Eagle and Ally) have relatively flat response curves, whereas Topik (clodinafop) has quite a steep one. Precise information that could be used to tune treatment to infestation levels is not available for most products and weed species and so decisions on what dose to apply to the non-patch areas are difficult and this exaggerates farmers' concerns about the risks associated with the technique.

Because of the difficulty of accessing reliable information on appropriate doses it is tempting for potential users to adopt the simpler approach of spray/no spray, as this avoids the need to decide on what dose to use. It is also attractive as a number of current conventional sprayers already have the ability to switch on and off boom sections. It is also more attractive as the reduction in product use is greater in a spray/no spray system than for low dose/high dose ones (see Section 7). BUT modelling research has indicated that there is a serious problem with a spray/no spray approach. Paice (Paice & Day, 1997, Paice *et al*., 1998) explored the long term impact of spray/no spray and low dose/high dose strategies and concluded that the former was likely to fail in the long term, because small patches and isolated plants outside the sprayed patches acted as foci for re-colonisation of the field. Such patch evolution is suppressed by the low dose/high dose strategy. It is not clear whether this is reflected in practice and some longer term field studies would be needed to confirm whether the modelling conclusion was right or wrong. It should be noted that the patch spraying project of Nordmeyer is based on a spray/no spray strategy (Nordmeyer, 2006) and this seems to have been successful over several years and the areas treated have not increased. The economic issues related to spray/no spray and low dose/high dose strategies are discussed in the next section.

6.3 Conclusions

The technology exists to convert the initial weed maps into treatment maps, but there is a lack of advice (and confidence) in the choice of doses needed. This applies particularly to those needed to suppress low level infestations that do not justify a full rate treatment. There has been no public sector research supporting herbicide use (except in the context of herbicide resistance) since the screening work carried out from 1970's–1990's at WRO and Long Ashton stopped in the early 1990's e.g. (West, 1994). As a consequence, information on low doses is hard to acquire and is largely based on word of mouth advice. In contrast, HGCA has funded a substantial research project on appropriate fungicide doses (Lockley & Clark, 2005). The lack of information on appropriate doses, and reluctance to advise low doses, because of legal liability, contributes to the general belief that patch spraying is 'not worth the risk'. Although Weed Manager has created a good tool to explore the longer-term impacts of failing to achieve good weed control in one season, showing that there are management tools available to minimise problems in subsequent years, there is still a strong belief that poor weed control in one year will result is serious problems for a long time thereafter (one year's seeding gives seven years weeding!). Weed biology studies would suggest that this is not true for many arable weeds, as seed longevity for grass weeds such as black-grass is relatively short (Lutman *et al*., 2003). There are a lot of attractions in adopting a spray/no spray strategy, as this avoids the problem of what dose to use, but the issue as to whether such strategies will fail in the longer term, because of seeding by weeds in the no spray area, remains to be resolved.

7. Economics

The uptake of all new technologies needs to be seen from the standpoint of the overall prosperity of arable crop production, as profitable crop production leads to greater investment in new equipment and technologies. In reality, commodity prices (as exemplified by cereal prices) have declined (until autumn 2006) whilst input costs, especially fertilisers and energy, have increased (Figure 7.1). Mean annual farm income for farmers growing cereals over the last five years has been only £16,200 (Defra, 2005). (http://statistics.defra.gov.uk/esg/publications/auk/2005). This lack of profitability has discouraged purchases of costly farm machinery and of the uptake of new technologies with a perceived high initial cost, unless the benefits are clearly obvious. Tractor sales in 2006 are still 2% lower than the five year mean (Farmers Weekly, 19 Jan. 2007). Only a third of farm sprayers are less than five years old (Garthwaite, 2004). But the majority of new sprayers work on farms that are larger than average. These tend to own self-propelled or trailed types, where a greater percentage are newer than the average. Approximately 9% of sprayers had GPS guidance in 2004 but 59% of the arable area was treated with variable rate sprayers, which would have some potential to patch spray.

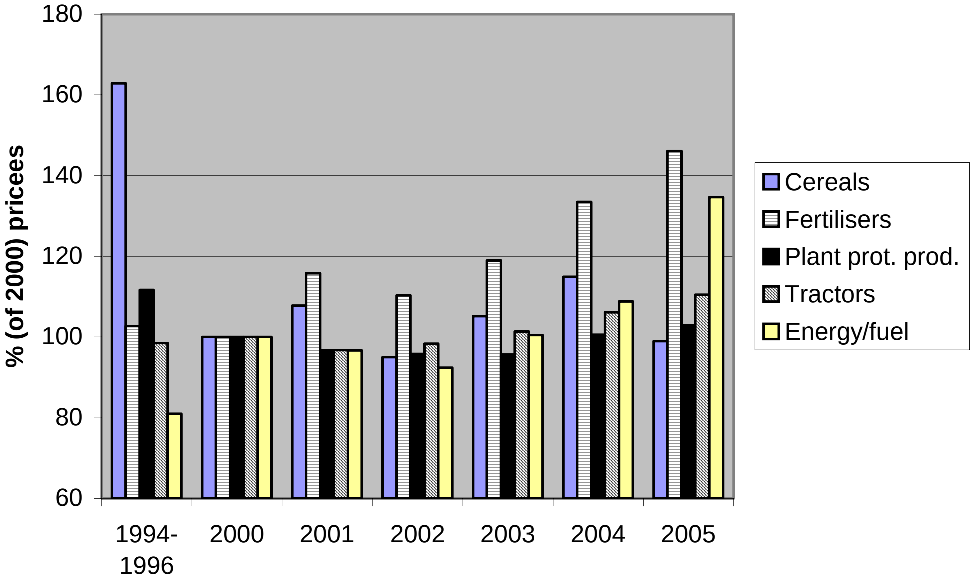

Figure 7.1 Relative changes in agricultural prices 1994 – 2005 in the UK (prices at 2000 set as 100%) – input and output prices (Defra, 2005)

The economic attractiveness of the patch treatment of weeds basically depends on the cost of mapping (if done as a separate operation) and the equipment need to patch spray, compared to the cost savings associated with reduced herbicide use.

7.1 Potential financial benefits from the reductions in herbicide use

The financial savings achieved by patch spraying will depend on the area to be treated, the doses used on the patch and non-patch areas and the cost of the herbicides. Calculations are presented here, based on the weed infestations mapped in the previous LINK projects, but updated with current costs and products, and with weed control strategies appropriate to 2007. Several scenarios have been compared.

7.1.1 Black-grass

The most appropriate scenario for the management of severe black-grass problems in winter wheat would be a sequence of pre-emergence Crystal (flufenacet + pendimethalin) followed by Atlantis (mesosulfuron + iodosulfuron). If the full rate of both products was used, this would cost c. £69/ha (Table 7.1). A spatially variable treatment could be a uniform rate of Crystal either at its full rate (4 L/ha) or its reduced rate (3 L/ha) followed by a (spray/no spray) patch treatment with Atlantis. Assuming that the black-grass patches only required 65% of the field to be treated, this would reduce the cost of the full rate treatment from £69/ha to £59/ha, resulting from the reduced use of Atlantis alone. If the Crystal was also patch applied with, for example, the 4 L rate on the patch area and 3 L/ha on the non patch area, the herbicide saving would increase to £13/ha. However, if a less risky approach is taken of applying a low dose of Atlantis to the non- patch area the reduction in cost is only £3/ha. If the black-grass patch treated area covered only 55% of the field these savings from only on/off patch spraying Atlantis would increase to £12/ha and for patch treatment of both Crystal and Atlantis to £17/ha. These are both expensive treatments and so farmers may not use both. An alternative would be a lower cost treatment of trifluralin, perhaps with IPU, overall, followed by Atlantis applied on an on/off spatially selective basis (Note: both trifluralin and IPU may not be registered in the future.). In which case, the saving from patch spraying would still be c. £10/ha. By comparison, a patch treatment of black-grass with Topik (clodinafop) + oil would save only £6/ha on a spray/no spray strategy with black-grass present on 65% of the field, or only c. £2/ha if a low dose/high dose strategy was used (Table 7.1). This reflects the lower cost of this product, emphasising that patch treatment is more attractive with expensive products.

Table 7.1 Estimates of herbicide costs and savings from patch spraying three contrasting weed species in winter wheat (or set-aside). (% area infested to be treated on data from the previous project (Lutman *et al.*, 2002)

Weed species	% of area within the patch treatment	Herbicide Product	Full dose (L/ha or g/ha)	% of full dose applied to non-patch area	Herbicide cost of full rate (£/ha)	Herbicide cost of patch treatment (£/ha)		Cost savings (£/ha (%))	
						spray/ no spray*	low dose/ high dose*	spray/ no spray	low dose/ high dose
Black-grass	65	Crystal	4L	75%	41.12	26.73	37.52	14.39 (35)	3.60 (9)
		Crystal	3L	n/a	30.84	20.75		10.79 (35)	
		Atlantis	400g	70%	28.00	18.20	25.06	9.80 (35)	2.94 (10)
		Topik	0.125L +oil	70%	17.86	11.61	15.99	6.25 (35)	1.88 (10)
Black-grass	55	Crystal	4L	75%	41.12	22.62	36.49	18.50 (45)	4.63 (11)
		Crystal	3L	n/a	30.84	16.96		13.88 (45)	
		Atlantis	400g	n/a	28.00	15.40		12.60 (45)	
Cleavers	40	Starane	1L	70%	19.98	7.99	16.38	11.99 (60)	3.60 (18)
	65	Starane	1L	70%	19.98	12.99	17.88	6.99 (35)	2.10 (11)
Common couch	49	Roundup	2L	70%	3.30	1.62	2.80	1.68 (51)	0.50 (15)

* spray/no spray means – full rate on the patch area, no treatment on non-patch area: low dose/high dose means – full rate on patch area and a lower (70-75% dose) on non patch area

7.1.2 Cleavers

The cost savings from patch spraying cleavers in winter wheat with Starane (fluroxypyr), when only 40% of the field was treated would be £12/ha on a spray/no spray strategy but only £4/ha on a low dose/high dose treatment, with the non patch area receiving 70% of the full dose (Table 7.1).

7.1.3 Common couch

If common couch was a serious problem on a set-aside field, or at a time of the year when there was no crop present, it would be attractive to patch spray the Roundup (glyphosate) for its control. However, the cost of this product is now so low that even on a spray/no spray strategy with couch on about 50% of the field, would result in a saving of less than £2/ha. The absence of cost benefits from patch spraying glyphosate has also been noted by Bakker (pers. comm., 2006). He patch sprayed with glyphosate, reducing herbicide use by 36% but only saved £1.82/ha.

7.1.4 On/off (spray/no spray) or low dose/high dose

The previous sub-sections show that financial savings are much greater if an on/off strategy is used for the patch/non patch areas, rather than the low dose/high dose one. However, our perception is that the risks of not achieving acceptable weed control especially in the longer term are much greater in the former because of the consequences not treating small areas of weed that will then form the focus of future new patches (see Section 6.2).

With the low dose/high dose strategy, we have the issue of what dose to use on the low dose areas. This has already been discussed in Section 6.2. The suggested use of 70-75% of the full rate on the non-patch area, in these economic calculations, is based on conservative estimates of the likely dose response curves of the products. The German researchers have based their patch treatments on either 0%, 70% 85% or 100% of the full rate of each product, depending on the infestation level in each of their spray pixels (Gerhards & Oebel, 2006). This in turn was based on the Danish DAPS advisory system (see Section 6) (Gerhards & Christensen, 2003). It should also be noted that current sprayers do not have an adequate turn-down ratio to permit changes in dose appropriate for low dose/high dose treatment, although they do have enough flexibility to adjust for changes in sprayer speed. Sprayers with greater flexibility require further changes to their design to achieve variable rates.

From the previous paragraphs it can be concluded that savings of c. £10/ha would be possible from the patch treatment of black-grass in winter wheat, using an on/off strategy. Savings tend to be less than £5/ha when the preferred low/dose high dose approach is used. For other weeds in other crops, savings may be less than

£10/ha. The results from the research in Germany by Gerhards (Gerhards & Oebel, 2006) and by Nordmeyer (2006) concluded that it was possible to achieve a 50-60% reduction in herbicide use for the control of broad-leaved weeds and cleavers in winter wheat and 40-70% reduction in grass weed treatments (primarily black-grass, loose silky bent (*Apera spica venti*) and annual meadow-grass). These savings, particularly for grass weeds are much greater than those calculated above, and so for example a reduction of 60% in Atlantis use for black-grass would save c. £17/ha. The reasons for the greater savings may relate to the greater dose ranges they have tested and in the case of Nordmeyer by the predominant use of spray/no spray strategies. Oebel and Gerhards (2006) have calculated that their patch spraying of grass and broad-leaved weeds in four winter cereal fields saved on average €36/ha (£24/ha) (range € 25–51/ha) but their earlier work (Gerhards & Sokefeld, 2003) on 18 winter cereal fields concluded that the savings were €21/ha (£14/ha). Savings in both papers were somewhat lower for winter rape, sugar beet and spring barley at €0-34/ha, but are still generally higher than those calculated from the UK wheat data.

7.1.5 Conclusion

Without further practical tests with a commercially designed patch system on ‘real’ fields it is not possible to be more precise as to the likely savings that could accrue from patch treatment and whether the more financially attractive option of on/off treatment would be successful, or whether the less risky low dose/high dose approach would be needed to ensure continued acceptable weed control. In the absence of this information, it would be prudent to base any cost benefit analysis on cost reductions of £10/ha with an on/off strategy, but less than £5/ha with a low dose/high dose approach. The previous project based its calculations on a saving of £6/ha. whilst commenting that for some weeds in some crops savings would be appreciably greater (Lutman *et al*., 2002). A spreadsheet ‘calculator’ was devised in this project to estimate potential savings based on the % of field to be treated, the herbicide rates to be applied to the patch and non-patch areas and the herbicide cost.

7.2 Costs of patch spraying

The costs of patch spraying include the cost of mapping, a in-field location device, appropriate computer control systems and software to manage the maps and respond to the instructions generated, and a sprayer with an ability to change doses, as directed by the controller.

7.2.1 Cost of mapping

Mapping can be done automatically, as with the “Gerhards system”, or as part of another operation or as a separate activity. Clearly, if mapping is done as part of another activity (fertiliser spreading, harvesting) there may be no labour cost, but as discussed in Section 5, it is debatable as to whether mapping whilst doing another operation is really possible, because of the risk of distractions leading to erroneous maps and a reduced work rate of the primary task. However, when mapping is required as a separate operation there is a labour cost. This was estimated in Section 5 as being between £2.50/ha and £13/ha, depending whether the mapping was done by farm staff or by contractors/consultants. Such mapping costs could be discounted if, for example, mapping only had to be done one year in three, as suggested for black-grass. This would reduce costs to between £1/ha and £4.50/ha, using the above figures. If it became necessary to increase mapping payments to increase uptake by consultants/contractors, there is a high risk that the cost of mapping would absorb all the savings derived from reduced herbicide use.

With the German approach, the cost of mapping is included in the overall cost of the sprayer, GPS and computer equipment and does not have a cost specifically for detection. Gerhards and Sokefeld (2003) estimated the application costs to be €14.8/ha for patch spraying, as opposed to €5.2 for a conventional sprayer, an increase of c. €.10/ha. These figures assumed a sprayer costing €22.000, treating 1,000 ha/year and lasting for 10 years. We consider that these values are a little optimistic, as our estimate below (Section 7.3) assumes that the sprayer will only last five years and will treat 500 ha of arable crops/year.

7.2.2 Cost of equipment

There are a range of components needed for patch spraying. The costs that can be attributed to weed control, depends on what other aspects of precision agriculture is also being exploited on the farm. The farmer may be using GPS guided steering on his tractor, or GPS based yield monitoring, both of which would mean that a GPS location unit would already be owned by the farmer and any annual fee for a differential signal (c. £1000 yr) could be discounted. For example, the cost of a John Deere Starfire GPS would be c. £2,600 but lower cost options such as offered by Patchwork technology are also available. Some companies roll the cost of GPS location in with the cost of the sprayer controller. Thus, Patchwork will provide a GPS and controller for c. £2,500. Another option would be a Zynx controller + GPS which would be c. £6,000, but only £4,500 if the tractor was already equipped with a GPS.

The most expensive option would be to incorporate injection metering, which would permit two (or more) products to be applied at once (one product in the liquid supply, which could alternatively be water and a second via the injection system). This is the most flexible approach, as it can also deliver boom section control, but the cost is high. J & S Industries would charge c. £18,000 for an injection system to be built onto a conventional boom.

According to the Garthwaite (2004) survey, 9% of farmers already have sprayers linked to a GPS and 60% of sprayers could be modified to patch spray, as they have a variable rate option. Over 95% had the potential to switch off boom sections. Thus, all the component parts to patch spray are available. More and more tractors and combine harvesters are being sold equipped with GPS equipment. For John Deere, 60% of the biggest tractors and 40% of combines (mainly the larger ones) sold recently are GPS compliant (Mark James pers. comm. 2006). Top end sprayers such as John Deere 800i are fitted with a GPS, flag technology to map weeds, variable rate potential and boom section control. But this sprayer is £13,000 more than the standard 700 series sprayer. The question that is difficult to answer is 'how much of the added cost of a controllable GPS guided sprayer can be attributed to patch spraying and how much to overlap control and optimisation of headland applications'. For example, RDS's PRO series Apollo Sprayer controller is fitted as standard to Househam's self-propelled sprayers and similar systems are present on the John Deere 800i. This makes these sprayers ready to patch spray (but only with full boom variable treatments, not section control) with minimal change.

The conclusion we reached was that there is an equipment cost associated with the potential to patch spray, as if the farmer was not interested in this or in other precision agriculture features he could buy a less 'high-tec' and cheaper sprayer. Some farmers may want a GPS location system for automated tracking but it is reasonable to allocate some of this cost to patch spraying if this is also being planned. An arbitrary decision was made that there would be an overall cost of £8,000 associated with setting up a sprayer from whole boom spatially variable treatment. If boom sub-section variable dose was required this would be much more expensive and would not be available 'off the peg' from manufacturers. This cost could be discounted over the life of the sprayer. The Garthwaite (2004) survey concluded that over 50% of self-propelled sprayers and about 20% of trailed sprayers were less than five years old and about 80% of self propelled and 60% of trailed ones were up to 10 years old (we have ignored mounted sprayers, as these are smaller and less used by large farmers and contractors who would be attracted to precision agriculture techniques). Larger farms also tended to have newer sprayers. Consequently, as the pace of change in technology was appreciable, we concluded that it would be reasonable to assume that the estimate £8,000 cost of patch spraying should be discounted over five years.

The final component is access to relevant software to control the sprayer. Farmade, RDS and Patchwork Technology have all designed programmes appropriate to control and record patch spraying treatments. We concluded that as many of the sprayers with the capability to patch spray, already incorporated the relevant software into their systems (see above) so there would be little or no extra cost for the software. Similarly, if a sprayer was to be upgraded with control systems for automated steering and/or variable rate application, that upgrade could include software with patch treatment potential

Hence, we have concluded that the cost of patch spraying has two elements: the cost of mapping and the cost of the equipment. The former we estimated to be between £2.50 and £13/ha, (see above) which could be discounted, depending how often the field needed to be mapped, perhaps once every three years for black-grass and cleavers, reducing the cost to c. £1 - £4.50/ha. However, a new user would probably wish to map more frequently in the early years of adoption to reassure himself that the patch spraying was not resulting in increasing weed problems. Equipment cost we have estimated as c. £8,000 which could be discounted over five years (i.e. £1,600/yr) and additionally, there would be an annual cost for the differential GPS signal and to service the cost of the sprayer, approximately £500/year. This cost is only part of the total licence fee for the differential signal, as some of the costs would be linked to other precision farming activities (e.g. yield mapping, automated steering systems). It should be noted that the costs of equipment to patch spray were estimated in 2002 to be £8,000 (Lutman *et al.*, 2002), indicating that there has been little change in the cost of adoption. However, what has changed is the availability of relevant equipment and its reliability. In 2002 the technology was really only appropriate for 'enthusiasts' whereas now it is available to mainstream farmers.

7.3 Cost-benefit comparisons

7.3.1 Costs

The previous section has estimated the cost of patch spraying to be approximately £2,100/year (£1,600 for equipment + £500 for services) and the cost of mapping to be between £1 and £13/ha. The lowest mapping cost is probably over-optimistic as new users would probably map more often that was really necessary, so a minimum mapping cost of £3/ha has been used in this section. On the basis that the technology is more likely to be used by larger farmers we have assumed that the area of arable crops treated would be in the region of 500 ha/farm/year, so the annual equipment cost would be £4/ha. This gives a total cost of £7/ha. Interestingly, this value is not very different from the €10/ha estimated by Gerhards and Sokefeld (2003).

7.3.2 Benefits

Section 7.1 has discussed the potential benefits associated with reduced herbicide use patch spraying weeds, primarily in winter cereals. The reductions in cost depend on the species to be treated, the cost of the herbicide, the patchiness of the weeds and on the spray strategy adopted: spray/no spray or low dose/high dose. Taking black-grass as an example and assuming only 65% of the field needed treatment (the mean value from fields assessed in the previous LINK project (Lutman, 2002)) we have estimated that using a common treatment of Atlantis that a spray/no spray strategy would save a little over £10/ha, whilst a low dose/high dose approach would save about £3/ha. A similar extent of infestation of cleavers treated with Starane would save either £7 or £2/ha. Obviously if less of the field was infested the savings would be greater, but if cheaper products were used the savings would be less. Section 7.3 demonstrated the small reduction in costs achieved by patch spraying glyphosate (less than £2/ha). These cost savings are quite similar to those calculated for the previous project, where it was estimated both from modelled calculations and from 'real fields' that savings would be in the region of £5-12/ha depending on spray strategy. This is not unsurprising as pesticide costs have not changed very much since 2002 (Figure 7.1). The only exception in the previous project arose when *C. arvense* (creeping thistle) was sprayed with clopyralid on a spray-no spray basis in sugar beet. In this case savings nearly reached £20/ha, but that was relatively sparse infestation and an expensive herbicide.

Overall we have concluded that the less 'risky' approach of low/dose high dose treatment is unlikely to save more than £5/ha and in many situations would be less than this. The more financially attractive approach of spray/no spray could save around £10/ha.

7.3.3 Comparisons

Comparing the costs in Section 7.3.1 with the benefits in Section 7.3.2 suggests that a low-dose/high dose weed control strategy, which is our preferred approach, is unlikely to yield adequate cost savings to pay for the mapping and the cost of equipment. Treatment costs would be £7/ha, whilst savings in herbicide would only be c. £5/ha. If the mapping costs actually are greater than our minimum estimate of £3/ha, then the economics look even less attractive. In contrast, the spray/no spray approach does seem to be potentially profitable, as the savings of c. £10/ha exceed the costs, provided that it does not result in increasing weed problems in the longer term and that mapping costs are not greater than £3/ha. A crucial element of this analysis is the cost of mapping. If the cost of £3/ha (which is our minimum cost) could be reduced by the introduction of some type of automated detection, it makes the financial attractiveness of the technique much greater.

It should be noted that the smaller the spray 'pixel' size the lower the area that has to be treated to control weeds in a specified patch. Thus, marginal profitability would be enhanced if the sprayer had the potential to apply herbicides differentially along the boom, by having boom section control capability. BUT such a sprayer would cost more.

8. Environmental 'benefits' of patch spraying

Patch treatment is a tool that can help deliver improved within field biodiversity. A key current objective of British farming, as mentioned in the introduction, is to enhance the biodiversity of agricultural ecosystems. The recent review of the uptake of the different environmental ELS (entry level scheme) options by farmers shows that off-field options (e.g. hedgerow management, field corners and buffer strips) were much preferred to in-field ones (e.g. conservation headlands and uncropped cultivated strips for rare arable weeds) (Boatman *et al*., 2007). However, there is much debate as to whether optimal benefit to wild life can be delivered by off-field measures only. A recent paper (Butler *et al*., 2007) has concluded that in order to meet government environmental targets, greater emphasis would have to be put into improving the value of the cropped area for biodiversity. Currently, it is difficult, if not impossible, to quantify in economic terms the value of increased biodiversity. To our knowledge no-one has quantified the financial value to UK plc of increased numbers of birds, for example, on arable farms. It is a socio-political goal, and schemes such as ELS provide farmers with indirect economic benefit for adopting environmentally beneficial activities, to compensate them for income foregone and added costs. There are different incentives (points) associated with different options, endeavouring to encourage farmers to adopt the most environmentally beneficial ones. The points allocated during 2005-6 for the different options, clearly did not provide adequate incentive for in-field options. At the moment ELS options do not include low input weed management, except in conservation headlands. However, the lack of uptake of in-field options, so far, may result in greater encouragement in the future, when the ELS/HLS schemes are reviewed, by the provision of more in-field options and increased 'points'. This could provide an economic incentive in future for patch spraying weeds to deliver biodiversity.

A potential future 'driver' towards the adoption of patch spraying is the EU Water Framework Directive. Pesticides in water are already known to be of concern in a number of the River Basin Districts defined under the WFD (however nitrogen and phosphorus are generally more significant). A recent review of the 40 catchment sensitive farming areas currently under study, suggests the pesticide use is only an issue in 7 of them (Kennedy pers. comm. 2007; http://www.defra.gov.uk/farm/environment/water/csf/pdf/catchment-priorities.pdf). Strategies may have to be adopted to reduce levels of pesticide to meet the WFD limits and reduced use in field, as delivered by patch spraying, could be one option.

A third 'environmental' benefit derived from patch spraying relates to traceability. The technology associated with patch spraying will deliver maps showing precisely where products have been applied, at what dose and when. This information can be used to meet crop assurance requirements and to provide evidence of compliance with environmental regulations on pesticide use.

At the moment there in no direct financial incentive for farmers to adopt patch spraying to improve on farm biodiversity.

9. Future developments

9.1 Injection metering

While the advantages relating to the cleaning and maintenance of a crop sprayer that has had only clean water in the main tank and pump are likely to become more important, there is little evidence that the further development of injection metering control systems is regarded as a realistic large scale alternative to existing conventional tank mix approaches. This is likely to be because the limitations/disadvantages identified in

Section 4 of this report will continue to be relevant and act as a barrier to the larger scale adoption of such approaches. The use of sensors and sophisticated control systems is likely to continue to develop but the expensive components associated with injection metering, particularly on the pressure side of the main pump, are likely to continue to dominate the rate of development of this technology.

Concerns have been expressed in Australia where the larger self-propelled machines are using main tanks of around 5000 litres capacity and the degree of agitation is questionable. Injection metering is then seen as a way of achieving good control of delivered dose. However, there is no indication that these concerns map to the use of sprayers in the UK or elsewhere in Northern Europe.

9.2 Automated detection

This study has shown that the detection of weeds and weed patches is critical to the successful implementation of a spatially variable herbicide application approach and therefore it is likely that considerable research and development effort will continue to be directed at producing an automated weed/weed patch detection system. The important challenge is to develop a system that can discriminate between weed and crop in relatively dense canopies and to do so at a speed that will enable adequate areas to be sampled within an appropriate time window. Such systems are likely to be based on the collection of images that can be analysed and interpreted using data from a range of sources. Previous work has shown:

(i) that discrimination on the basis of colour alone is unlikely to be sufficiently robust even if frequent in field calibrations are included in the operating strategy (Zwiggelaar, 1998);
(ii) that discrimination on the basis of shape is also complex because of the degree of vegetation overlap in the images and the uncertainty associated with fitting plant leaf shapes within these images.

Future developments are therefore likely to be based on:

(a) increasing computing power that will enable more detailed analysis of collected images;
(b) data synthesis techniques that will combine information obtained from imaging systems with other sources of data relating to factors such as position within a field (both at field and plant scales), agronomic factors (e.g. fertiliser and crop protection chemical status), weather conditions and crop/weed histories;
(c) the reducing costs, in real terms, of sensing systems and output data analysis that could provide additional inputs for the data synthesis techniques.

Evidence to support the above analysis of possible future direction comes from an examination of current and planned research projects. In the UK, a Horticultural LINK project has just started aimed at the control of volunteer potatoes in carrot and onion crops following the loss of appropriate selective herbicides as part of the EU pesticide review process. The position and size of the volunteer potato plants within the crop is to be detected using image analysis and data interpretation techniques and the identified plants then treated with a total herbicide or equivalent treatment. Such a project will involve the further development of image analysis based techniques for weed/crop discrimination that can be applied in practical field conditions. Research to further develop weed detection approaches based on image analysis combined with other information is being conducted at a number of European and US research centres (see Section 5.1.2.2) but there is little evidence to date that there will be rapid progress towards producing systems that are sufficiently robust for practical field operation.

9.3 Plant scale treatment

This review has been concerned with the potential for the spatially variable treatment of weed patches within arable crops in typical UK conditions that would involve the targeting of treatments to areas of at least 4 m^2 and greater. There is a related research approach for use particularly in widely spaced crops such as vegetables that aims at detecting crop plants, plant rows and weeds and applies treatments to individual weeds. Such approaches have been mainly based on image analysis to provide information both about the crop, the positions of crop plants and also weeds, with possible applications for weed mapping as well as treatment. Such robotic approaches have been reported by a number of research teams, particularly in Denmark (e.g. Sogaard and Lund, 2005) and the USA (e.g. Giles *et al.*, 2004) and have been comprehensively reviewed by Blackmore *et al.*, (2005) with the economics evaluated by Pedersen *et al.*, (2005). Because such approaches can only achieve low work rates it has been proposed that they should operate autonomously using information from a range of sensors to provide positional as well as functional information. Treatment methods based on pulsed syringes with appropriate formulations to prevent contamination of non-target plants have been reported. Research scale experiments have shown the feasibility of such approaches and the benefits that they could deliver but it is considered that such research is a long way back from providing systems that will be of commercial relevance to arable crop production in the foreseeable future. It is however expected that there will be spin-off benefits particularly relating to weed detection and that initial practical developments of this technology will be in high value widely spaced crops.

10. Conclusions

The overall uptake of precision agriculture technologies in the UK, with the exception of guidance systems, remains relatively low. There is significant interest in spatially variable nutrient applications, but the patch application of pesticides appears to be restricted to a limited number of ‘enthusiasts’. The reasons for this lack of uptake have been collated from discussions with various experts involved with precision agriculture and from the meeting held by the Precision Farming Alliance on patch spraying (see Appendix A). Over the last four years there have been advances in the component technologies required to patch spray weeds and in general understanding of the biology of weeds. These are summarised again below. Additionally there have been changes in the ‘incentives’ or ‘benefits’ that can accrue from patch spraying.

10.1 Benefits of patch spraying

The main driver for precision agriculture is an economic one – to make crop production more profitable. There can be financial benefits from patch spraying and these economic aspects are discussed in more detail below. However, there are also environmental and regulatory issues associated with the technique and these have become of greater significance in recent years. Precision agriculture techniques provide the facility to record precisely what pesticides and fertilisers have been applied, where and when. This information can be used to demonstrate compliance with various national and EU regulations and for crop assurance purposes. There has been increasing concern about the impact of arable agriculture on the rural environment, as demonstrated by various government initiatives in recent years, not least the linking of EU support to delivery of environmental value. The ability to patch spray potentially provides a component to assist meeting these national requirements that pesticide use be minimised, as it provides the tools to apply pesticides only to those areas of the field affected by the pests, weeds or diseases, thus minimising usage. This could be invaluable, if pesticide rationing were ever to be introduced. The debate about where and how to deliver biodiversity on farms is still not resolved and whether it can be delivered by off field compensation practices, or will require in field mitigation (as could be provided by patch treatment) is still unclear.

10.2 Advances in navigation technologies

Geo-referencing technologies have become more reliable over the last four years and are increasingly incorporated into farm machinery. GPS is now integral in many new tractors, sprayers and combines, especially those at the top end of the market, used by larger arable producers. In 2004 9% of sprayers had a GPS facility and perhaps 50% of the larger tractors sold in 2006 included GPS controls (primarily for tractor guidance systems). Uptake of automated guidance systems for tractors and self-propelled sprayers seems to be increasing quite rapidly.

10.3 Map-based systems versus real time detection and treatment

The two alternatives for patch spraying:

- creating a map and controlling the sprayer with the map;
- mapping and spraying in one operation (real time treatment).

The former has been the primary focus of research and development for arable crops, because it gives the user time to consider treatment before application, permits the calculation of pesticide use prior to treatment, allows the sprayer to be appropriately loaded and uses less computer power. The latter is used in industrial weed control but not in arable agriculture, as automated detection is not yet fully commercially viable and users have difficulty assessing how much product is needed. However, farmers seem to prefer the fully automated system, as it avoids extra visits to the field to create maps.

10.4 Weed detection

We conclude that patch spraying in arable crops, for the immediate future should be founded on map-based systems. The map could be created visually by a human recorder, or automatically.

10.4.1 Automated detection

Although much research has been done since 2002 on possible automated detection techniques, none has yet come to market as a practical tool for detecting weeds in major arable crops such as wheat and oilseed rape. Machines that will detect plants against a soil background have been commercialised, but mainly for industrial purposes. In the longer–term we believe that uptake of the technology would increase if reliable automated detection, differentiating crops and a range of weeds, became available. The German systems developed by Gerhards and colleagues (see Gerhards & Oebel, 2006) appear to be able to deliver automated detection, already, but so far commercial uptake has been limited. However, our perception is that automated detection would be more feasible in cereal (and other arable crop) if row-widths could be increased from 12 to 24 cm, simplifying weed identification between the wider rows.

10.4.2 Resolution

It is clear that the mapping pixel size should be as small as possible to ensure the creation of a sound map. But this has to be balanced by the cost of achieving small application pixel sizes, which for example would require boom section control, which is more costly than whole boom management. In practice, most usage in 2007 is likely to be based around pixels the width of the sprayer, even though this may not deliver optimum herbicide reductions. On/off spray treatments with sub-boom width pixel widths is possible with some sprayers and this is likely to become more widely available, but sub-divided boom width, with low dose/high dose options, is not likely to be common in the near future, because of the added cost of the engineering required and the increased complexity of such a system.

10.4.3 Visual mapping

Research on visual weed mapping since 2002 has been very limited and although, as shown in the previous project, is a viable option, there is a great reluctance by farmers to spend time mapping weeds, even as part of other operations. However, farmers are paying contractors to analyse soils to assist the delivery of spatially variable fertiliser treatments and so may be contract mapping could be a way forward, if adequately financially attractive (see economics). However, it is doubtful whether crop consultants have enough time to allocate to such tasks. Increasing the attractiveness of mapping to contractors by raising the mapping cost would further reduce any savings resulting from reduced herbicide use.

10.4.4 Mapping frequency

How frequently it is necessary to remap patches to ensure that the map is accurate has a considerable impact on costs. We have suggested, from the work done in the previous LINK project, that black-grass and cleavers should be mapped every three years, perennials like common couch less often and weeds such as wild-oats and sterile brome more often. In our finance calculations we have assumed an average of mapping every other year, but field data to support these conclusions is limited. It is also likely that new adopters would map more often to gain confidence in the reliability of the maps and then would decrease mapping frequency as they became more familiar with the system.

10.5 Advances in sprayer design and control systems

Many current sprayers now have the ability to change volume rate to accommodate changes in speed and this gives them the potential to apply variable doses. However, standard nozzles do not have the potential to change rates by a high percentage, as the turndown ratio is not adequate. Approaches such as twin fluid nozzles and multiple nozzle systems do offer the potential to achieve greater volume rate range, and hence dose flexibility. Injection metering, which has been available for some years, still has a number of disadvantages, especially the lead and lag time associated with the position of the metering device relative to the nozzle (the amount of piping between injection and nozzle). These problems can be overcome but the cost of injection metering makes it currently unattractive for most arable farmers. The other options available in 2002 have been refined a little but there has not been a large increase in their commercial adoption. The use of multiple boom lines, as used on the Micron "Patchspray" sprayer in the previous project, is probably the approach that has received most commercial interest.

Advances in computing systems have substantially improved the ability to record weed presence/absence and population density information assessed visually, compared with the situation in 2002. Units based on programmable data loggers are able to interface with mapping software, with location technologies (e.g. GPS) and use dedicated keys to record observations. Many of these systems are now directly compatible with, or are part of, the sprayer control system (e.g. Blackbox from Patchwork Technologies; control systems and mapping software from John Deere/Farmade). However, the limitations associated with the manual visual assessment of weed patches remain; particularly the time involved, the effects of fatigue and distraction when doing other operations such that switches or buttons are not reset when situations change.

10.6 Advances in knowledge of spatial biology

It is still generally believed by weed biologists that many of the major arable weeds are spatially aggregated, but there is still uncertainty as to how stable patches are. It is agreed that patches are 'relatively' stable, but how often it is necessary to remap needs some more study and will of course depend on the species. In the absence of better data we have retained the conclusion of the previous project (Lutman *et al.*, 2002) that black-grass should be mapped every three years, wild-oats and brome more frequently and perennials, such as couch and creeping thistle less often. Larger seeded species tend to have more clearly defined patches than smaller seeded ones.

10.7 Advances in advice on herbicide use associated with patch treatment

Lack of good advice on the dose of herbicide to use to control/suppress low infestations of weeds, outside the main patch areas, is still a major constraint on uptake. The issue of liability for low dose recommendations is also a deterrent to advising lower rates. Farmers also appear fearful of the long-term consequences of choosing the wrong dose and failing to get good control, leading to increased weed problems in subsequent years. This issue applies probably to a greater extent to spray/no spray strategies, which are financially more attractive than the less risky low dose/high dose strategy.

10.8 Economic and management aspects of patch spraying

Overall farm profitability has remained low over the last four years. Commodity prices have remained low whilst input costs have increased, especially for fertilisers. The higher value of cereals and oilseeds in 2007 may improve farm profitability and encourage a greater spend on new equipment and modern technologies but the higher price for crops needs to be sustained for longer before substantial investment decisions will be made as a result.

10.8.1 Cost of adoption

Despite the fact that the cost of adoption has not increased since 2002, uptake has been very low. We estimated a total cost of £8,000 to patch spray, the same as in 2002. It is difficult to estimate costs as components needed for patch spraying can also be used for other precision agriculture activities (e.g. yield mapping, automated steering). Also, the relevant software for patch spraying is sometimes already 'bundled' with the software for controlling the sprayer to achieve overlap control and prevention of headland overdosing. However, as a result of this, the availability and reliability of the equipment is now much better than it was in 2002. The £8,000 cost can be re-calculated on an annual basis as £1,600/year, on the basis that the sprayer would be replaced after five years. There would be a further annual cost linked to the licence for the DGPS signal, estimated at £500/year. This gives a total cost of £2100/year, which assuming that the sprayer was used on 500 ha, results in a cost of £4/ha. Despite the greater availability of equipment and control systems, farmers are reluctant to spend what is needed to provide them with the relevant tools (without a clear payback in cost reductions from lowered herbicide use).

The cost of visual weed mapping is a major deterrent and minimises profits (longevity of the map and hence time to remapping could be critical to make the approach profitable). Costs are in the region of £2.50-£13/ha, depending on whether farm staff, contractors or advisors do the mapping, but these could be discounted over time, if mapping was not every year. An average cost of £3/ha was thought to be appropriate.

Thus, total costs would be in the region of £7/ha.

10.8.2 Cost savings from different spray strategies

The herbicide savings from our preferred low dose/high dose approach are lower than that from spray/no spray systems (but the risk of not controlling small patches is greater). For control of, for example, black-grass in wheat, savings are in the region of £5/ha on a low dose/high dose system and £10/ha for a spray/no spray approach. Clearly such savings will depend on the patchiness of the weeds and on the costs of the products used, but these figures seem to be appropriate not only for black-grass but also for other weeds.

10.8.3 Cost-benefit comparisons

From the previous two sub-sections it appears that low dose/high dose patch spraying is unlikely to deliver cost savings, as the costs of the equipment plus mapping are greater than cost savings from the reduced herbicide use. The spray/no spray approach generates greater savings that would make the approach profitable, provided that the system did not result in increased weed infestations. We have inadequate information to assess the longer term risks associated with both approaches and cannot really assess whether the predicted riskiness of a spray/no spray strategy would be reflected in practice.

10.8.4 Management complexity

Farmers are reluctant to add complexity to their weed management programme, as they endeavour to manage larger areas with fewer staff. They prefer simple weed control programmes for all fields with a specified crop and are reluctant to tailor treatments to specific fields, or parts of fields, and are not keen to return to fields to apply an additional patch treatment.

The economic incentives to adopt patch spraying do not appear to be adequate, or certainly are not clearly enough defined, to convince farmers to purchase and use the equipment needed. A pesticide tax has been discussed by government for some years and if this was ever to be introduced it would increase the economic attractiveness of patch spraying.

10.9 Environmental drivers promoting patch spraying

The increased national concern about the decline in biodiversity and increased legislation relating to the presence of pesticides in water (i.e. Water Framework Directive) are also relevant to the uptake of patch spraying. It is accepted that many arable fields contain very low number of weeds and it is thought that this has consequent effects on numbers of invertebrates and consequently birds and mammals. The government is promoting environmental schemes to increase on farm biodiversity but currently this in mainly focussed on off field areas. It may be necessary to increase diversity within fields and if this became a serious issue, patch spraying would be one of several tools that could be used to achieve this. Additionally, if there was stronger legislation to reduce pesticide use, like the pesticide ‘rationing’ in Denmark, to meet WFD goals, then patch spraying could help to deliver that reduction. At the moment there is no clear evidence that either of these two issues will become a reality.

Patch spraying technology also delivers records of where products have been applied which could be used to show compliance with environmental requirements as to the application of pesticides.

10.10 Overall conclusions

The technologies associated with the spatially selective weed control have become more effective since 2002, making patch spraying of weeds a less complex task. Equipment is now more available and more reliable. However, although there has been a considerable increase in using GPS for vehicle guidance, uptake of the technologies of spatially variable treatment has been slow, especially so for pesticides. Although the component technologies to achieve weed patch spraying are available, there are a number of reasons why uptake has been poor:

- The economic benefits are still not clear cut. Financial savings from low dose/high dose strategies appear not to cover the cost of equipment and mapping, but spray/no spray approach, which is more risky, seems more financially attractive.
- Patch spraying weed is still perceived as a risky tool and there appears to be little increased farmer credibility with his peers if adopting this technique.
- There is a lack of field data to reject the view that patch spraying is inherently risky, due to the risk of re-invasion from unsprayed or low rate treated areas.
- Farmers are reluctant to spend time mapping and would prefer automated detection techniques. Mapping costs are one of the reasons for the lack of financial saving from patch spraying.
- Automated detection for weeds in arable crops such as wheat and oilseed rape is not yet available, though much R&D is in progress. Real time detection and treatment is not appropriate for arable crops herbicide treatment.
- There is no regulatory incentive to reduce herbicide use, although the Government policy is to minimise pesticide use. Compliance with requirements of the WFD could promote patch spraying.

11. Recommendations to HGCA

1. The technology has advanced since 2002 and it is now more accessible to a greater range of farmers (not just the technology enthusiasts). We believe the cost of adoption is much the same as in 2002 but the tools are more reliable and more widely available.
2. Lack of clear financial benefit, associated with farmer perceptions of the risks, have deterred uptake. The benefits appear to be greater for spray/no spray strategies, whilst we have concluded that savings from low dose/high dose approaches will struggle to cover the costs of mapping and equipment. Substantial field demonstrations of the technique could clarify the cost/benefit analyses and resolve whether the spray/no spray strategy was more risky (see 3 & 4 below).
3. Farmers believe that patch spraying is ‘risky’. It would need some sound demonstrations over several seasons to provide evidence to convince farmers to the contrary.

4. The spray/no spray approach to patch spraying is currently more financially viable, and is immediately available on some current sprayers. However, modelling work has concluded that this is a more risky approach as it could lead to re-infestation from small patches in the 'no spray' areas. Field tests are needed to determine whether this actually occurs, as previous research and the published literature are not adequate to resolve the question.
5. From first principles we prefer a low dose/high dose management approach, despite its lower reduction in herbicide use. But lack of available information on low/appropriate doses to use on lightly infested areas, is a severe constraint (with links to the perception of risk). There is no equivalent herbicide work to that of the appropriate fungicide project. This needs to be resolved but would require considerable expenditure to generate the required data.
6. Automated detection appears to be preferred by farmers, and would reduce costs (eliminating mapping costs) but more R&D would be needed to build on work such as that of Gerhards and Tillett & Hague, to deliver a farm usable system. This might also require work on the impact of increasing cereal crop row widths to 24 cm to accommodate the weed detection.
7. If environmental concerns, including the Water Framework Directive and other EU regulations, led to pesticide rationing, British farmers would need to have tools available to meet such a need. Patch spraying could help deliver the required reductions. This would again mean availability of data on appropriate doses, either for overall treatment or for patch treatment (see 5 above).

Four areas of work are needed to address the outstanding issues that are deterring uptake of the technology.

a) Field demonstrations/tests on a number of farms to demonstrate conclusively the economics of patch spraying using both spray/no spray and low dose/high dose strategies.
b) Field tests over a minimum of four years to determine whether the spray/no spray strategy results in increases in weed infestations over time. Such work could also be used to assess reliability of mapping.
c) A substantial research programme to define the dose responses of a range of major herbicides (starting with winter cereals) to provide sounder guidance on impacts of applying lower doses to non-patch areas. This work would also deliver more widely on the performance of lower than recommended herbicide doses.
d) Funding to deliver practically functional automated weed detection in winter cereals.

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Appendix A

Precision Farming Alliance meeting

2 November 2006

Patch Spraying in Arable Crops: Barriers, Prospects and Potential

(Report on Precision Farming Alliance meeting 2 November 2006)

Background

This meeting was held to review issues associated with the spatially variable applications of pesticides, especially herbicides. There were three talks in the morning (Peter Lutman, John Hanbury and Clive Blacker) and then a more open discussion with a panel of five experts, chaired by Professor Miller. There were 32 attendees from a cross section of industries and activities associated with patch spraying (machinery manufacture, research, farming practice).

The following notes are based on those taken by Peter Lutman and hopefully reflect the views and conclusions of the meeting.

Introduction

Although many of the component technologies for 'patch spraying' have been available for at least five years, the farming industry has not taken it up? A few 'enthusiasts' have explored its potential but more widespread adoption has not happened. Silsoe and Rothamsted ran a LINK project from 1998 to 2002 that ended with a demonstration of mapping weeds, creation of a weed map and delivering herbicide onto the target areas with a 'patch' sprayer - proof of concept!

What are the reasons for the lack of uptake?

To achieve spatially variable weed control (and indeed other pesticides and PGRs) the following components are required:

a) Ability to geo-reference the distribution of the target (and the sprayer!).
b) Appropriate software to create a map of the distribution.
c) A relevant sprayer controller that can respond to the map.
d) A suitable sprayer able to apply the pesticide, as required by the map.
e) Sound techniques for assessing the spatial distribution of the target .

f) Access to relevant advice on the product and dose to use on the within patch and without patch areas.

NB - if using real time detection and treatment (in one operation) you don't need aspects b) and c), but you do need a sprayer controller to respond to the information from the target detector. Detection is directly translated by the software and the controller into spatially variable application. You don't need geo-referencing except to create a record of where the treatment has been placed.

Even if components a) – f) can be achieved/met there are other issues, primarily 'is it economic?' Is it simple enough for the user to be 'comfortable' with the system and to want to use it or is it worryingly complex?

The meeting mulled over these issues and the following is a summary of the issues raised and conclusions.

General issues

Several speakers emphasised the critical issue of SIMPLICITY. If farmers were to take up patch spraying they were much more likely to do it if they could buy a package off the shelf and it delivered the required technology, with minimum problems. Weed detection – that too needed to be as simple as possible.

Availability and functionality of the various components required to deliver an attractive 'package' to patch spray

a) Geo-referenced locations

How reliable and precise are current GPS systems. The general conclusion was that GPS technology was now part of mainstream farming (e.g. automatic steering, yield mapping). Reliability seemed good and sub-metre accuracy achievable with DGPS (more than adequate for patch treatment on a field scale). RTK systems are also available to provide greater accuracy. There were reports that RTK was becoming available as a regional service provided by local companies for the benefit of groups of users. (This was reported to be happening in USA and The Netherlands.) (Ordnance Survey offers RTK at £2K/year in the UK).

b) Appropriate software to create maps

A number of companies will provide software to create treatment maps from weed maps. It was pointed out that there are often a lot of demands on software writers and so requests to provide treatment maps need to be kept simple. Different sprayer controllers required different software. This made delivery more complex.

c) Controlling spray application

Computers and related sophisticated sprayer controllers capable of delivering spatially variable treatments were available (e.g. Zinx, LH Agro, RDS) both as standalone items, or as part of a complete spray application system (e.g. John Deere GreenStar).

d) Delivering the appropriate dose to the relevant area of the field (patch spraying)

There had been a lot of advances in sprayer design in recent years. There was a lot of discussion of the merits of conventional spray application, using either whole boom or boom sections, and direct injection. Conventional application using section control was already available for headland spray management. Sprayers already have twin booms to adjust volume rate more simply (and hence dose). Thus, spatially variable application rates of one product from 25% to 100% of normal rate was available. With single boom systems volume rate (and hence dose) can be changed by automated switching to different nozzles, or perhaps by using variable orifice nozzles (are the latter accurate/reliable??). The possibility to apply more than one product at a time using multiple spray lines was not generally available, though representatives of the manufacturers were happy they could do this if requested. The problem would be cost. This would allow users to apply Product A uniformly and then apply Product B on a spatial basis (e.g. Treflan/Hawk overall and Atlantis on black-grass patches; Ally overall and Starane on cleaver patches).

The alternative technology that could be used to patch spray was direct injection of spray concentrate into boom sections (or even behind each nozzle). The main spray tank provides clean water. Products were diluted with a small amount of water and this concentrate was injected. Multiple products could be injected if required.

Problems:

i) Standard injection systems (either whole booms or boom sections), result in a distinct fan of product distribution as the machine switches in and out of a product. This fan can be up to 100 m long. Knight sprayers incorporate a recirculating system that cycles to spray solution through the boom/boom section), thus reducing the lag fan to a few metres. This is being incorporated into other sprayer designs (injection behind the nozzle overcomes this) but requires more engineering.

ii) Some products are not stable when added to a small quantity of water (solution needed for injection into the sprayer line).

iii) Container designs vary greatly between manufacturers and this causes problems when devising transfer systems that preferably should be automated.

There was a perception that direct injection would be the ‘best’ technique, but at present boom section control with conventional systems was probably most appropriate for spatially variable treatment.

e) Soundly based detection systems

Problems with the detection of weeds remain a major disincentive to uptake of the technology. Automated detection by combinations of reflectance, colour, shape etc was still not a practical reality (though progress was being made, especially in Germany). A lot of research effort is being put into the ‘science’ of weed detection. Automated plant detection in wide-row crops was possible as the sensor was comparing soil and plants. In narrow row crops, such as wheat, detection meant separating out crop plants from weeds, a much more difficult task. Silsoe researchers had made progress on automated detection and the possibility of linking historic mapping data with real-time detection could be helpful. If real-time detection was used, the operator does not know how much product to put in the tank and there is a risk of leaving the field with many litres of unused solution. Direct injection would remove most of this problem.

Visual mapping, as used in the Silsoe/RES LINK project was not attractive. It was too time consuming. Those that had endeavoured to map whilst doing another field operation (fertiliser spreading, harvesting) identified some problems. There was a high risk that other ‘events’ could distract the operator from mapping, the strongest risk being to leave the ‘weed present’ button on, when it should have been turned off. On the other hand, increasingly sophisticated support systems such as GPS guided steering, does give the operator more time for weed detection. If, for the immediate future, human eye detection was the only practical option, how should it be done? N-sensor system providers are now providing a sampling service – doing the soil sampling required to produce the maps needed for spatially variable N treatments. Could weed advisors do the same for farmers? Is it feasible? What would be the cost? Another alternative was to persuade the farmer and advisor to create a hand drawn map of the ‘worst’ areas of each field. This could then be digitised and form the basis of the application map. It could then be altered over years, as more information became available. Its success would depend on the patchy nature of the weeds – it would function best in fields with a few big patches and worst where there were many small ones. A similar approach would be to manually turn the sprayer on and off as weed patches were observed (in real-time) and at the same time geo-reference where the treatment was applied, thus creating a map.

f) Choice of product and dose

There was discussion of the merits of changing dose to achieve spatially variable control and switching different products on and off. Both options have supporters and detractors. Ability to apply more than one product at a time required more engineering than changing volume rate of one product. The former needed multiple tanks or direct injection, with multiple product containers. The issue of how to select lower than recommended doses and the legal liability if the manufacturer's recommended rate was not used was raised. Agronomists frequently recommend lower than normal rates already, so is this very different? Decision Support Systems such as Weed Manager (see www.wmss.net) try to help. Some newer products do have different recommended rates depending on the target species. The economics of reducing dose by a small amount e.g. 25% for example, was questioned. This raises the issues discussed in section d) as to whether the best option is to switch on costly products to treat the patches and to spray all the field with a background product that is cheaper but somewhat less effective, rather than trying to be 'clever' with doses. I suspect the answer depends on the target species, its susceptibility, and the risks attached to getting it wrong (see Section g)).

g) Economic considerations

The meeting did not discuss economics in any detail, though the point was made that clear economic calculations are needed to show the 'value' of the technique. If the product is cheap, then the savings from patch spraying will not be great (e.g. 36% reduction in use of glyphosate only saved £1.82/ha). Clearly the technique is most attractive with expensive products and the new black-grass herbicide Atlantis and oilseed rape herbicides in general were quoted. There is clearly a need to quantify the costs of setting up a patch spray system and look at the financial benefits that were likely to arise from patch spraying (in terms of reduced pesticide use). One of the issues around economics was the cost attached to getting it wrong. Some delegates were clearly worried about the impact of seed return for future crops in areas of the field which were not effectively treated (because the area was not mapped appropriately or because too lower dose was chosen). This is an issue but is probably over-emphasised, as appropriate post-harvest management would reduce the impact of carry-over (Weed Manager can advise on the rotational management of weeds).

Another issue was that farmers often apply a cocktail of products at any one time. If patch treatment was needed for one product an extra pass would be needed on the field to apply the spatially variable treatment – an extra cost (both time and money) (this would be overcome if multiple booms, delivering different products were used).

The issue of the economic viability of the technique needs to be reviewed again. The previous LINK project did cost the benefits that could be achieved.

h) Environmental considerations

The viability of the technique of patch spraying from a purely economic angle is not yet clear (see above). BUT there is increasing bureaucratic regulation aimed at reducing the environmental impact of farming. Farmers are already increasingly required to justify their use of pesticides and fertilisers and this may (will?) increase in the future. One facet of this could be a requirement to identify where products have been applied (and where not) and why. The technology of patch treatment would deliver this information.

i) Resolution

How small an area should be treated. From a biological viewpoint the smaller the application pixel the greater the saving in product used (in a spray/no spray system). A 3 x 3 m pixel would be very good. From an engineering viewpoint more precise application (boom section control and single nozzle application) are more expensive and some manufacturers would prefer single/whole boom management.

If it is not economically justifiable to commercialise boom section control systems then there is no point in mapping more accurately than one tramline at a time. Similarly, if it is not feasible to map at greater resolution than a tramline, there is no reason to develop a sprayer that can be more precise. Conversely, if a new, expensive, but widely used product is marketed, the attraction of developing a boom-section patch spray system would be greater.

j) Other issues

Interfaces – the greater the number of different manufacturers involved with the manufacture of the tools to patch spray, the greater the risk that they will not interface correctly. Is this a problem in practice? Some users had suggested it was?

Conclusions

Much of the technology required to deliver spatially variable weed control, is in place: DGPS works, software and computer hardware will deliver weed maps and control the sprayer and suitably designed sprayers will respond to the instructions. There is still some debate as to whether direct injection offers sufficient advantages to balance the extra complexity of adoption. Problems are in weed detection and in decisions on optimum strategies (what herbicide dose), for the within and without real time patch areas (especially the latter). To date the problem over how to detect weeds and the absence of systems, coupled with uncertainties over the economic attractiveness of adopting the system, have deterred uptake.

Attendees

Mr Chris Allen	Chafer Machinery
Mr Martin Baxter	Teejet N W Europe
Mr Clive Blacker	Precision Decisions
Dr Rosie Bryson	BASF plc
Mr Andrew Cragg*	Brooker Fms Romney
Mr Chris Dawson	C. Dawson Associates
Mr Peter de Haan	Agriware / Bever
Mr John Edwards	Pear Technology
Dr Carl Flint*	Masstock Arable Gp
Mr Richard Goddard	CNH UK Ltd
Mr Simon Griffin	SOYL UK Ltd
Mr John Hanbury*	J&S Industries
Mr Peter Henley	Farmade Man. Systems
Mr Tony Houghton	Sky Farm Ltd
Mr Mark James	John Deere Ltd
Mr Andrew Kneen	Househam Sprayers
Dr Peter Lutman	ex Rothamsted Res
Mr Ben Magri*	Syngenta Crop Prot.
Mr Hugh Mason	Maurice Mason Ltd
Prof Paul Miller	The Arable Group
Mr Stuart Murdock	Stuart Murdock Cons.
Mr Neil Payne	CNH UK Ltd
Mr Sven Peets	Cranfield Univ.
Ms Carla P-Gasparin	Cranfield Univ.
Mr Michael Picton	GT Picton Ltd
Mr Richard Price	Patchwork Technology
Mr Stuart Robertson*	Chafer Machinery
Major Johnny Shaw	Welburn Manor Farms
Mr Robin Thompson	Precise Crop Nutrition
Dr Nick Tillett	Tillett & Hague Tech.
Dr Roger Williams	HGCA
Mr Bryan Wood	Hounslow Hall Estate

* Members of the discussion panel