PROJECT REPORT No. 291

**DEVELOPING A WEED PATCH SPRAYING SYSTEM
FOR USE IN ARABLE CROPS**

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FOR USE IN ARABLE CROPS

by

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Abstract

The overall aim of the project was to develop weed patch spraying (GPS location, weed mapping, creation of a treatment map and application of the herbicide) into a commercially viable package that could be used by farmers and contractors. It was concluded that the most appropriate weeds to be targeted were black-grass, wild-oats, bromes, cleavers, thistles and common couch.

Weed mapping. As the project aimed to develop a system for 2002, it was decided that weed detection should be based on visual mapping. Over 60 geo-referenced presence/absence weed maps were created from tractors, ATVs and combine harvesters. The optimum time for mapping varied between the test species. Practical recording systems based on voice recognition and toggle switches were developed. Some weed maps were validated by quadrat counts on a 5m grid. Correlations were acceptable, though mapping small grass weeds in cereals was difficult. Weeds could be mapped at 3-4ha/h, depending on the vehicle used. The potential of automated detection was also explored, but video images failed to detect weeds in cereals, reliably. However, semi-automated, reflectance based 'vegetation anomaly' detection was quite successful. Both these techniques need further research.

Behaviour of weed patches. Knowledge of the spatial behaviour of weeds is essential if patch spraying is to be based on historic maps. Research showed that patches were fairly stable, as the core areas only moved 3-4m over several years, and so patches of most species only need re-mapping every 3 or so years. However, this did not apply to wild-oat patches, which were potentially unstable, because small numbers of seeds, which were moved some distance by the combine, had the potential to create new patches. Studies of the causes of patches showed that soil characteristics could be linked to the patch distribution in some fields.

Creation of the treatment map. The 'raw' weed map has to be 'processed' before it can be used by the computer control system (such as Fieldstar) to control the sprayer. Software was developed in association with Patchwork Technology that will interpolate data from the weed maps and add buffers to account for possible patch movement and location variation. Finally, appropriate products and doses can be selected and the application map prepared.

Herbicide application and system testing. The project used the dual boom, variable volume rate, Micron Patchspray sprayer for most herbicide applications, though the AGCO Spra-Coupe was also studied. Several fields were sprayed, as controlled by the treatment map. In the majority of treated fields, full rates of product were applied to patches and reduced rates to the rest of the field. Applications were generally successful. As well as demonstrating the system at 'Cereals' and 'Sprays & Sprayers' a specific demonstration of the project was held in February 2002 at SRI.

Economics and other aspects relevant to farmers. It was estimated that average herbicide savings of £6/ha were possible from patch spraying. In some situations, this could increase to £20/ha. Cost of patch spraying equipment ranges from £8000 down to less than £2000, depending on whether the user already using 'precision agriculture' equipment. Weed mapping would cost *c.*£1/ha. Thus, overall the equipment would have to used on approximately 2000 ha, to recoup the costs. The technology also provides printed evidence of herbicide application, of relevance to crop assurance schemes and to regulatory authorities.

Summary

Background

The availability of satellite spatial location technology in the 1990s stimulated interest in the possibility of locating weedy areas of fields and then using that information to selectively apply herbicides to the weed patches. A previous LINK project explored the possibility of achieving this target, showing that patch spraying was a practical possibility, but the tools used were experimental rather than practical. The project reported here was started to establish whether it was possible to create a patch spraying system that a technically enthusiastic farmer or contractor could use.

Objectives

The aim of the project was to optimise herbicide use in arable crops by developing and integrating all the component elements of a spatially selective weed control system into a commercially viable package that could be bought and used by UK farmers. The project would explore both automated and manual weed mapping systems.

Specific objectives
1) To quantify factors which affect patch stability and dynamics, to assist in the prediction of the longevity of the accuracy of weed maps.
2) To develop effective field mapping procedures based on visual detection, including assessment of alternative mapping platforms and the conversion of weed maps into treatment maps.
3) To investigate the feasibility of automated weed detection for narrow row arable crops and to explore the potential for semi-automated 'anomaly' detection systems.
4) To validate the system, develop recommendations for use and demonstrate it to the arable farming community.

It was concluded that the major weed targets for spatially selective treatments were species that were a) aggregated in distribution, b) were expensive to control and c) which received specific herbicides. These weeds could occur in any arable (or horticultural) crop, but greatest emphasis was on winter wheat. Using these criteria the project has concentrated on six weed species: the annual weeds black-grass, wild-oats, brome grasses and cleavers, and the perennial weeds creeping thistle and common couch.

Weed biology

The biological studies were aimed at improving knowledge about the spatial stability of patches and identifying the causes of seed movement. This work was aimed to provide information on the frequency of re-mapping and also started to explore the causes of weed patchiness. Detailed studies were done with defined patches of cleavers and wild-oats. Patches of the former were not very mobile, with potential to move only 3-4 m/year, as a result of cultural operations. This was similar to previous studies with black-grass. Contrastingly, although the core patches of wild-oats did not move very far (3-4 m), individual seeds (with potential to form new patches) were moved up to 30 m by the combine harvester. Natural dispersal was less important than movement due to agronomic activities. The overall conclusion of this work was that patches of wild-oats (and bromes) could be unstable and therefore would need mapping every two years. The other annual weeds studied (cleavers, black-grass) would need mapping every three years, whilst the perennial such as common couch and creeping thistle could be mapped less frequently.

A further issue relating to re-mapping frequency is the familiarity of the user with the field. Weed patches wax and wane depending on the establishment achieved each year. Therefore when coming 'fresh' to a field there is need to map probably each year for 2-3 years, to ensure that the full extent of the patches are established. Once the distributions are reasonably well defined, re-mapping can be reduced to the frequencies defined above.

Studies in the project gave some indication that the distribution of the weeds was influenced by soil characteristics. In one field the distributions of cleavers, black-grass and wild-oats were associated with the heavier parts of the field (higher clay content) and in a second black-grass was linked to an area of the field at the bottom of a slope where again the soil was heavier soil. In a third field, where the range of clay contents was lower than in the first field, there was no link between the weeds and soil characteristics. In the first field many other soil characteristics such as % carbon and nitrogen contents, and levels of mineral nutrients such as potassium and magnesium, were also correlated to the weed distributions but were also very strongly correlated with each other. Caution is needed when interpreting these conclusions, as other researchers looking for correlations between weeds and site characteristics often identify significant correlations, but these invariably differ between reports. It is probable that although soil characteristics can link to weed occurrence, other factors such as poor weed control and bad crop establishment, that lead to high seed production in restricted areas of fields, can cause new patches. Indeed, random events in a uniformly infested field can lead to the development of patches.

Weed mapping

Visual mapping

During the project we developed methods for mapping weeds during the year. Spatially geo-referenced presence/absence could be recorded from an ATV, tractor or combine. It was also possible to map on a low/high basis and to map two or three species at once. More than this was too complex. During the project 61 maps were created. There were few problems with the reliability of the GPS signal, unlike in the previous project, although the system does not work effectively 100% of the time. It should not be taken for granted. Different weeds could be mapped at different times of the year. For example, the easiest time to map black-grass was in the middle of the summer, when the heads were visible, but it was also possible to map this weed during the later winter/early spring. Common couch could only be mapped at harvest. Three different mapping systems have been included in the project. Initially, the 'Fieldstar' touch sensitive screen was mounted on the ATV, or in the tractor, and this was used to create the weed map. There were practical difficulties with this, as the user had to interrupt the scanning of the field to look at the Fieldstar screen to input the information. Consequently, SRI developed an alternative voice recognition system, whereby the operator simply speaks the name of the weed into a microphone (e.g. black-grass on / black-grass off) and the computer uses this information to form the basis of the map. This worked well but its long-term commercial practicality still needs validating. Finally, in the last year of the project AGCO developed a toggle switch bar to mount in the tractor or ATV, linked to Fieldstar, which could record presence/absence of four weeds (or two levels of two weeds).

On some fields the presence/absence weed maps were compared with quadrat counts recorded on a 5 m grid. The latter reflected the true distribution of the weeds, but such a technique was far too labour intensive for use in practice. The presence/absence maps correlated reasonably well with the quadrat counts but had limitations. For example, when travelling over a wheat field in early spring it was not possible to see low densities of grass weeds, especially when small. Additionally, when mapping from an ATV or tractor the observer cannot see the full width between passes and so an element of kriging is needed to fill in the gaps to create the overall weed map. This element of uncertainty in the distribution of the weeds, combined with other facets of weed behaviour, led us to conclude that the weed treatment map should use a strategy that applied high rates of herbicide to the patch areas and a low rate to the rest of the field (low dose/high dose), rather than simply applying herbicide to the patches and nothing to the rest (spray/no spray). A spray/no spray strategy could be adopted once the patch distribution had been well-defined or where clearly identified patches were to be treated in the same season as the map was made.

As part of the mapping aspect of the project we estimated the time taken to map fields and also explored whether it was possible to combine mapping with another field activity such as combining or

fertiliser application. Weed mapping from an ATV can be done at approximately 3 ha/h and from a tractor at a faster 4 ha/h. We only had limited experience of mapping whilst doing other operations, but initial conclusions were that it was feasible, provided the mapping was kept simple (e.g. presence/absence of one weed).

Automated detection

Two areas of automated detection were explored in the project: a) the possibility of using video images to detect weeds and b) the use of reflectance differences (vegetative anomaly mapping) recorded soon after emergence to detect areas that may have weed infestations.

The work with video images, using a video camera was not very successful, as it was not possible to detect green weeds reliably in a green crop, under the variable lighting conditions common in the UK. For example, the camera had to be recalibrated at every pass, depending whether the vehicle was travelling into or away from the sun. The semi-automated reflectance system seemed to offer more potential for a practical system. Experiments in 2001 showed that spectral reflectance sensors mounted on a spray boom could detect differences in greenness in crops (and weeds) based on a computed Normalised Difference Vegetation Index (NDVI). Artificial patches of oats in wheat, and barley in rape were detected. However, other areas of the fields also had high vegetative index values, because of double drilling, for example. Detection of rape in wheat was less successful as the rape did not grow very vigorously. Thus, the concept of this semi-automated system was to use the sensors to create a greenness map and then visit areas of the field with high reflectance to check whether it was due to weeds and to what species, and amend the map accordingly. Our results showed some value in the use of vegetative index maps to aid weed patch detection but only if they were to be obtained to support other aspects of precision crop management.

Neither technique is fully practical at the moment, but both fully automated and semi-automated practical systems may be developed over the next 10 years. There is a lot of research in progress, as potential users appear to want automated detection, although there is still some debate as to whether this should be associated with real-time or map-based patch treatment.

Creation of the treatment map

Having created a weed map, it is necessary to convert it into a treatment map, as the 'raw' weed map is not appropriate. This involves several processes. Firstly, it may be necessary to interpolate data to include parts of the field, for example between tramlines, which were not assessable from the mapping vehicle. Secondly, the patches may need to be extended with buffers to account for factors such as weed and seed movement in the period between assessment and treatment, and uncertainties relating to the performance of the in-field

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location system. Finally, the treatment areas for the doses and products to be applied need to be defined. 'Patchwork' software was used as the basis to carry out this task. The initial software has been upgraded during the project to improve the designation of the patch areas and to add a variable buffer around the patches. The choice of products and doses was not part of the project, but clearly plays an important role in the performance of the system and its economic viability. Doses were selected by using 'expert opinion', but in the future could be linked to computer-based Decision Support Systems.

Herbicide application and system testing

Spatially selective weed control requires a sprayer that will respond to the geo-referenced weed/treatment map. The PatchSpray application system developed by Micron Sprayers and SRI at the end of the previous project was further refined in this project. This sprayer operates with a dual boom, with different nozzles in each boom, and achieves a 300% variation in herbicide dose rate by switching between booms and changing volume rate and pressure. Solenoid valves controlled by compressed air control the nozzles. The 'Fieldstar' computer system delivers instructions to the boom controller as to the rate to apply and the controller calculates which combination of nozzles and pressure to use, to control weeds in defined areas of the field. At the moment the PatchSpray controller controls the entire boom and not boom sections. The decision was made at the outset of the project that the engineering complexities and increased costs outweighed the herbicide benefits that would accrue from splitting the boom into perhaps 6 m sub-units. Ideally, the herbicide pixel (application area) should be as small as possible, as this maximises herbicide reductions. If pixel size is too large, herbicide savings are minimal.

A second sprayer, the injection metering AGCO SpraCoupe, was also investigated for its suitability for patch spraying weeds. This machine injects herbicide concentrate into the spray line and appears to have appreciable potential as a vehicle for patch spraying. The original prototype SRI patch sprayer, used in the previous project, used this technology. It is possible for it to apply two herbicides at once, one is added to the water container and is applied uniformly across the field, whilst the second is injected into the spray-line when needed. Some engineering modifications are needed before this machine could be used in practice. Also, currently, it would be restricted to a limited number of products, as many are not formulated to form the concentrated herbicide solution needed to inject into the spray line.

The PatchSpray sprayer was linked to the 'Fieldstar' controller in the tractor cab, which in turn was linked to the GPS receiver, which gave the geo-referencing for the application. Six fields were sprayed with this sprayer, five on a low dose/high dose basis and one on a spray/no spray basis. On the low dose/high dose fields, which were all for weeds in winter wheat, the patches were sprayed at the products' recommended rate and doses were reduced by 20-70% for the rest of the field, depending on the product involved. Practical field experience provided guidance on dose selection, as some herbicides have greater

dose flexibility than others. Results from the single field sprayed on a spray/no spray basis were also acceptable. The creeping thistle, which was the target of this treatment, was very visible and so there was no need for low doses on the rest of the field. Post-application assessments indicated that the herbicides had been applied as directed by the sprayer, but grass weed control was not always 100%. This was caused by delayed application, which meant that the plants were rather too large to be controlled completely by the products used, rather than any problem with the patch treatment.

As part of the system testing part of the project, a demonstration for more than 60 delegates, covering all sectors of the industry, was held at SRI in February 2002. Following a series of presentations on the project, a marked area of a SRI field was mapped, the weed map was converted to a treatment map and the area was then sprayed with the PatchSpray machine. In this way we were able to demonstrate how all the components worked together. A further interactive demonstration was also held at the 2002 Sprays & Sprayers event (June 2002), whereby a video camera demonstrated how the sprayer responded to the presence of weeds, recorded on a the weed map.

Economics

Commercial uptake of this technology will largely depend on the cost/benefit analysis. If herbicide savings are adequate, then farmers will consider purchasing the required equipment. How much they need to buy, depends on their involvement in other aspects of Precision Agriculture. If the farmer was already yield mapping and varying fertiliser on a spatial basis then he/she would already have much of the equipment needed, apart from the sprayer. Preliminary estimates are that purchasing all the equipment necessary to patch spray weeds would cost in the region of £8,000. This would cover the cost of the GPS location and computer control systems (e.g. AGCO 'Fieldstar') (c. £4,500), relevant software (£500) and a conversion kit such as developed for the Micron PatchSpray which would enable the sprayer to apply herbicides on a spatial basis (£3,000). If a simple on/off application system was planned rather than one including variable doses there would be less need for modification to the sprayer and so costs would be lower.   Similarly, if the user was already yield mapping the total cost of the equipment could reduce to as little as £2000. The final element of cost relates to visual mapping. Assuming it is possible to map on average every two years then mapping costs would be around £1/ha.

The herbicide savings from treating the six fields on a spatially variable basis were calculated. For five fields in winter wheat herbicide treatments were on a low dose/high dose basis, and so it is perhaps not surprising that financial savings were not huge, varying from £2-10/ha, depending on the level of infestation treated and the product used. The sixth field with the spray/no spray strategy herbicide saving was nearly £20/ha. Further theoretical estimates of herbicide savings were established for another eight cereal fields

mapped during the project. In two contrasting scenarios, spray/no spray and full dose/half dose, the former generated savings of £4-18/ha (mean £12) and the latter £2-9/ha (mean £6). The savings in the conservative full dose/half dose scenario are similar to those generated in the actual sprayed fields.

Linking the costs and the savings together indicates that the patch sprayer would have to be used on approximately 2000 ha, to recoup the cost of all the location, control and spraying equipment and the mapping. This could be achieved over several years. If equipment costs were lower, as the user was already using Precision Agriculture techniques then perhaps the treated area could fall to around 1000 ha. These conclusions imply that a grower or contractor of a medium to large cereal acreage, with patchy weed problems could justify the purchase of patch spraying equipment.

Other benefits

The reductions in herbicide use achieved by patch spraying have environmental as well as economic benefits and address the government's objective of minimising the amount of pesticide use in UK agriculture. Additionally, the application plan produced by 'Fieldstar' post treatment will clearly identify how much herbicide has been used and where it has been applied. This may help growers in future to show compliance with crop assurance schemes and the demands of those purchasing the crop.

A map of the treatments applied could also demonstrate compliance with application requirements close to field boundaries where there is a risk of surface water contamination due to spray drift. A Local Environmental Risk Assessment for Pesticides (LERAP) needs to take account of both the characteristics of the spray tank mix and the nozzle/boom arrangement that will be used to apply the spray. For complete demonstration of compliance with such schemes, the field record would need to log nozzle type/boom configuration and the chemicals included in the tank mix. Methods for achieving this are now available and are being studied in separate project work at Silsoe Research Institute.

1.0 Introduction

Optimising weed management at the start of the 21st Century is not a simple issue. Economic pressures on farming both in the UK and elsewhere in the developed world have been increasing and consequently the amount spent on weed control has declined. Data from the Crop Protection Association (2001) shows that the sales of herbicides in agriculture and horticulture have declined from over £225M in 1996 to £185 in 1998 and to only £145M in 2000. Yearly variability in weather can impact on sales, but clearly the amount of herbicide being used is declining. Despite this reduction in sales, herbicides are still very widely used, and in many crops the vast majority of fields, except those grown under organic production regulations, are treated. For example, in 1999/2000 there were 3.4M ha of cereals and 5.1M ha were treated for the control grass weeds and 3.6M for broad-leaved weeds. Thus most fields were treated at least twice. Similar data from the most recent Pesticide Usage Survey in 1998 (Garthwaite & Thomas, 2000) showed that the 2.0M ha of winter wheat received 6.8M ha of herbicides. Thus, each field received approximately three treatments.

The reduction in the cost of weed control has primarily been achieved by reductions in doses used rather than by a reduction in the area treated. At present such optimisation of herbicide dose depends on the expertise of the farmer or his advisor, and generally aims to achieve, as far as possible, complete control of the weeds. Normally it does not involve targeting treatments towards infested areas of fields and leaving less infested or weed free areas untreated. This is done in some fields where there is a clear demarcation between weedy and weed free areas, by simply switching off spray booms on certain tramlines. The distribution of weeds does not generally lend itself to such a simple approach.

Environmental pressures are also impacting on herbicide use and on the industry's attitude to weeds. There is increasing evidence that some species of farmland birds have declined appreciably since the 1960s (Chamberlain *et al*., 2000). The causes of this decline are many, but one contributory factor may be associated with the increase in the effectiveness of weed control (Ewald & Aebischer, 2000). This concern about the effects of farming on biodiversity is expected to increasingly influence weed control strategies. The aim is to target weed control more precisely, so only weeds that pose the greatest threat to the crop are controlled, whilst those of less concern are left to provide food for birds and invertebrates. Current proposals are that this more targeted approach should be achieved by treating only noxious species such as black-grass (*Alopecurus myosuroides* Huds.) and cleavers (*Galium aparine L.*) and leaving less damaging ones such as annual meadow-grass (*Poa annua L*.) and chickweed (*Stellaria media L.)* untreated (Marshall, 2001). At present, an alternative approach involving the spatially selective application of treatments, focussing on the dense weed patches and leaving less weedy area untreated, has not been explored. Such an approach could help to deliver the desired biodiversity benefits.

Other environmental pressures are also impacting on weed management. The presence of pesticides, especially herbicides, in drinking water has caused the water industry some concern. Since 1990 the industry has spent over £1 billion removing pesticides from drinking water so that it meets the EU defined limit of 1 µg/litre, for each pesticide (Hillier & White, 2001). Management agreements and agricultural stewardship plans have endeavoured to reduce this problem, without total success. Similarly, concerns over the effects of direct pesticide drift onto water courses have led to the introduction of controls on the application of pesticides close to such areas (Anon 2001). Spatially selective pesticide application can ensure that pesticides are only applied where they are required and where they are legally permitted and additionally the technology can provide printed evidence (application plan) of where the pesticides have been applied, to comply with requirements of Crop Assurance Schemes.

Consequently there are both economic and environmental reasons for optimising herbicide use by utilising the potential for spatially selective applications. Such an approach can help to deliver reductions in herbicide use, provided weeds are spatially aggregated and appropriately selective herbicides are available. Research and commercial developments have successfully shown that substantial savings in herbicide use can be achieved by selectively targeting weed patches (Miller & Paice, 1998). The use of a map-based control system enables weed patch detection to be undertaken at a time when it can be conducted effectively to give relatively accurate maps both in terms of weed species/density and also position, (Perry *et al.*, 2001). The approach also has advantages associated with the selection of both product/formulation and dose rate and this may be via an interface with a decision support system. Defining those materials that are needed for the treatment of a particular field also limits the loading and transport of herbicides to that which is actually required.

1.1 Spatial distribution of weeds

The utilisation of spatially selective herbicide application techniques depends on the fact that weeds are aggregated in distribution. Is this true? Visually it appears that this is so, as observations of weed infestations just prior to harvest do indicate a patchy distribution (Fig. 1.1). This conclusion is supported by objective data such as those reported by Marshall (1988), Wilson & Brain (1991), Johnson *et al.*, (1995) and Hausler & Nordmeyer (1999). The previous LINK project on the spatial treatment of weeds (Lutman *et al.*, 1998) investigated the distribution of weeds on c. 20 fields. Most fields mapped were infested with black-grass (13), but wild-oats (*Avena fatua* L.) and common couch (*Elymus repens* (L.) Gould) were also assessed on four and six fields, respectively. Single fields of barren brome (*Anisantha sterilis* (L.) Nevski). Italian ryegrass (*Lolium multiflorum* (Lam.) Husnot), onion couch (*Arrhenatherum elatius* (L.) J.&C.Presl) and creeping thistle (*Cirsium arvense* (L.) Scop.) were also mapped. In all cases the weeds were aggregated but the levels of infestation varied from 2 to 85%. Thus one can conclude that weeds can be spatially

aggregated, providing a target for spatially selective weed control. This highlights a question. Why are the weeds aggregated? This could be due to differences in soil characteristics, which could result in synchrony of distribution of several species. Conversely, the spatial distribution may be related to other, non soil, factors, in which case different species will not necessarily have similar distributions. This aspect of weed biology is discussed later (see Chapter 2).

Fig. 1.1   Example of a field of winter cereals, just prior to harvest, with distinct patches of *C. arvense* (creeping thistle)

In order to benefit fully from the spatial aggregation of weeds the patches should be stable. If this occurs frequency of re-mapping is low. If the patches are unstable then fields will have to be mapped yearly. Initial work reported by Wilson & Brain (1991) indicated that patches of the UK's major arable weed, black-grass, were stable over a 10 year period. More recent work reported by Colbach *et al.* (2000) suggests that patch stability varies between species. This aspect of the biology of patches is important and is considered in more detail in the section of this report on weed spatial biology.

1.2 Attributes of weeds contributing to their suitability for patch treatment

There are three attributes of weeds that are beneficial to the success of spatially selective treatments.

1. Firstly the weeds must be aggregated, as discussed above.

2. Secondly, the weeds should be targeted with specific rather than broad-spectrum herbicides. Weeds do not always occur in fields as single species stands, and so fields often contain aggregates of three or four different species. These may be the prime target for a single broad-spectrum herbicide treatment and so if their distributions are not similar the target area must be increased so that all infestations of all species are treated. Savings in herbicide are potentially greater if only one weed species is targeted, unless the distributions of all the species are similar.

3. Thirdly, the weeds should be costly to control. There is greater financial incentive to reduce herbicide use when the product is expensive. Initial expenditure on equipment will be recovered more rapidly and it will be easier to cover the cost of mapping.

In discussions we have concluded that the prime targets for spatially selective weed control in arable crops in the UK are black-grass, wild-oats, cleavers, creeping thistle and common couch (Perry *et al.,* 2001). Other possible targets would be barren and other brome species, and bracken (*Pteridium aquilinum* (L.) Kuhn). These species are all treated with specific herbicides, which tend to be more expensive than the broad-spectrum herbicides used for general broad-leaved weed control.

1.3 Spatially selective treatment of weeds

The utilisation of the spatially aggregated distribution of weeds by targeting the herbicide treatments at the weed patches requires a number of spray application components.

1) The first requirement is for the geo-referencing of the location of weeds and sprayer. This requires the use of the satellite Global Positioning System (GPS) developed initially for military purposes but now generally available. A receiver in the farm vehicle (ATV, tractor, combine harvester) locates its position. The first agricultural use of the technology was in yield mapping linked to fertiliser treatment in the mid 1980s (Robert, 1999) but GPS systems can also be linked to pesticide application. In the context of patch treating weeds, the location information is linked to the weed map and the sprayer controls. Initially GPS systems were somewhat unreliable and the precision of the vehicle location could vary. This was reduced by incorporating a static 'differential' signal when locating position (DGPS), which could come from a land-based beacon or from a geo-stationary satellite. A 'differential' is still widely used, but is becoming less necessary as the precision of the satellite location, without the differential, improves.

2) The second requirement is the creation of a weed map. This could be done with automated detectors mounted on a tractor or ATV or by visual assessment by the operator. Details of mapping techniques are given in Chapter 3. Most emphasis in the project has been placed on visual mapping, though the possibilities for automated and semi-automated systems are explored.

3) The third requirement is for a computer-based platform for both collecting and transforming weed patch information and delivering a treatment map to the application vehicle. The 'raw' weed map needs to be modified to account for any drift in the GPS location, the response time of the sprayer and any need to inflate the weed patch map because of, for example, seed/patch movement or areas of low infestations. This map controls the output from the sprayer.

4) The fourth requirement is for a sprayer with the potential to continuously vary herbicide doses. This needs a method of controlling the application system with a capability of operating over a wide range of dose rates without compromising the physical delivery of the herbicide, (Paice *et al.*, 1996).

5) The final requirement, which is not directly part of the project, is the choice of product and dose to apply to the patch and non-patch areas of the field. The advantages and disadvantages of applying a high dose to the patch and a low one to the rest of the field (high/low strategy), compared to treating only the patch areas (spray/no spray strategy) will be discussed.

All these aspects will be considered in subsequent sections of the report. All of the components are now commercially available, particularly relating to the application machinery. Methods of detecting and recording weed patch positions are the subject of continuing research including that detailed in this report (e.g. Perry *et al.*, 2001) and equipment for recording the results of visual assessments is now readily available. Finally, for the technology to be a commercial success it must offer financial benefits to the user and environmental benefits to the countryside. What is the cost of the technology and what are the potential savings in herbicide use? What are the benefits of the technology to the environment?

1.4 Project objectives

The aim of the project was to optimise herbicide use in arable crops by developing and integrating all the component elements of a spatially selective weed control system into a commercially viable package that could be bought and used by UK farmers. The project would explore both automated and manual weed mapping systems.

Specific objectives

1) To develop effective field mapping procedures based on visual detection

- evaluate the potential of different field operations to provide a platform from which to create reliable and accurate weed maps
- explore the possibilities of extrapolating/interpolating weed distributions to parts of the field that are not mapped
- develop methodologies for the conversion of weed maps to treatment maps

2) To quantify factors which affect patch stability and dynamics

- develop simple approaches to predict changes in patch morphology and dynamics
- investigate the longevity of the accuracy of individual field maps
- predict the longevity of weed maps

3) To investigate the feasibility of automated weed detection for narrow row arable crops

- build on existing research on weed detection by incorporating other techniques such as stereoscopic image analysis
- incorporate *a priori* knowledge to improve robustness of discrimination
- compare classification accuracy of automated and visual systems
- explore potential for semi-automated 'anomaly' detection systems using spectral reflectance to detect area of different vegetation levels

4) To validate the system and develop recommendations for use

- validate the system by mapping, treating and re-mapping the weeds
- explore the practical and financial potential of alternative weed control strategies (high/low dose, spray/no spray)
- demonstrate the system

2.0 Weed Patch Biology

2.1 Introduction

If weed patches are to be treated with spatially selective treatments using historic weed maps, it is more likely to be successful if the patches remain relatively static. Information on the stability of weed patches is important because species with a stable distribution will only require infrequent re-mapping, whereas species with a rapidly changing distribution will need frequent re-mapping or will be unsuitable for patch spraying with historic maps. Even if the patch is relatively stable there will be a need to extend the patch boundaries with a 'buffer zone' to account for factors such as short-distance weed and seed movement in the period between detection and treatment and uncertainties relating to the performance of the in-field location system. Thus, there is a need for information both on the overall stability of weed patches and on the extent of short-distance movement.

The 10 year study reported by Wilson & Brain (1991) indicated that patches of black-grass were relatively static over a 10 year period, though the density within patches varied from year to year. Gerhards *et al*. (1997) also found patches of several annual weed species to be stable. However, Colbach *et al.* (2000) suggest that patches of annual species whose seeds are dispersed before combining are generally more stable than those whose seeds are still on the plant at harvest and hence have the potential to be moved around and even between fields by the harvester. Some support to this theory is given by the work in the previous project (Lutman *et al.,* 1998) and by the work of Howard *et al.* (1991). The former work found little evidence of seed movement by the early shedding black-grass, whereas the latter found that some brome (*Bromus/Anisantha* spp) seeds were moved appreciably by combine harvesters. Intuitively, one would also suspect that patches of perennial weeds such as thistle or couch grass, that propagate primarily vegetatively, would be more stable than weeds that are propagated by seed.

The following chapter reviews what is known about spatial stability of weed patches, gives detail of experiments in the project on spatial stability and concludes by discussing the causes of weed aggregation.

2.2 Factors affecting patch stability

2.2.1 Vegetative spread

Most of the examples of the spread of weed patches are for clonal perennials (Cousens & Mortimer, 1995). There are two ecological strategies by which species or biotypes may be compared:

i)   those types which spread quickly along a main axis producing new plants (ramets) separated by some distance so that they invade a large area but do not dominate it are known as guerrilla strategists;

ii)   those who spread steadily outwards along a front, occupying and consolidating as they go, and engulfing the area into which they spread are called phalanx strategists (Lovett Doust, 1981).

Most studies of vegetative spread of weeds have concentrated on the clone edge. Schippers *et al.* (1993), used a simulation model to examine the importance of three dispersal mechanisms in the spread of yellow nutsedge (*Cyperus esculentus* L.). This is a species that perennates by means of small tubers, which over winter to give rise to shoots during the growing season, which in turn form rhizomes and tubers. Spread of tubers may result from natural dispersal as a consequence of rhizome growth and tubers may be placed up to 0.7 m away from the parent shoot. Dispersal over longer distances may occur as a result of mechanical farming operations. Lapham *et al.* (1985) measured the radius of clones of yellow nutsedge over two years. They found that the clones increased by an average of 1.3 m per year, over a two year period, but that the radius decreased slightly at the end of the growing season, due to shoots at the edge dying back. Horowitz (1973) monitored plants of johnsongrass (*Sorghum halepense* (L.) Pers.). Over 2.5 years, clones spread an average distance of 3.4 m, however, variation between clones was large. The spread was not always even around the clone, depending on direction of growth of the main rhizomes, though over the duration of the study, differences in direction cancelled out so that clones remained fairly circular. Amor & Harris (1975) found large variations in the rates of spread of clones of creeping thistle (*C. arvensis*) in an Australian pasture. Average rates of spread in three successive years were 1.48 m, 1.57 m and 0.80 m per annum. However, in undisturbed ground with no competition the spread can be extremely rapid, up to 12 m in a single year (Roberts, 1982). Bakker (1960) found that creeping thistle seedlings can spread 1.25 m in the first year, and up to 5 m in the second, whilst the stolons of coltsfoot (*Tussilago farfara* L.) can reach 1.25 m in the first year and 3.5 m in the second. Common couch (*E. repens*) spreads by means of underground rhizomes, and clones can spread at a rate of 2 m per year in undisturbed sites (Mortimer, 1990). In undisturbed conditions new ramets are formed usually by the rhizome tips turning upwards. Couch is extremely efficient in producing new rhizomes throughout the summer months (Cussans, 1970), though McMahon & Mortimer (1980) recorded shoot emergence throughout the year in the UK.

From the available literature, it appears that the rate of spread of patches of perennial weeds in crops is relatively slow, and that patches of these species will remain relatively stable over time. However, much of the published data refers to undisturbed habitats, and although actual patch expansion is likely to be less in agricultural fields, movement of rhizome and root fragments is likely to be greater.

2.2.2 Seed dispersal

2.2.2.1 Natural seed dispersal

The rate of spread of patches of annual weeds is dependent on seed dispersal, both by natural means and as a result of agricultural operations such as harvesting and cultivations. Natural seed dispersal from the parent plant is a function of several variables: i) height and distance of the source of seed; ii) concentration at the seed source; iii) dispersibility of the seed and iv) the activity of distributing agents (e.g. wind speed and velocity) (Harper, 1977). Howard *et al*. (1991) recorded seed dispersal distance in sterile brome and interrupted brome (*Bromus interuptus* (Hack.) Druce), away from a sown strip of parent plants within a winter wheat crop. They found seeds of both species were dispersed close (< 0.5 m) to the source plants. Blattner & Kadereit (1991) investigated seed dispersal distances in two species of poppy (*Papaver argemone* L. and *P. rhoeas* L.). Dispersal patterns were slightly different for the two species, with the majority of *P. argemone* seeds dispersed up to 0.3 m from the parent plant, whilst most *P. rhoeas* seeds were deposited between 0.5 and 0.6 m from the source. Nadeau & King (1991) found that the majority of seeds of toadflax (*Linaria vulgaris* Miller) also fell within a 0.5 m radius of the parent plant. In a study of distribution of plants associated with arable field edges, Marshall (1989) found that the majority of species were only found within 2.5 m of the field margin, suggesting seed dispersal of these species is limited. Although creeping thistle patches spread by creeping roots, seed production may be important for maintaining genetic diversity of the species. Ninety percent of seeds are found within 10 m of the parent plant, though a small amount of seeds can travel as far as 1000 m (Heimann & Cussans, 1996).

It would appear that for the majority of species which do not rely on wind dispersal for their seeds, natural seed dispersal only occurs over a short distance.

2.2.2.2 Mechanical seed dispersal

Tall weeds, especially those which retain their seeds through to harvest, are likely to be subject to movement by combine harvesters. Combines are responsible for seed movement both within and between fields. McCanny & Cavers, (1988) found that seeds of proso millet were deposited at a fairly even density in a 45 m strip behind the combine, and an average of 3.3% of seeds were carried more than 50 m from the source patch. Howard *et al*. (1991) introduced painted seeds of brome into a combine during harvesting of a barley crop. Seeds were recovered on sheets of polythene behind the combine. The majority of seeds were moved an average of 1.9 m behind the point of introduction. However, 40 % of seeds recovered were carried forward in the direction of machine passage. No brome seeds were moved more than 20 m from the point of introduction. Unpublished data from Peters (pers. comm.) shows that a small percentage of brome seeds can be moved at least 20 m from their source. Work in the previous LINK project reported by Lutman *et al*. (1998) showed that the majority of black-grass seeds were not moved by the combine, though individuals could be carried up to 50 m away. They also showed that 97% of black-grass seeds had been shed from the

parent plant before harvest. The construction of the combine harvester may also impact on the distance seeds are moved, as Ballaré *et al*. (1987) found that the dispersal distances of thornapple (*Datura ferox* L.) seeds harvested along with a soyabean crop differed between combine harvesters. Two makes of harvester tested moved seeds between 0 and 21 m from the source, but a third model moved seeds between 0 and 98 m.

The amount of movement by combine harvesters will depend on the extent of seed shedding prior to harvest. Also, larger, awned seeds (e.g. brome, wild-oats) may become trapped inside the combine and moved a greater distance than smaller, non-awned seeds (e.g. black-grass, cleavers). Wilson (1970) found date of harvest to have an effect on the amount of wild-oat seed remaining on the plant, and hence available to be moved by the combine. In a winter barley crop harvested in July, only 16% of wild-oat seeds had been shed, whilst in a spring barley crop harvested in August, 94% of the seeds had been shed. However, of the wild-oat seeds still present on the plant at harvest, only a small proportion is redistributed by the combine.

Rew & Cussans (1997) investigated the horizontal movement of seeds of barley, field bean and oilseed rape by four different tine implements (straight-, flexi-, spring- and rotary power harrow), a mould-board plough and seed drill. Flexi- and spring-tined machines moved seeds a greater distance than straight tine or power harrow. They found no overall difference between ploughing and flexi tine seed movement. The small seeds of oilseed rape were moved a greater distance than the larger seeded barley and beans. Over 84% of seeds were moved less than 1 m from the source. Howard *et al*. (1991) and Fogelfors (1985) also found the majority of seeds to be moved less than 1 m by a rotary harrow. Marshall & Brain (1999) reported the horizontal movement of seeds to be less than 2 m, with ploughing and drilling moving seeds the least distance. Grundy *et al*. (1999) showed that a rotovator can cause backward movement of seeds, whilst a power harrow had the greatest capacity for moving seeds in a forwards direction.

In conclusion, combine harvesters are the most likely method of long distance seed dispersal, but only for species that retain their seeds through to harvest, and particularly for large, awned species, which are more likely to become trapped in the combine. In contrast, soil cultivations have the potential to move all seeds a short distance. Most information available on the rate of spread of weed patches is for perennial species such as common couch and creeping thistle.

2.3 Field experiments

As information on black-grass patch ecology had been generated in the previous LINK project (Lutman *et al.,*1998), it was decided that the work in the current project should concentrate on patch stability of two other economically important weeds, wild-oats and cleavers, both of which can have a patchy distribution. Additionally, as there was little evidence available of the extent of natural primary dispersal for most important spatially aggregated weed species, work was done on the natural dispersal of wild-oats, sterile brome (*A. sterilis*), black-grass and cleavers. These two areas provided evidence of patch movement

and thus give guidance on the frequency of re-mapping and on the size of buffer zones that need to be established when converting weed maps to herbicide treatment maps for spatially selective weed control in current and future years.

2.3.1 Stability of patches of wild-oats and cleavers

Eight patches (3 m x 3 m) of wild-oats and cleavers were established in winter wheat crops in 1997 and 1998, respectively. Wild-oat patches were established at two initial sowing densities, 10 (low) or 50 (high) plants/m^2. Cleaver patches were sown at a single density of 16 plants/m^2. All cultivations and harvesting directions were kept constant after the establishment of the patches. Half of the total number of wild-oats patches was treated with clodinafop-propargyl herbicide in spring 2000, and all wild-oats patches were sprayed with this herbicide in spring 2001. No herbicide was applied to cleavers patches. Panicle numbers (wild-oats), plant numbers (cleavers), seed production and seed movement were monitored, together with patch shape, and location of any outlying plants. No data were collected in 2000 on the cleaver populations, as the ploughing in autumn 1999 successfully buried the seeds and no plants were observed. Re-ploughing in autumn 2000 brought seeds to the surface and the subsequent seedlings were monitored in 2001.

Following seeding, harvesting and cultivation, the majority of seeds of both wild-oats and cleavers only moved 1-3 m away from the original patches, though some individual wild-oats seeds moved up to 30 m away from the source, probably carried by the combine during harvest of the crop. The distribution of seeds post-harvest in a transect down the centre of the plots closely followed the distribution of panicles (wild-oats) (Fig. 2.1) and plants (cleavers) (Fig. 2.2). However some individual wild-oat seeds were moved up to 30 m away from the source, probably carried by the combine during harvesting of the crop, and subsequently led to the occurrence of outlying plants away from the main patch (Fig. 2.3). These outlying plants could lead to the formation of new patches if not controlled effectively. Outlying plants did not occur in the cleavers experiment, suggesting that cleavers seeds are not redistributed around the field by combines, but are either deposited immediately behind the combine, or are taken away from the field altogether as a contaminant of the harvested grain.

Patch areas of both species tended to increase during the course of the study (Tables 2.1, 2.2) and in the absence of herbicide more than trebled in size in two years. The application of clodinafop to some of the wild-oats patches in 2000 resulted in the patches being held at their 1999 area or decreasing in area, but the herbicide did not achieve complete control. Those which were left unsprayed, further increased in area. The herbicide treatment in 2001 again failed to achieve complete control and resulted in an increase in patch areas in some of the patches, but panicle density and seed production within each patch was greatly reduced compared to previous years. The front edges of the patches typically advanced by 3 m in the direction of cultivations and harvesting (Figs. 2.4, 2.5).
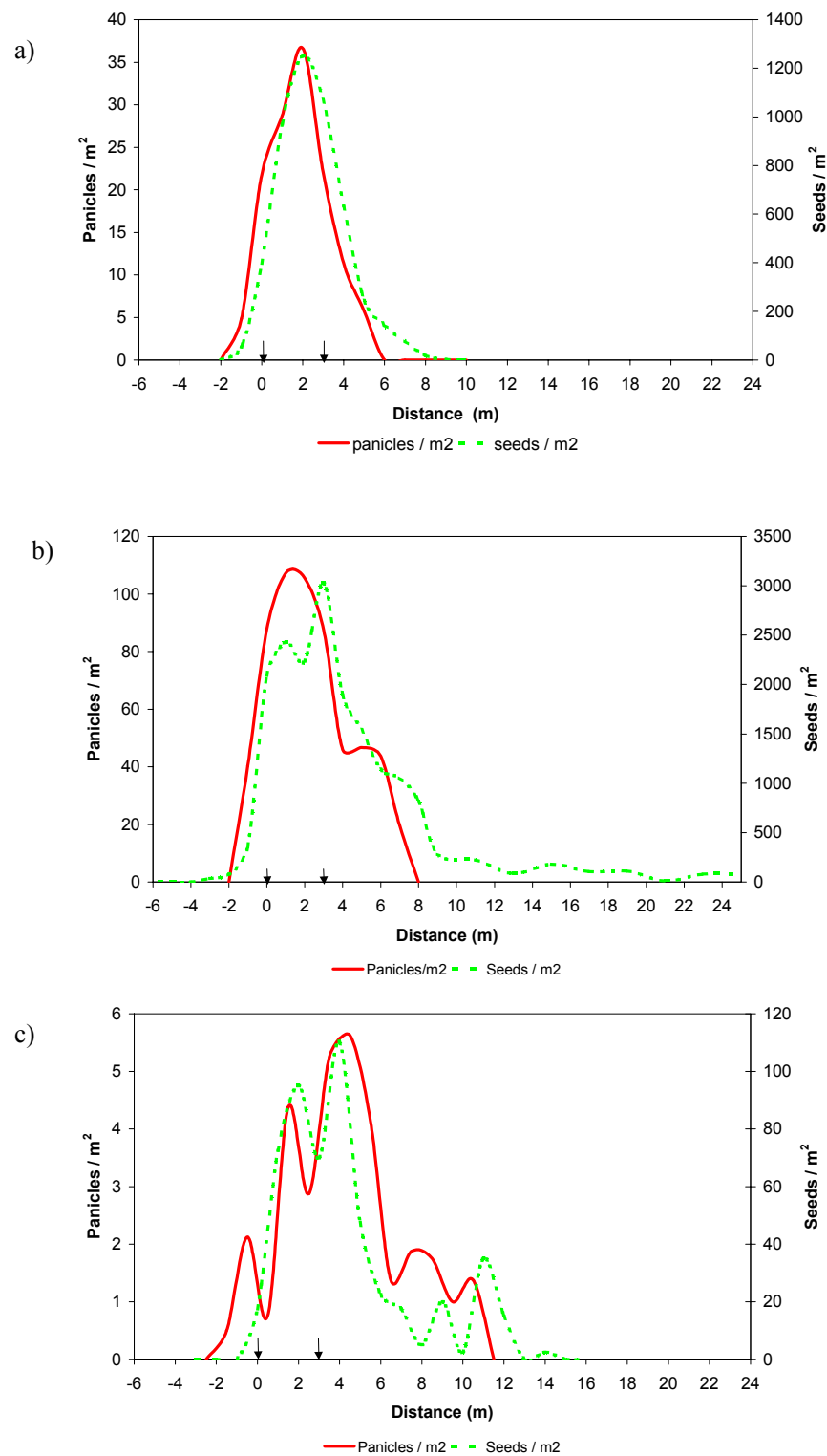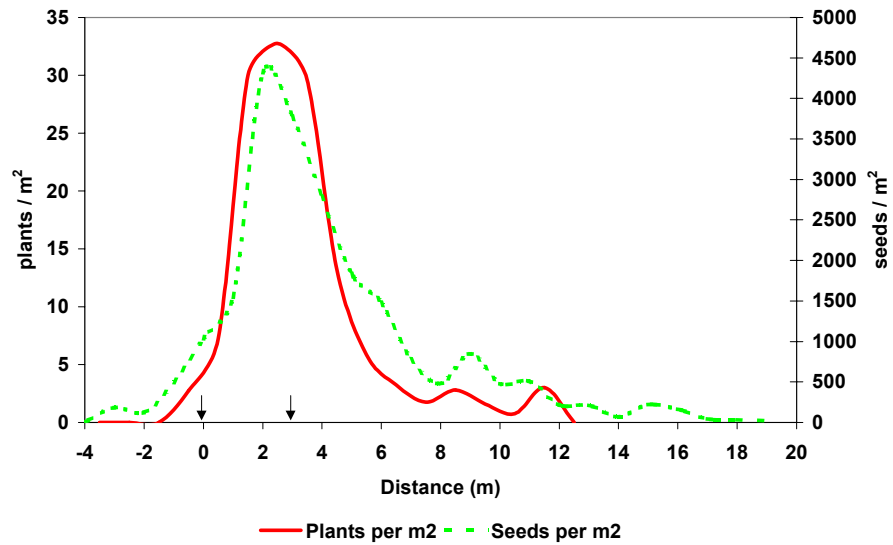
Fig. 2.1 Wild-oat panicle and seed distribution (Mean of all plots) in a) 1999, b) 2000 (sprayed plots only) and c) 2001
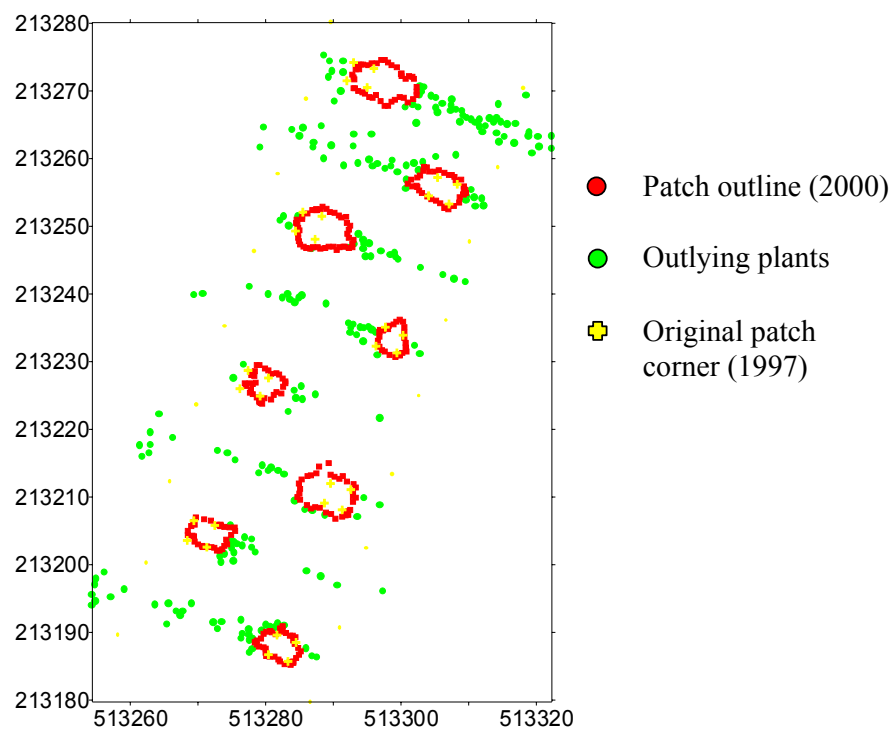
a)
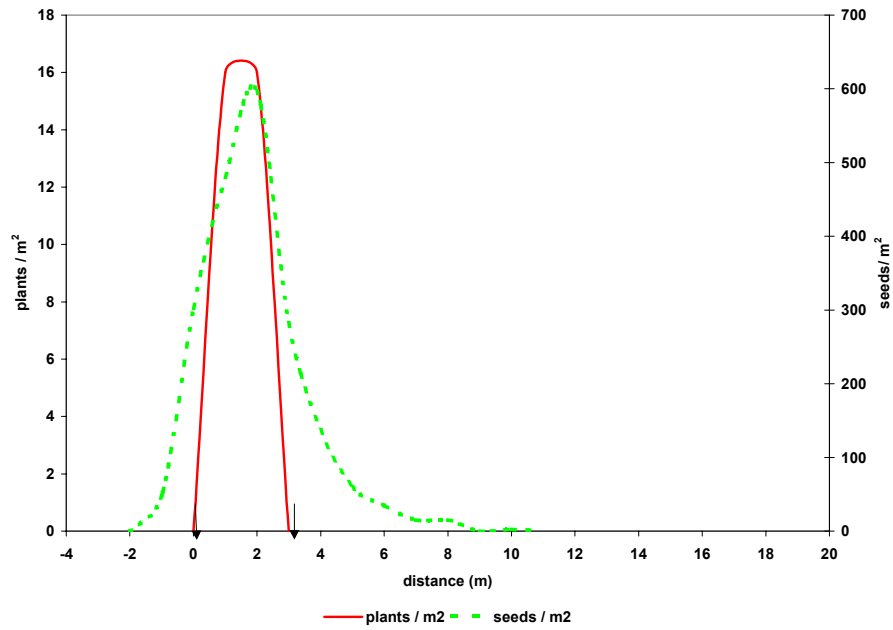
b)

Fig. 2.2 Cleavers plant and seed distribution in a) 1999 and b) 2001 (Mean of all plots)

Fig. 2.3 Location of patches and outlying wild-oat plants in 2000

Table 2.1 Change in wild-oat patch areas (m^2)

Plot	Density	Area 1997/98	Area July 99	Area July 00	*% change 99-00*	Area Oct 01	*% change 00-01*	*% change 99-01*
1	low	9.00	20.28	20.60[a]	*1.6*	25.97[b]	*26.1*	*28.1*
2	high	9.00	21.96	20.47[a]	*-6.8*	10.69[b]	*-47.8*	*-51.3*
3	high	9.00	27.19	42.20	*55.2*	49.98[b]	*18.4*	*83.8*
4	low	9.00	12.67	17.87	*41.0*	4.42[b]	*-75.3*	*-65.1*
5	low	9.00	18.48	15.73[a]	*-14.9*	22.40[b]	*42.4*	*21.2*
6	high	9.00	26.89	38.42[a]	*42.9*	16.72[b]	*-56.5*	*-37.8*
7	low	9.00	17.37	28.36	*63.3*	30.11[b]	*6.2*	*73.3*
8	high	9.00	29.50	40.98	*38.9*	58.82[b]	*43.5*	*99.4*

[a] Sprayed in 2000

[b] Sprayed in 2001

Table 2.2 Change in cleaver patch areas (m^2)

Plot	Area 1998/99	Area May 01
1	9.00	35.52
2	9.00	38.47
3	9.00	28.71
4	9.00	34.90
5	9.00	30.24
6	9.00	35.71
7	9.00	20.77
8	9.00	27.86
Mean		31.52

Significantly more panicles were produced per plot on the high sowing density wild-oat patches in 1998 ($P<0.001$), 1999 ($P<0.001$) and 2000 ($P<0.01$). However, by 2001, when all plots had received herbicide treatment, there was no significant difference in the number of panicles produced per plot. As a consequence of more panicles per plot on high density plots in 1998-2000, there were also significantly more seeds produced on the high density plots compared to low density plots ($P<0.001$ 1998, $P<0.01$ 1999, 2000), but once again this effect had disappeared by 2001. The initial sowing density did not affect the number of seeds that were produced by each panicle.

Unsurprisingly, the application of clodinafop to some of the patches in 2000 significantly reduced the number of panicles per plot ($P<0.001$), the number of seeds per panicle ($P<0.001$) and the number of seeds per plot ($P<0.01$) compared to those which were left unsprayed in 2000. In 2001, when all plots received an application of clodinafop, there were no significant differences between initial sowing densities or previous herbicide application.
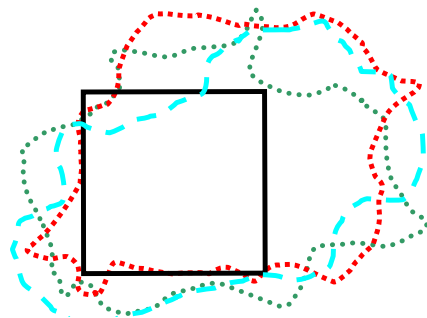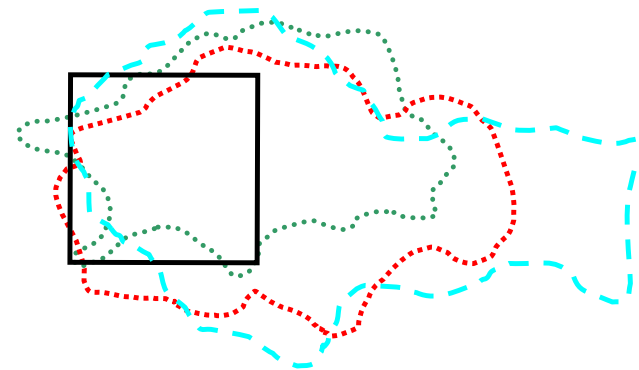
Low density sprayed 2000

—	1997	$= 9\ m^2$,
······	1999	$= 20.3\ m^2$
····	2000	$= 20.6\ m^2$
– –	2001	$= 25.9\ m^2$
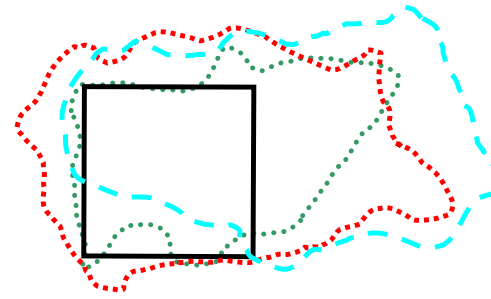
Low density unsprayed 2000

—	1997	$= 9\ m^2$
······	1999	$= 17.4m^2$
····	2000	$= 28.4\ m^2$
– –	2001	$= 30.1\ m^2$
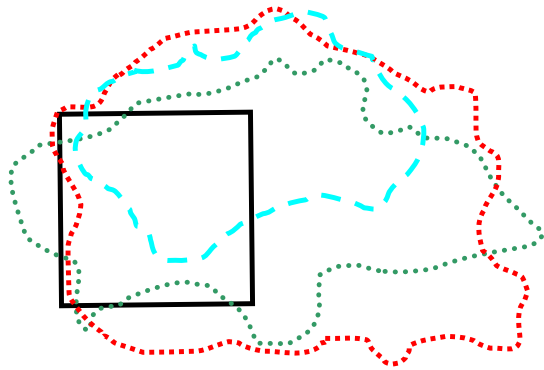
High density sprayed 2000

—	1997	$= 9\ m^2$
······	1999	$= 26.9m^2$
····	2000	$= 38.4\ m^2$
– –	2001	$= 16.7\ m^2$

High density unsprayed 2000

—	1997	$= 9\ m^2$,
······	1999	$= 29.5\ m^2$
····	2000	$= 41.0\ m^2$
– –	2001	$= 58.8\ m^2$

scale

3 m

Fig. 2.4 of wild-oats between 1997 and 2001 (herbicide treate

cultivation and harvesting direction

25

scale
|———————|
3 m

cultivation and harvesting direction
——→

Area of cleaver patch

——— 1999 = 9 m^2
········· 2001 = 30.2 m^2
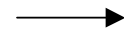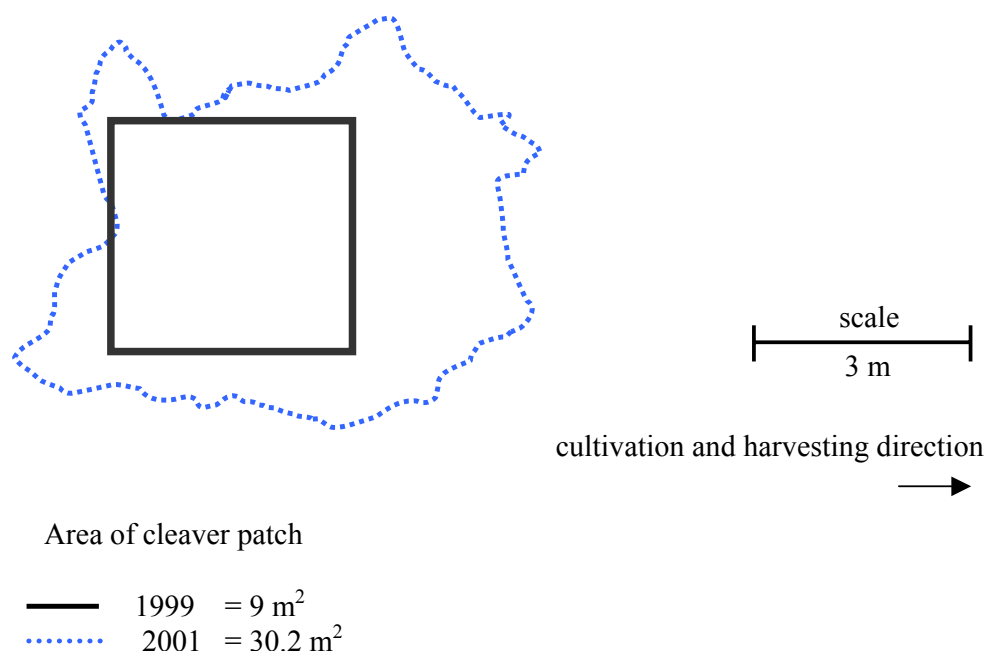
Fig. 2.5 Change in area of a patch of cleavers between 1999 and 2001 (example from one plot)

2.3.2 Natural seed dispersal

2.3.2.1 Dispersal distances

Patches (1 m^2) of wild-oats, brome, black-grass and cleavers were established within winter wheat crops in 2000 and 2001. There were four replicates for each species. Seed traps were sited at distances of 0.25, 0.50, 0.75, 1.00, 1.50, 2.00 and 3.00 m, in four directions, from the centre of each sown weed patch. Seed traps consisted of a 15 cm length of plastic drainpipe sunk into the ground, with an 11 cm diameter plastic funnel placed on the rim of the pipe and filled with coarse sand to lie flush with the soil surface. Seed traps were emptied on a regular basis during the period of seed shedding prior to and immediately after harvest of the crop, and the number of seeds present in each trap recorded, thus giving information on both distance and timing of seed shedding.

The experiments on natural seed dispersal showed that seeds of the taller wild-oats and brome were deposited up to a maximum of 1.5 m away from the parent plants, whilst seeds of black-grass and cleavers remained closer to their source (Fig. 2.6). However, the mean dispersal distance for all the grass species was close to 0.5 m, whilst for cleavers it was 0.37 m (Table 2.3). There is greater potential for increase in weed patch size in the taller species such as wild-oats and brome, but these effects are much less than those recorded for agricultural operations. For the taller species, wild–oats and brome, there was some evidence of greater dispersal in the downwind direction as the panicles tended to lean away from the prevailing wind. This did not apply to the shorter black-grass, nor to the scrambling cleavers.

Table 2.3 Dispersal distances of seeds and percentage seeds remaining on plants at harvest (Mean of 2000 and 2001 data). Figures in parentheses are standard errors (SE) of means

Species	Mean dispersal distance pre-harvest (m) (SE)	% seeds remaining on plant at harvest (SE)
Wild-oats	0.51 (0.059)	7.0 (0.96)
Sterile brome	0.50 (0.019)	12.6 (1.53)
Black-grass	0.49 (0.040)	2.0 (1.07)
Cleavers	0.37 (0.052)	43.5 (7.91)
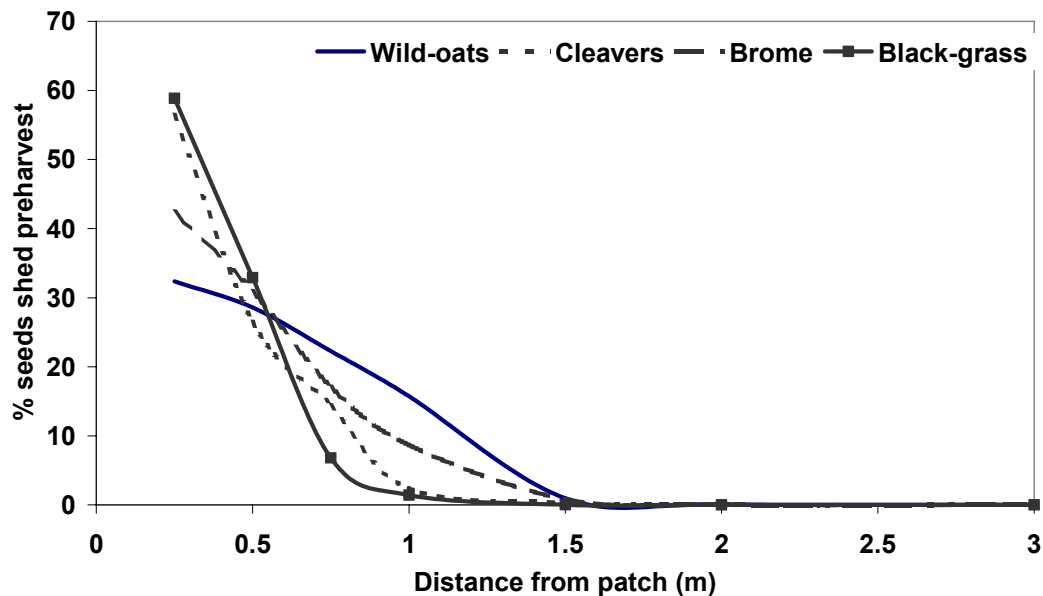
Fig. 2.6 Dispersal distances of seeds collected in seed traps pre-harvest (mean of 2000 and 2001 data)

2.3.2.2 Date of seed shed

Barren brome and black-grass were the first species to start shedding seed in 2000, followed by wild-oats, whilst in 2001 black-grass seeds were the first to be shed, followed by brome and wild-oats. The majority of grass seeds had been shed by the time the crop was harvested, however, a significant proportion of the cleaver seeds were still on the parent plants at harvest in both years (Figs. 2.7, 2.8). An attempt was made to estimate how much cleavers seed was removed in the grain at harvest time and initial conclusions were that perhaps over 30% of the seeds ended up in the grain. Interestingly, less that 10% of the wild-oat seeds were collected post-harvest indicating that the movement of seeds by the combine, described in the

previous section, only concerns a minority of seeds in winter wheat. The potential to move seeds will be much higher in the earlier harvested winter barley, as the proportion shed before harvest will be much smaller. If the barley is harvested in early August only a minority of wild-oats and brome will have been shed, and appreciable quantities of black-grass seed could still be present on the plants. None of the cleavers seeds would have been shed prior to barley harvest but with this late maturing weed a proportion of the seeds would not have been fully formed at this time.

2.4 Conclusions of work on patch stability

A buffer strip of 4 m around mapped patches of wild-oats and cleavers would be sufficient to account for the movement of seeds by natural dispersal and by agricultural machinery, as has been found by Rew *&* Cussans (1997) studying black-grass. However, the fact that individual seeds of wild-oats can move up to 30 m from their source means that there is the potential for new patches to form, and patches of this weed are probably relatively unstable compared to patches of cleavers which did not show this effect. Therefore wild-oats would need re-mapping at more frequent intervals.

There is greater potential for natural increase in weed patch size in taller species such as wild-oats and barren brome, but these effects are much less than those recorded for agricultural operations. Most grass weed seeds were shed prior to the harvest of winter wheat, whilst over 40% of the cleavers seeds collected were still on the parent plants at harvest time. As most grass weed seeds are shed before wheat harvest, they will not be subject to movement by the combine. However, the small percentage of seeds remaining on the plant at harvest will have the potential to be moved around and between fields by the combine, particularly in awned species such as wild-oats and brome. Smaller seeds of species such as black-grass and cleavers are more likely to pass straight through the combine without being carried any significant distance. The potential for the movement of seeds will be much greater in earlier harvested crops such as winter barley.

Table 2.4 gives recommended guidelines on weed patch re-mapping frequencies based on our knowledge of the stability of weed patches.

Table 2.4 Weed re-mapping frequencies

Weed Species	Frequency of Mapping	Confidence in Estimate
Wild-oats	1-2 years	✓
Barren brome	1-2 years	✓
Black-grass	3 years	✓
Cleavers	3 years	✓?
Thistles	3+ years	?
Couch	3+ years	?
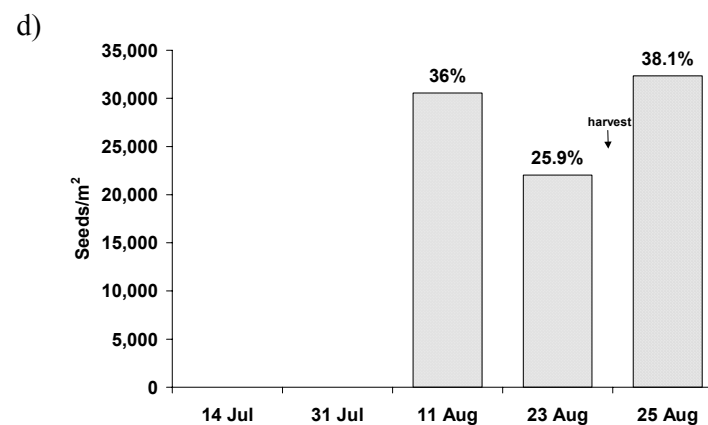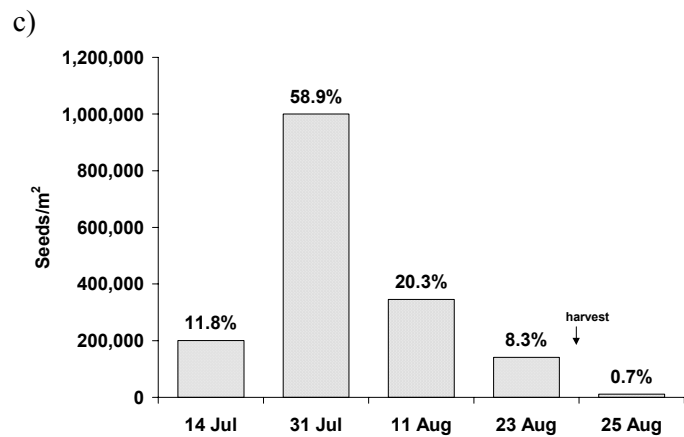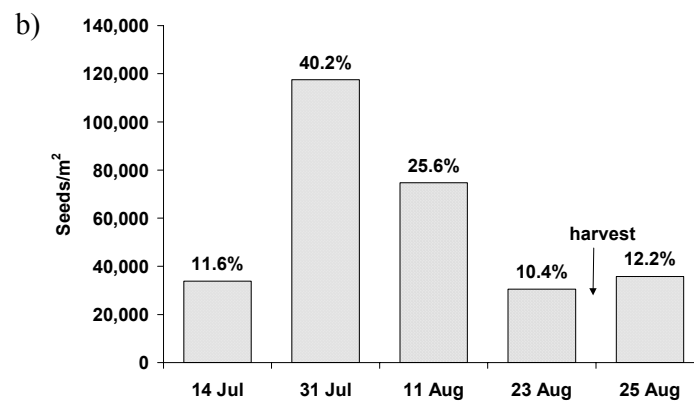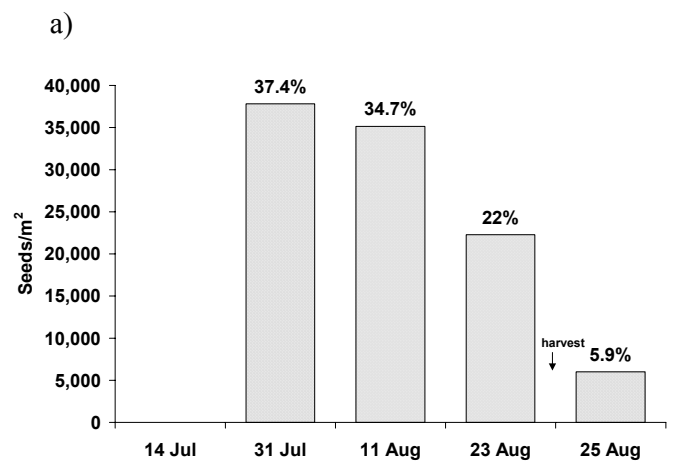
Fig. 2.7 Amount of seed collected in seed traps pre- and post-harvest in 2000 a) wild-oats, b) brome, c) black-grass, d) cleavers
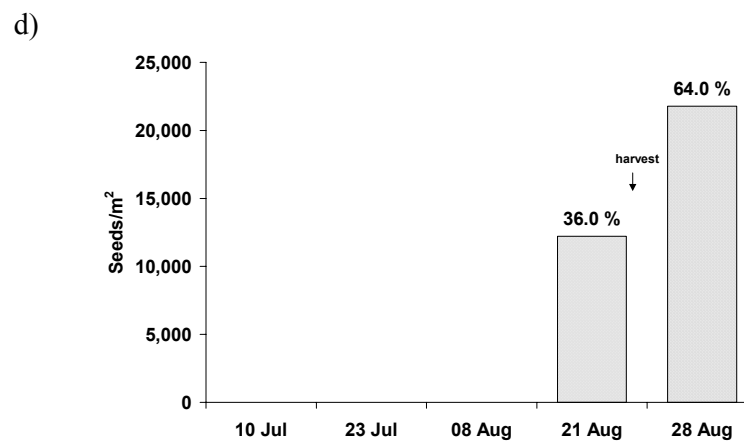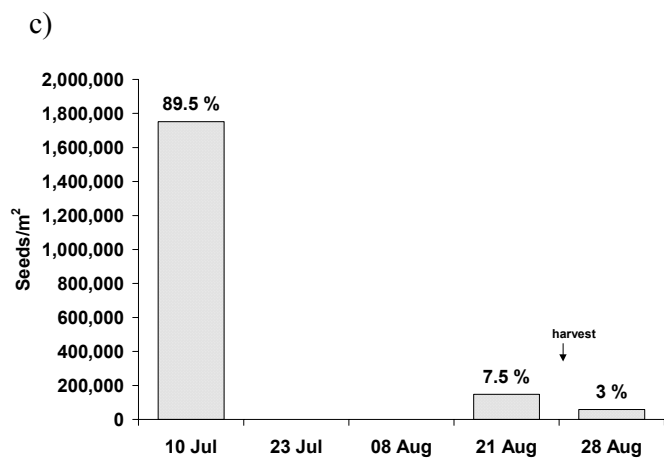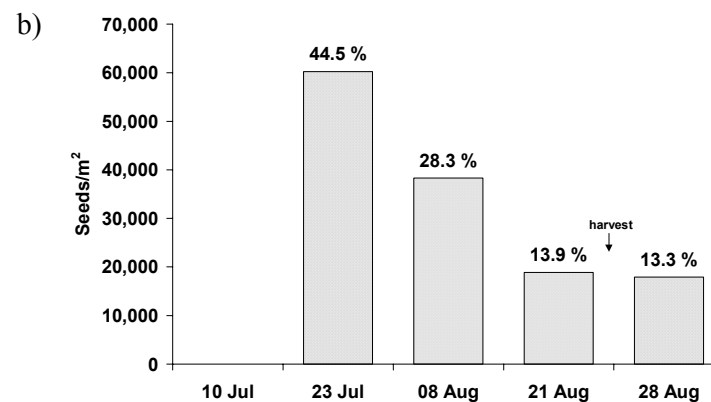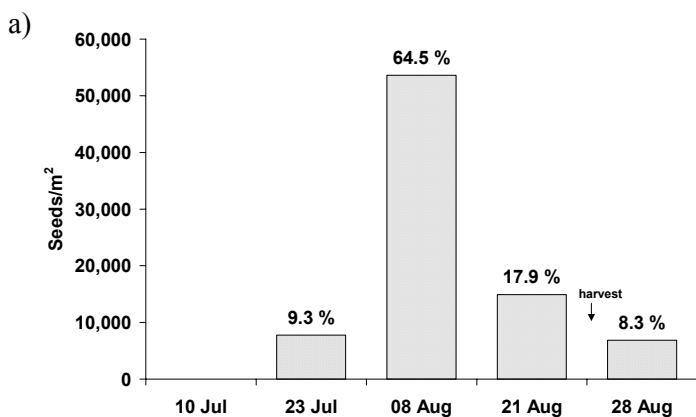
Fig. 2.8 Amount of seed collected in seed traps pre- and post-harvest in 2001 a) wild-oats, b) brome, c) black-grass, d) cleavers

2.5 Causes of spatial aggregation

As weeds seem to occur in patches, what are the reasons for this? This aggregated distribution may be linked to non-random seed (or vegetative propagule) dispersal or by environmental variability and agricultural activities. A patch of weeds with a substantial seed bank will tend to re-appear each year in approximately the same place but why did the patch arise initially? In some situations patches can be started as a result of amalgamating two fields, the soil at a former hedge or fence line containing higher densities of weed seeds than the rest of the field, sometimes with different species. Similarly, when two fields are amalgamated one field may historically have had a different flora to the other. Patches may arise in restricted areas of fields, as a result of catastrophic failure of weed control in one year, permitting a high level of seed return, which provides a focus for a new patch. Poor matching of spray swathes, or blocked nozzles can have this effect. Similarly, poor crop establishment in parts of a field will result in more vigorous weed growth, which can result in poorer performance from the herbicide treatments. A further cause of patchiness is the variability in aspect or in soil type in the field that may favour weed growth differentially. Finally, stochasticity (variability) itself can result in the creation of patches. Wallinga (1995) and Paice *et al.* (1998) have shown that random events, even starting with a uniform distribution, can result in the spatial aggregation of plants.

A number of researchers have investigated the relationships between soil characteristics, both physical and chemical, and weed numbers. Local topographic variation may also cause variation in weed distributions, but these differences may be correlated with changes in soil characteristics (Dieleman *et al.*, 1999). Soil characteristics can have direct effect on the success of weed species, but can also have indirect effects through variation in the performance of herbicides, particularly residual, soil-acting ones. We already know that activity of these herbicides tends to be greater on lighter soils, and this is reflected in variations in recommended doses for different soil types (e.g. heavy, light, organic).

Do certain soil characteristics favour some species? In general, it is known that some species prefer heavy soils (e.g. *G. aparine* (cleavers)) whilst others prefer light soils (e.g. *Cerastium fontanum* Baumg. (common mouse-ear) *Senecio vulgaris* L. (groundsel)). However, it is less clear whether specific soil characteristics favour certain species and thus could be a cause of spatial aggregation. A review of published information is presented in Table 2.6. Nordmeyer & Dunker (1999) found several correlations between weed densities and soil properties. *A. myosuroides* (black-grass) and *Viola arvensis* Murray (field pansy) both showed significant positive correlations with plant available magnesium, whilst *P. annua* (annual meadow-grass) distribution was found to be associated with decreasing clay content, plant-available magnesium and potassium, total nitrogen, and organic carbon. However, they found no significant correlations between the occurrence of *A. sterilis* (barren brome) and the soil properties measured. Similarly, Streibig *et al.* (1984) found that magnesium had a positive effect on the distribution of *S. media*

(chickweed), whilst *P. annua* was positively correlated with potassium and sodium content. *Chenopodium album* L. (fat-hen) was positively influenced by soil organic matter, potassium and magnesium, but showed a negative correlation for soil calcium and sodium. Andreason *et al*. (1991a, 1991b), have explored the relationship between soil properties and the occurrence of 37 common weed species in Denmark. This large-scale study encompassed 316 fields sown to eight different crop types. Soils were analysed for clay content, loss on ignition, pH, P, K, Mg and Mn. Weed species presence or absence was recorded in ten 0.1 m^2 quadrats per field. Nine weed species showed increased frequency in response to decreasing clay content, including *C. album*, *Myosotis arvensis* (L.) Hill (field forget-me-not) and *V. arvensis*. In contrast, *G. aparine* (cleavers), *Sinapis arvensis* L. (charlock) and *Veronica persica* Poiret (common field speedwell) were more frequent on soils with a high clay content. *S. media* was found to be highly correlated with soils with a high potassium content.

An overall comparison of the different published studies on the relationship between weed occurrence and soil properties shows that the relationship between the two is not clear (Table 2.6). In some cases conflicting results are obtained, for example, Streibig *et al*. (1984) found a positive relationship between *C. album* and soil organic matter and phosphorous, whilst Andreasen *et al*. (1991b) found the relationship to be negative. However, a number of soil properties show no significant correlation with distribution of the weed species studied. Additionally, where the same field has been studied over several years there are appreciable variations between years. The reasons for the variability in the comparisons between soil attributes and weed densities are complex. Firstly, the range of values present in the soil samples in one experiment may not include those that might influence the behaviour of the weeds. In which case no relationship would be seen. Secondly, there can be strong correlations between different soil characteristics and so an apparent association between one soil characteristic and weed infestation level may only be due to its association with other soil characteristics. For example, Walter *et al*., (2002) in their paper on the associations between weed densities and soil characteristics, found a strong link between sand content and pH, and between soil organic matter and phosphorus levels. Finally, infestation levels vary between years and it is easier to identify links between weed levels and soil characteristics when densities are high and areas of low and high infestations are more apparent. In years with low weed levels it is likely that weed plants will only be apparent in the most densely infested areas and so for much of the field weed densities will be close to zero, adversely affecting the comparisons between soils and weeds.

2.5.1 Comparisons between soil characteristics and weed infestations: Warren and Broadmead fields
Selected areas (c 1 ha) in both Warren and Broadmead fields (Woburn farm, Rothamsted) were surveyed using a grid of quadrats (5 m x 5 m) in February 99, December 99 and April 2001   (See Section 3.2.6 Figs. 3.10-3.12), thus covering the growing seasons 1998/99, 1999/2000 and 2000/2001.   Black-grass densities (plants/m^{-2}) were recorded on both fields and wild-oats and cleavers were also mapped on Warren

field. In March 2000 2.5 cm (diameter) soil cores (30 cm deep) were taken at every other grid point (10 m x 10 m grid) and the soils of both fields have been analysed for soil texture (clay, silt and sand), % carbon % nitrogen, pH and available (Olsen) phosphorus levels. Additionally, total levels of potassium, magnesium, calcium, sodium and manganese were measured on the Warren samples (Aqua regia digests). The results from the soil samples have been correlated with the weed infestation levels in the three years. Because of the high frequency of sample points with low numbers of weeds, in some years, it was decided that the weed density data should be transformed to $\log_{10}$ values.

2.5.1.1 Soil characteristics

Both soils are primarily sandy loams or sandy clay loam soils, but the variability in the sampled areas was somewhat greater in Warren than it was in Broadmead. This was especially true for the soil physical characteristics. Samples from Warren had clay contents over 40% (Table 2.5, Fig. 2.10), whereas the maximum on Broadmead was 28%. The relationships between the different soil characteristics were explored for Warren, where more nutrients were assessed. There was a very strong correlation, with an r^2 in excess of 0.87, between the 'heaviness' of the soil, as identified by the % clay content, and total calcium, potassium, magnesium and manganese contents, and % carbon and % nitrogen. As expected there was also a strong (negative) correlation between % sand and % clay. These comparisons indicated that there was no real benefit from the detailed metal ion analyses and so they were not done on the samples from the adjacent Broadmead field. Other research has not shown similar close correlations between trace elements and clay content (e.g. Walter *et al*., 2002), so the strong correlations seen on Warren field may not be universally present. Available phosphorus levels were high on both fields, as the minimum of 14 ppm was well in excess of the accepted threshold for wheat of 10 ppm.

Table 2.5 Details of the textural content and levels of nutrients in the soil samples from Warren and Broadmead

Soil characteristics	Warren		Broadmead	
	Mean	Range	Mean	Range
% Nitrogen	0.23	0.16 – 0.33	0.22	0.17 – 0.36
% Carbon	2.35	1.66 - 3.23	2.42	1.99 – 3.98
PH	7.1	6.6 – 7.4	7.3	7.0 – 7.7
Available phosphorus (ppm)	37.7	14.4 – 93.8	20.7	14.4 – 33.4
Total calcium (ppm)	6151	3911 – 9579		
Total potassium (ppm)	2734	1998 – 4384		
Total magnesium (ppm)	3414	2389 – 5417		
Total managanese (ppm)	122	76 – 204		
Total sodium (ppm)	130	93 – 205		
% Sand	45	19 - 67	55	42 – 62
% Silt	26	18 - 33	26	21 – 31
% Clay	29	15 - 50	18	14 – 28

Table 2.6 Relationship between soil properties and weed occurrence from the published literature

	Soil Property											
Species	clay content	pH	Organic matter	C	N	P	K	Mg	Mn	Ca	Na	Reference
Alopecurus myosuroides	0	0		0	0	0	0	++				Nordmeyer & Dunker (1999)
Chenopodium album		0	++			+	+			0	0	Streibig *et al*. (1984)
	0	0	--			-	0	0	0			Andreasen *et al*. (1991b)
Cirsium arvense	0	0	0			0	-	0	0			Andreasen *et al*. (1991b)
Elymus repens		0	0			0	0	0		--	0	Streibig *et al*. (1984)
Galium aparine	+++	0	0			0	+	0	0			Andreasen *et al*. (1991b)
Lamium amplexicaule	0	++	0			0	0	0	++			Andreasen *et al*. (1991b)
Lamium purpureum	-	-	0			+++	0					Walter *et al*. (2002)
Myosotis arvensis	---	0	+			0	0	-	0			Andreasen *et al*. (1991b)
Plantago major		0	0			0	0	0		0	+	Streibig *et al*. (1984)
	0	+	+++			0	0	0	0			Andreasen *et al*. (1991b)
Poa annua		0	0			0	+	0		0	+	Streibig *et al*. (1984)
	0	---	0			0	0					Walter *et al.* (2002)
	0	0	+++			0	0	0	0			Andreasen *et al*. (1991a & b)
Polygonum aviculare	---	0	0			0	0	0	++			Andreasen *et al*. (1991b)
Sinapis arvensis	+++	0	0			--	0	0	0			Andreasen *et al*. (1991b)
Stellaria media		0	0			0	0	+		0	0	Streibig *et al*. (1984)
	0	0	0			0	+	0	0			Andreasen *et al*. (1991a & b)
	+	-	0			0	0					Walter *et al.* (2002)
	0	0		0	+++	+	0	+				Nordmeyer & Dunker (1999)
Veronica hederifolia					-							Dammer *et al*. (1998)
Veronica persica	+++	+	0			0	+++	0	0			Andreasen *et al*. (1991b)
Veronica spp.	0	---	-			+	-					Walter *et al.* (2002)
Viola arvensis	---	0	0			0	--	0	0			Andreasen *et al*. (1991a & b)
	---	0	+			0	-					Walter *et al.* (2002)
	0	--		0	+	-	0	+++				Nordmeyer & Dunker (1999)

0 : no significant effect: +: positive relationship: -: negative relationship

2.5.1.2 Relationships between soil characteristics and weed densities – Warren field

As the soil analyses were done in March 2000 one would expect a closer relationship between the soil characteristics and the weed levels in December 99 than with the weed assessments in February 99 and April 01. This is what was found for both G. aparine and A. myosuroides (Table 2.7).

Black-grass

The correlations between the soil parameters and the black-grass densities in Warren field varied markedly between years. The poorest relationships were in February 1999, where the correlations between $\log_{10}$ black-grass numbers and soil parameters were not significant for any of the soil parameters (Table 2.7). However, there were some marginally significant relationships from the non-transformed analyses. When the December 1999 infestation (log transformed) was compared to soil parameters, strong correlations (%va in excess of 50%) were identified between the weed level and % nitrogen, % carbon, % clay and levels of the mineral elements, Calcium, Magnesium, Potassium and Manganese. As these soil properties were all strongly correlated (see Section 2.5.1.1), this was not surprising. Fig. 2.9 shows the relationship between weed numbers and % clay content of the soil. Relationships between the soil information and black-grass numbers in April 2001 were similar to those found the previous year, although the overall level of correlation was lower (%va up to 42%). Nevertheless the correlations to the same soil parameters continued to be highly statistically significant. Visual inspection of the soil maps (Fig. 2.10) clearly shows the higher levels of mineral nutrients and clay and organic carbon at the top of the mapped area. This links well with the higher infestation area of black-grass (see Fig. 3.10).

Table 2.7 Correlations between $\log_{10}$ weed densities (black-grass, wild-oats, cleavers) and soil parameters for Warren field. (data are % variation accounted for, and significance level (5% = *; 1% = **; 0.1% = ***)

Soil Charact-Eristics	Black-grass			Wild-oats			Cleavers		
	Feb 1999	Dec 1999	April 2001	Feb 1999	Dec 1999	April 2001	Feb 1999	Dec 1999	April 2001
% Nitrogen	10.5	**63.2*****	**37.3*****	**26.6****	**25.3****		**37.5*****	**37.7*****	**30.7****
% Carbon	10.4	**60.6*****	**34.7*****	**26.6****	**25.7****	N	**36.8*****	**35.9*****	**29.5****
PH	0	12.8	10.3	0.9	6.1	O	2.1	0	0
P ppm	0	**39.6*****	**27.1****	11.5	15.5	P	2.7	7	10.0
Ca ppm	10.1	**65.0*****	**41.7*****	**26.0****	**25.0****	L	**39.0*****	**41.8*****	**33.4****
K ppm	11.6	**56.9*****	**32.5*****	**26.3****	**21.4***	A	**44.1****	**49.2*****	**41.8*****
Mg ppm	10.9	**62.6*****	**36.3*****	**26.8****	**23.3***	N	**40.7*****	**45.1*****	**38.3*****
Mn ppm	9.6	**53.6*****	**32.7*****	**23.1***	**25.6****	T	**35.3*****	**40.3*****	**27.4****
Na ppm	11.1	**37.5*****	**19.9***	5.0	9.0	S	**29.2****	**32.8*****	**34.3*****
% Sand	10.2	**53.8*****	**28.5****	11.2	**22.4***		**44.2*****	**43.5*****	**33.4****
% Silt	6.8	**19.5***	7.0	3.7	8.4		**34.9*****	**29.0****	15.6
% clay	9.8	**62.8*****	**35.8*****	13.1	**25.7*****		40.3	**42.3*****	**36.3*****

Wild-oats

These were only present on Warren field. Correlations between soil parameters were not as strong as for black-grass. There were few wild-oats present on the mapped area in seasons 1998/1999 and virtually none in 2000/2001. Consequently, the data could not be analysed in 2000/01. Correlations were significant in both 1998/99 and 1999/2000 but were not high, as all the % variances accounted for were below 30%. The strongest relationships were with % carbon, % nitrogen, and with levels of the trace elements calcium, potassium, magnesium and managanese (Table 2.7). These soil parameters were all highly correlated. Fig. 2.9 shows the relationship between % clay content and infestation level in 1999. As with the black-grass, the main infestation tended to be associated with the heavier soil, at the top of the maps (see Fig. 3.12).
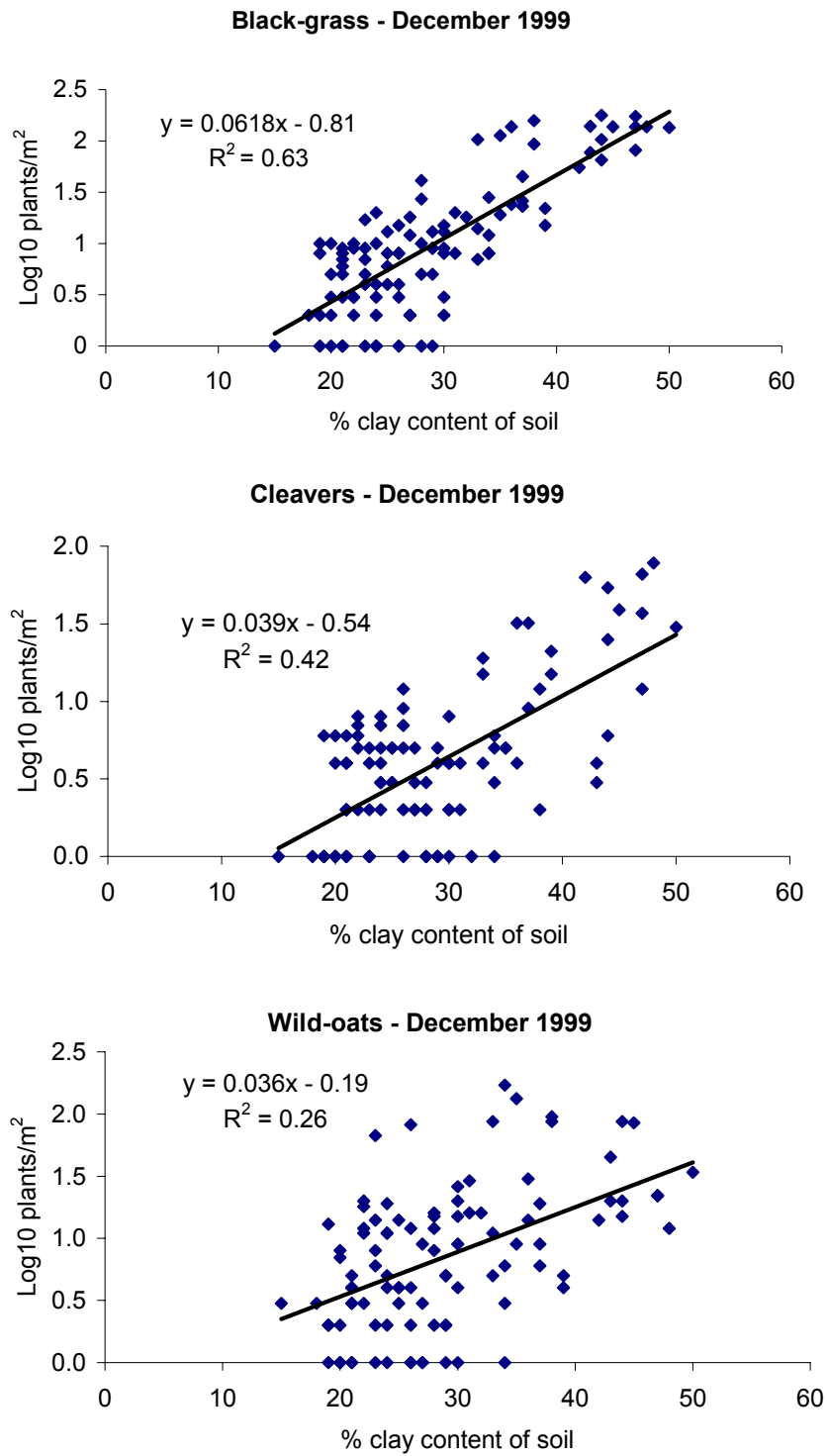
Cleavers

The response of the cleavers in Warren field to the soil parameters mirrored that of the two grass weeds. More were present in the heavier part of the field. Correlations were better than those achieved with wild-oats but were not as good as those with black-grass (Table 2.7, Fig. 2.9). Significant relationships were found in all three years, despite the low cleaver levels in the third year. The variation accounted for was in the region of 35-45%. Again the cleavers were most abundant on the heavier part of the field (see Fig. 3.11).
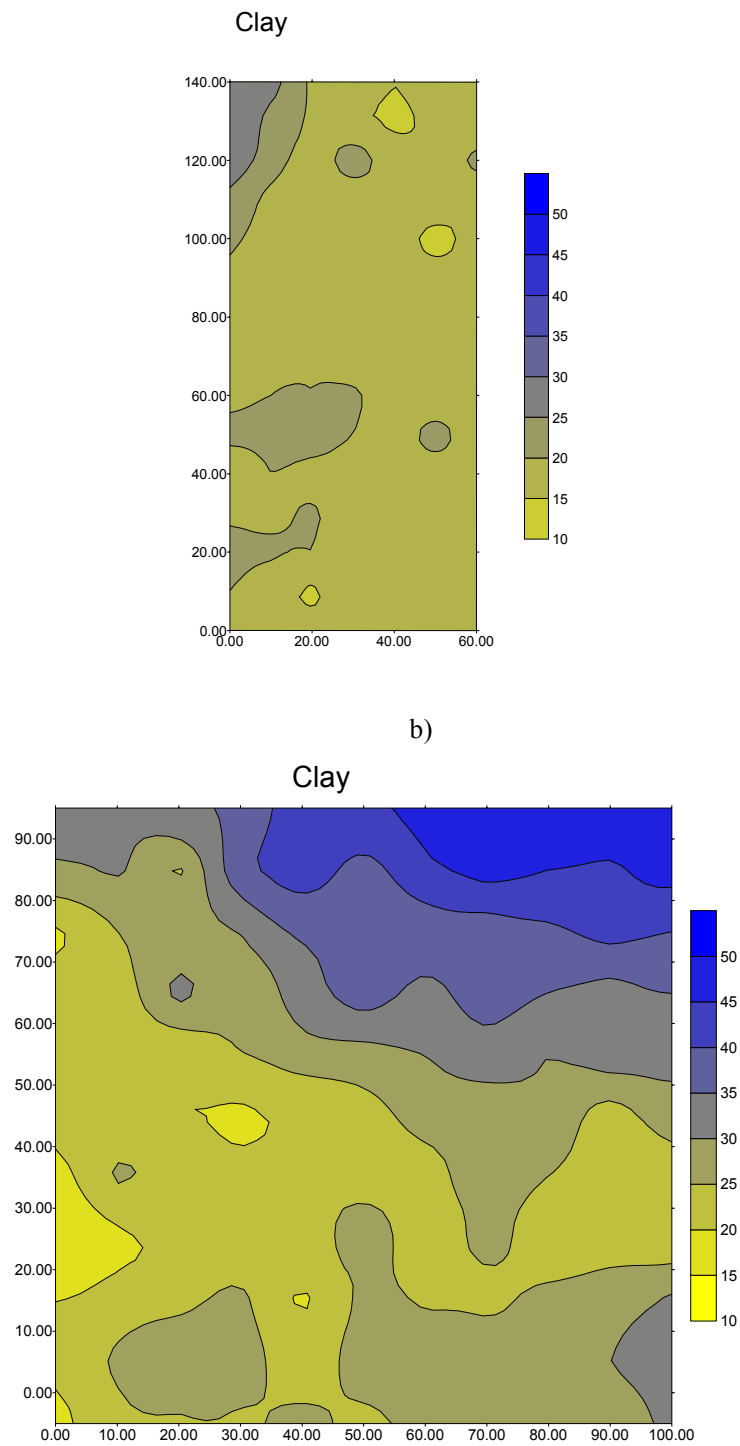
2.5.1.3 Relationships between soil characteristics and weed densities – Broadmead field

The relationships between soil characteristics and the distribution of the infestation of black-grass on the mapped area of Broadmead were very poor. For most analyses there was no correlation between the weed distribution and the soil parameters. This applied in all three years and to all soil parameters. In some instances the % variance accounted for by the correlations reached 10-15%, but nothing was statistically significant ($p = 0.05$). As you can see from the maps in Fig. 3.13 of Chapter 3 the weed occupied most of the mapped area, but in 1999 areas of high density were recorded on the top left side of the mapped area. This did not appear to be related to soil characters (Fig. 2.10). The level of variation in the soil tended to be much lower in this field than it was in Warren and so the lack of association of the weed with soil parameters may simply be a reflection of the lack of variability in the soil on the site (see above). There were, for example, no areas with a high % clay content, as there were on Warren (Table 2.5, Fig. 2.10). The spatial aggregation in the weed distribution may, however, be due to the development of herbicide resistance in the black-grass, as areas of the field adjacent to, but outside, the mapped area were found to contain a considerable % of resistant types. The high density areas may simply reflect poor control of the resistant types spreading into the mapped area. Thus, variation in soil characteristics may not be the only reason for weed aggregation.

Fig. 2.9 Relationships between infestation levels in Warren field of black-grass, wild-oats and cleavers in December 1999, and the % clay content of the soil at each sample point

Clay

b)

Clay

Fig. 2.10   Maps of spatial variation in soil characteristics: % clay content of soils of a) Broadmead and b) Warren fields (data mapped using **'Surfer'** software)

2.5.2 Comparisons between soil characteristics and weed infestations: Cashmore field

The soil characteristics of this field had been investigated as part of a different project investigating the causes of spatial variability in yields (Lark *et al*., 1998). Data in this report show that there are clear variations in topography as well as soil characteristics for this field. Black-grass infests the bottom of this sloping field but not the upper. (Fig. 2.11). This lower part has been surveyed and includes the Evesham, Bardsey, Enborne and Fladbury soil series, all of which (at 0-20 cm depths) are classed as clays or sandy clay loams. In contrast, the soil series present in most of the remainder of the field are classed as sandy loams. Thus, again the black-grass was associated with the heavier more water retentive soils. It must be noted that the quadrat maps of Cashmore field (Fig. 3.14 Chapter 3) only assessed the lower part of the field.
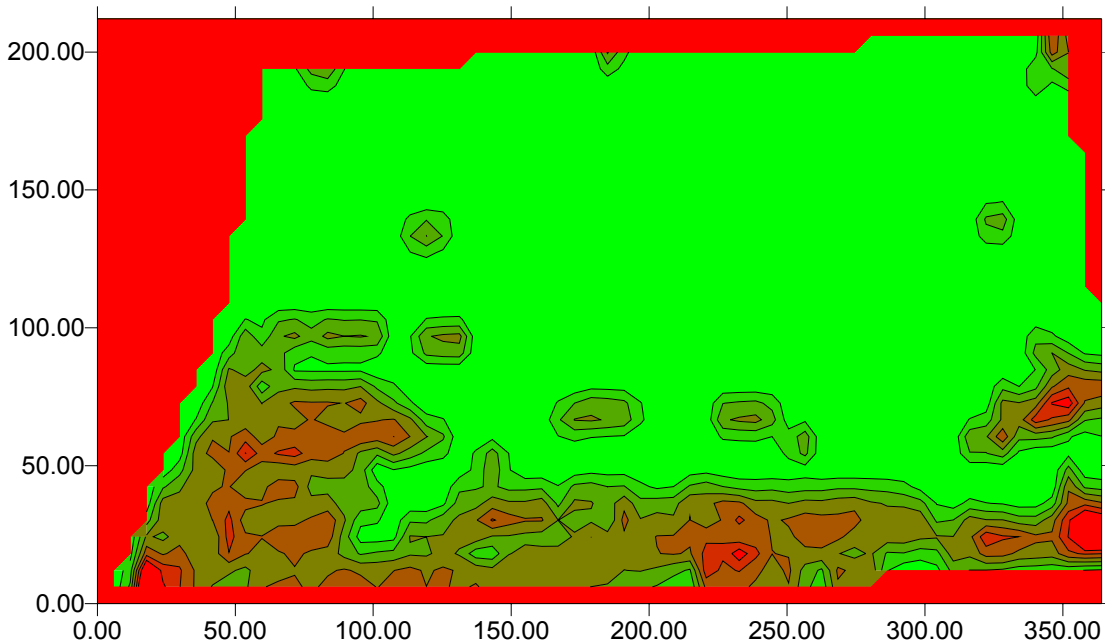
Fig. 2.11   Distribution of black-grass in Cashmore field recorded at harvest 1998.   (green = no weeds, red/orange = high density areas)

2.5.3 Discussion of causes of aggregation

It is clear from the work reported here and from the published information, that soil characteristics can influence the behaviour of weeds. But it is also clear that this relationship is complex and may not be the only cause of spatial aggregation. Indeed, it may not be the major cause. Our data shows black-grass (in Warren and Cashmore fields) to be associated with heavy soil, with a high clay content, but this was not noted by Nordmeyer & Dunker (1999) who only found a positive correlation with magnesium levels (Table 2.6). The association of cleavers and heavy soils agrees with other work (Andreason *et al.*, 1991b). The similar association of wild-oats with the high clay areas of Warren field is not supported by any of the published literature that we have reviewed. Dieleman *et al.* (1999) were able to predict within-field weed

species occurrence based on field-site attributes in Nebraska. Factor analysis using relative elevation, soil texture, pH, organic carbon, nitrate and phosphate was used to predict the occurrence of annual grasses, eastern black nightshade, common sunflower and velvetleaf. Two Danish groups have used co-kriging using soil properties to predict weed densities (Heisel *et al*., 1999; Walter *et al*., 1997). So it is possible that soil variation contributes to the spatial aggregation of weeds but it seems likely that agronomic factors, such as spray misses, and random events are as important in determining where weed patches occur.

3.0 Weed patch detection

3.1 Manual systems - introduction

Patch treatment of weeds can be based on maps created prior to treatment, or by real-time detection and treatment in one operation. The latter has the advantage of immediacy and does not require time and associated costs to create the weed map. However, it provides no opportunity for prior assessment of weed control strategy and treatment. Nor does it permit estimation of herbicide requirements prior to entering the field. Map-based systems provide potential to assess herbicide needs prior to spraying. As real-time treatment is dependent on automated detection systems that currently are not practical for narrow row crops, the project has concentrated on manual weed mapping.

The manual mapping of weeds has been widely studied over the last few years. It is vital for the success of spatially variable application systems that the map is a good reflection of the weed distribution. Two different methods have been studied: continuous recording of weeds from a moving vehicle and discrete assessments made on a regular grid. In both systems the location of the information is geo-referenced in order to create a suitable treatment map to control the sprayer. Counting weeds on a grid of regularly spaced quadrats is widely used for research purposes (e.g. Gerhards *et al*., 1997; Häusler & Nordmeyer, 1999; Heisel *et al*., 1999; Goudy *et al*., 1999). It provides definitive and quantitative information on weed levels within the field, assuming the sampling scale is suitable. However, the time taken to assess each grid point on a fine grid covering a large area, means that this form of weed mapping is not really suitable for commercial on-farm mapping. Only a relatively small area of the field is sampled in this way, and interpolation methods are needed to estimate the weed cover in unsampled areas. The most commonly used method of interpolation is kriging, though Rew *et al*. (2001) have suggested that this may not be the most suitable method for estimating weed densities. Additionally, because of the labour intensiveness of the technique there is a temptation to increase the size of the grid, so fewer assessments are made per hectare. The outcome of this is that the sample points are not relevant to the spatial scale of the weeds and this, together with the kriging used to interpolate the data, results in inaccurate maps (Rew & Cousens, 2001). In this project most of the weed mapping was done using continuous visual observations from a moving vehicle. Kriging has been used to interpolate data, when needed (see Section 4).

3.2 Visual mapping

Weed distributions in a considerable number of fields have been visually mapped, using a variety of platforms (ATV, tractor and combine harvester). Most maps have been based on continuous geo-referenced recording of weed presence and absence. Some maps have also been created with zero, low and high

infestation levels. Some fields have been mapped over a number of years to monitor changes in weed distributions. In three fields the weed distribution by the visual weed mapping has been checked against a grid of quadrat counts of weed levels. The mapping has concentrated on the key weeds identified earlier (black-grass, wild-oats, cleavers, creeping thistle and common couch), but some other species have also been mapped (Table 3.1).

During the project a total of 61 visual maps have been created, using either an ATV, tractor or combine harvester. Three typical maps are shown in Fig. 3.1. The first point to be made is that in general the geo-referencing signals from the GPS satellites, coupled with the differential provided by the Racal geo-stationary satellite, have been reliable. The problems experienced in the early 1990s of inaccurate location and loss of signal happened much less frequently. There can be situations when the signal is poor because of an inadequate number of satellites being visible, associated with a restricted horizon (e.g. in a steep sided valley). This problem is declining as the number of satellites available has increased year by year. Further, the USA government switched off the scrambling system during 2001, again improving the accuracy of the location.

The weed mapping work done in this project aimed to answer a number of questions:

i)   how did the weed mapping equipment function? How easy is it to map from the ATV, tractor or combine?;

ii) what weed species can be mapped and when during the year?;

iii) how long does it take to map a field and hence what are the costs?;

iv) how patchy are weeds in fields? This work built on that done in the previous project (Lutman *et al.,* 1998), providing more data to support the hypothesis that weeds are spatially aggregated;

v)   how representative are the maps of the 'true' weed distribution?;

vi) how much does the distribution of weeds change with time?;

vii) how easy is it to transfer the data to the computer controlling the sprayer?

3.2.1 Manual weed mapping systems – how to map?

Two different systems were used in creating the maps. Both required a GPS location receiver, a computer to process the data and a method of recording the presence/absence of the weeds. Both systems were tested on an ATV, tractor and combine. With the ATV and tractor, mapping is done from the tramlines, though with the ATV it is also possible to map in between the tramlines. The field of view from the ATV is restricted to a couple of metres either side of the tramlines but from the tractor it is possible to look up to about 6 m on either side. This ability to see left and right provides the potential to record weeds in the same way, thus increasing the precision of the map. With mapping from the combine the field of view is the combine header

and so the whole field can be mapped. With the other systems, strips of data are collected on each pass of the vehicle, frequently the tramlines, and this can then be interpolated to create a map of the whole field.

The AGCO 'Fieldstar' system used was based around the controller and screen used for yield mapping and generally mounted in combine harvesters. The 'Fieldstar' screen (Fig. 3.2) was mounted on the ATV or tractor.   The presence/absence of weeds was recorded by pressing the appropriate point on the touch sensitive screen. This proved to be rather difficult especially, from the ATV, as it required the operator to change from observing the field for weeds to looking at the screen to make the record. Also it was necessary to take one hand off the handlebars to press the relevant point on the screen. For this reason a hands-free, voice recognition system was developed.   At the same time AGCO engineered a four unit switch box (Fig. 3.3) to be used with 'Fieldstar'. This can be mounted on the detection vehicle and the operator simply turns the switches on and off to record the presence/absence of the weeds. This can be done by touch without necessarily stopping observing the field. There are four switches enabling four weeds to be recorded at one time, or two weeds at two at two levels of infestations (e.g. low or high), or with two positions (left, right). 'Fieldstar' has the potential to record eight markers, so more are available, if needed.

The hands-free system uses voice recognition software to record the presence of weeds (Figs. 3.4, 3.5). The operator wears earphones and a microphone. Once trained, the software will, for example, recognise spoken commands such as 'black-grass on', 'wild oats off' etc. This information is transferred to a computer file to create the map.   The control box designed in the project will record several weeds or types of infestations at once. This technique has the advantage that when mapping from an ATV the user does not have to take his/her hands off the handlebars. Also it makes mapping from a tractor a simpler operation. The system did not seem to be adversely affected by background noise from the tractor or ATV. However, it has the disadvantages that a robust portable computer is needed and the software has to be trained to recognise the voice of each user, prior to use. This takes some time.

A third mapping system has recently been developed by Patchwork Technology, using a Palm Pilot with a GPS receiver. This was not tested in the project.

Both the 'Fieldstar' and Hands-free techniques were tested from 1999 to 2001. 'Fieldstar' (with the toggle switches), or hands-free recognition, are practical and can be used to map weeds. In reality we found it difficult to map more than two weeds, or two levels of one weed at one time from the ATV, because of the need to concentrate to control the vehicle. A greater range of weeds or infestation levels could be mapped from a tractor, where the 'driving' was less stressful. However, there is a limit of perhaps four alternatives as the user can get distracted and although both the switches and the hands-free control box, have illuminated diodes it can still be confusing as to the status of each species, when mapping several at the same

time. The ATV is useful for mapping in winter (Fig. 3.6.) but is not suitable once the crops start to extend in spring. A tractor can be used as a mapping vehicle at any time during the growing season. Mapping from a combine is particularly useful as the whole field is covered and the speed is lower, but of course it is only suitable if the weeds are still visible at harvest.

3.2.2 What weeds can be mapped and when?

For a number of agronomic, economic and biological reasons (see Introduction) black-grass, wild-oats, cleavers, creeping thistle and common couch were identified as the most important targets for patch spraying weeds. As can be seen from Table 3.1 the project has explored the possibilities for mapping these species at various times of the year. Most of the mapping was done in winter wheat, as this is the dominant UK arable crop, and patch treatment of weeds must be effective in this crop for the technique to be economically viable. It was possible to map all five species but they varied as to their optimum times of 'visibility'. The mapping work also showed it was possible to map other weeds and fields containing ryegrass, onion couch and redshank (*Polygonum persicaria* L.*)* were also mapped successfully.   In the work on semi-automated detection (see below) infestations of volunteer barley in rape were easily mapped in autumn.

A further feature of the timing of weed mapping relates to the utility of the map. If the weeds are mapped in winter or spring, prior to treatment, it is possible to use that information to control applications of herbicide later in the same season. If the map is made in summer, or at harvest, the information can only be used to adjust treatment in the following crop. Additionally, the patches mapped in summer and at harvest will probably have been treated already and represent the areas of the field where control was poorest. This is not a serious problem, as those surviving treatment will provide most of the seeds that are the source of the seedlings in the following year, especially if the field is not ploughed. Secondly, these patches will probably identify the core areas of the weed infestation, where the seedbank and seedling density was the highest. This raises the issue of buffers, because if the map only represents the core of a patch, the area treated should be inflated to ensure that surrounding areas were also treated. It also raises the question as to whether a spray/no spray strategy or a low dose/high dose system is the most appropriate for managing weeds in a spatially selective way. This is covered in more detail in the section on the creation of the treatment map.
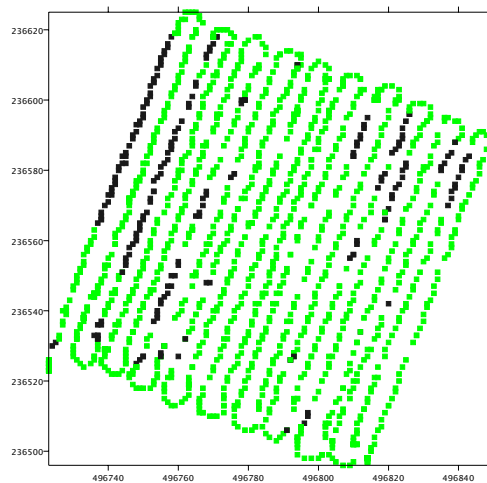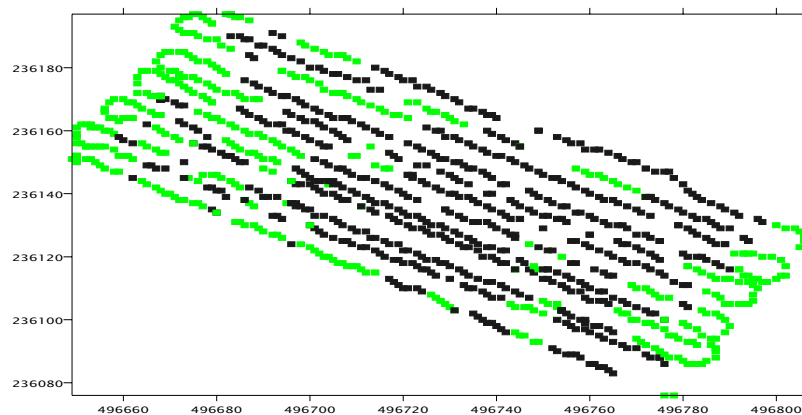
Pike hill

-      black-grass

-      July 2000
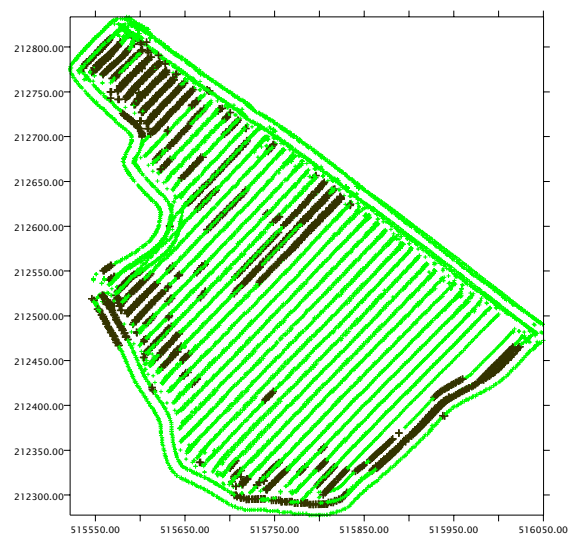
Warren field

–   cleavers

–   November 1999

Broadmead

-    black-grass

-    January 2000

Fig. 3.1 Examples of weed maps of three fields: a) Pike hill b) Warren c) Broadmead

Table 3.1 Fields mapped between 1999 and 2001 from continuous recording using 'Fieldstar' or Hands free systems (% infestation levels in parentheses)

Farm	Field	Recording system	Black-grass	Wild-oats	Cleavers	Common couch	Creeping thistle	Others
Woburn	Warren	'Fieldstar'	ATV Mar 99 (42.1%) Tractor July 99 (28.2%)	ATV Mar 99 (4.6%) Tractor July 99 (59.7%)	ATV Mar 99 (29.4%)			
		Hands free	ATV Nov 99 (67.9%) ATV Jan 00 (25.7%) Tractor July 00 (28.2%) ATV April 01 (85.7%) Foot June 01 (92.2%)	ATV Nov 99 (50.9%) ATV Jan 00 (55.5%) Tractor July 00 (12.1%)	ATV Nov 99 (13.5%) ATV Jan 00 (15.2%) Foot April 00 (5.7%)			
	Broadmead	'Fieldstar'	ATV Mar 99 (56.2%) Combine Aug 99 (54.8%)	Combine Aug 99 (8.8%)				
		Hands free	ATV Nov 99 (55.8%) ATV Jan 00 (59.9%) Tractor June 00 (88.6%) *ATV April 01 (44.1%)*	Tractor June 00 (7.8%)				
Silsoe	Cashmore	'Fieldstar'	*ATV Mar 99 (4.4%)*					

| Farm	Field	Recording system	Black-grass	Wild-oats	Cleavers	Common couch	Creeping thistle	Others
		Hands-free	*ATV Nov 99 (32.4%)* Foot May 00 (42.0%) *Combine July 00 (59.1%)* Combine July 01 (53.6)					
	Banqueting	'Fieldstar'	Combine Aug 99 (12.6%)	Combine Aug 99 (76.3%?) – not good est.				Redshank Aug 99 Combine (19.3%)
	Bypass	'Fieldstar'	Combine Aug 99 (4.5%)	Combine Aug 99 (6.2%)				
	Obelisk E	'Fieldstar'					ATV Mar 99 (8.8%)	
	Obelisk W	'Fieldstar'		ATV Mar 99 (28.7%) Combine Aug 99 (44.3%)			Combine Aug 99 (30.2%)	
	Taylors Piece	'Fieldstar'					Combine Aug 99 (16.7%)	
West end Farm	24 acres	'Fieldstar'					ATV Mar 99 (36.9%)	
	Barley cut	'Fieldstar'	*Tractor July 99 (4.6%)*	*Tractor July 99 (31.4%)*	*ATV Mar 99 (18.2%)*	*Tractor July 99 (17.8%)*		Grasses ATV Mar 99 (58.8%)
	Farmers field	Hands free	Foot Jan 00 (10.6%) Tractor July 00 (3.2%)	Tractor July 00 (6.7%)		Tractor July 00 (53.0%)		Onion couch (7.0%) Ryegrass (16.8%) Tractor July 00
	Pike hill	Hands-free	Tractor Jul 00 (12.6%)	Tractor Jul 00 (5.9%)		Tractor July 00 (40.9%)		Onion couch Tractor July 00 (40.9%)

Farm	Field	Recording system	Black-grass	Wild-oats	Cleavers	Common couch	Creeping thistle	Others
Shuttle-worth	Big field	Hands-free	Combine Sept 00 (43.5%) ATV Jan 01 (38.3%)	Combine Sept 00 (17.8%)				
	Shagsby 4	Hands-free	Combine Aug 00 (25.5%)					
Loddington	Bottom collie	'Fieldstar'				Combine Aug 99 (26.2%)		
Rothamsted	Blackhorse	Hands-free				Tractor June 00 (10.1%)		
	Pastures	Hands-free	ATV Nov 99 (29.7%)					

Fig. 3.2 'Fieldstar' touch-sensitive screen mounted in the 'Spra-Coupe' sprayer

Fig. 3.3 AGCO Weed mapping switch box to work with 'Fieldstar'
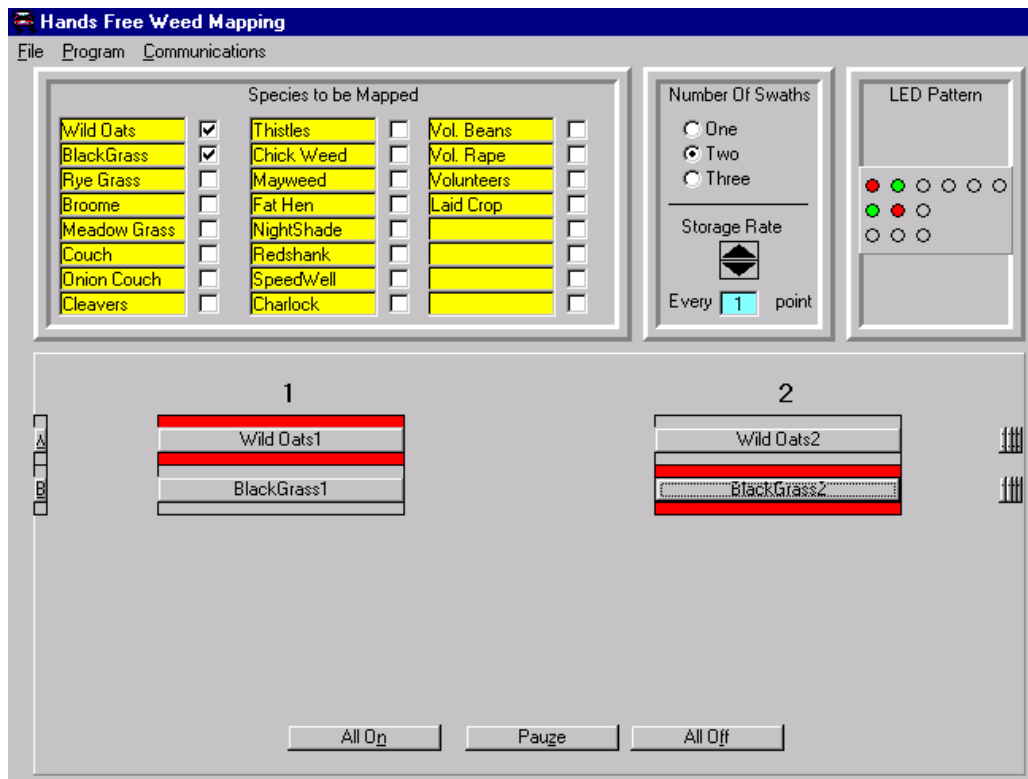
Fig. 3.4 Hands-free weed mapping screen

Fig. 3.5 Hands-free control box

Fig. 3.6 ATV mapping system

Table 3.2 Suitability of different weed species to mapping from a vehicle at different times of year

Species	Winter	Early Spring	Summer	Harvest
Black-grass	?	yes	yes	no
Cleavers	?	yes	yes	?
Wild-oats	?	?	yes	yes
Common couch	no	no	?	yes

? = sometimes possible to map, depending on the sowing date of the crop and the growth stage of the weed

Table 3.2 shows the conclusions on the optimum timing of mapping. It is not possible to be totally dogmatic, as the relative growth stage of the crop and weed, can impact on the visibility of the weed. Those times of the year are marked with a '?'. Mapping in winter can be difficult, especially if the crop is sown late (October or later) and the weeds are small. It is not possible to see 1-2 leaf black-grass from a moving vehicle, unless the density is very high. Similarly it is difficult to distinguish wild-oats in cereals, whilst they are small, but the same species in rape or beans would be easier to see. Even broad-leaved species are difficult to identify from an ATV or tractor when they are at the cotyledon or first true-leaf stages. At early growth stages it is easier to map from the ATV than from a tractor, as the observer is nearer to the ground and hence to the plants being mapped. Once the plants become bigger this is no longer of importance. Black-grass, cleavers and wild-oats are relatively easy to map in spring and summer, especially in June when

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the inflorescences of the grasses emerge and the cleavers have crawled onto the top of the crop. Wild-oats are also easy to map at harvest, as is common couch. However, although we do not advise mapping black-grass at harvest, we did successfully map some fields at this time by identifying the plants from the prominent rachis of the inflorescence, all that remained (all the seeds had abscised).

3.2.3 How long does it take to map a field and hence what are the costs?
It is not easy to quantify the costs of mapping as the number of hectares/hour will depend on a whole range of factors. If the weeds are being mapped from the combine or from a tractor conducting another operation (fertiliser spreading, application of fungicide) the speed of mapping is controlled by the other work. The speed of mapping and its cost will be of most concern when it is done as an independent operation. This is most likely in the winter and spring, when using an ATV.

The frequency and density of the patches will affect speed. A very weedy field will take longer to map than one with a few discrete patches, as the operator can travel faster in areas where weeds are not present. Dense patches are easier to map than light infestations, thus affecting speed of travel. The number of hectares mapped per hour will also depend how far apart each transect (tramline) is. If a field is mapped on 12 m tramlines it will take approximately twice as long to map than if it were to be mapped at 24 m intervals, but the 'quality' of the map will be less good with the latter frequency. Speed of mapping also depends on the evenness of the soil surface. There is limit to how fast it is possible to travel over an uneven field, especially in an ATV. Finally the shape of the field impacts on mapping speed. A field involving many short runs and an irregular shape will take longer to map than a rectangular field with long tramlines.

During the project the time taken to map some of the fields was recorded (Table 3.3). Overall, the mapping was faster from the tractor, but this was partly because it was easier to see the grass weeds in summer. The speed was slower on the small fields, as there was more turning required. Mapping from the ATV was slower, especially when endeavouring to map small grass weeds in wheat. It is noticeable that when mapping thistles the mapping speed was equivalent to that achieved when mapping from the tractor. The very slow speeds were due to an artefact as the prototype systems we were using at the time continued to record elapsed time even when the ATV was stationary. When mapping grasses in cereals from an ATV it is realistic to suggest that speeds would be approximately 3 ha/h and from a tractor around 4 ha/h. Assuming an average farm worker wage of £6/h, mapping from an ATV would cost approximately £2.00/ha and from a tractor £1.50/ha.

Table 3.3 Speed of mapping with tractor and ATV

Mapping vehicle	Field	Recording system	Crop/weed mapped	Month of mapping	Area mapped (ha)	Speed (ha/h)
ATV (6 m intervals)	Cashmore	Hands-free	w.wheat/black-grass	November	4	4.3
	Warren	Hands-free	w.wheat/black-grass + w.oats + cleavers	November	1	2.9
	Warren	'Fieldstar'	w.wheat/black-grass + w.oats + cleavers	April	1	2.7
	Warren	'Fieldstar'	w.wheat/black-grass + w.oats + cleavers	March	1	*1.3*[+]
	Broadmead	Hands-free	w.wheat /black-grass.	November	1	1.8
	Broadmead	'Fieldstar'	w.wheat /black-grass.	March	0.8	*1.3*[+]
	Broadmead	'Fieldstar'	w.wheat /black-grass.	April	0.8	1.9
	Pastures	Hands-free	w.wheat/black-grass	November	6	4.3
	Barley cut	'Fieldstar'	w.wheat/grass weeds	March	13	3.8
	24 acres	'Fieldstar'	Set aside / thistles + ryegrass	March	12.8	5.3
	Obelisk E	'Fieldstar'	Stubble/thistles + cleavers	March	6.4	4.2
	Obelisk W	'Fieldstar'	w.wheat / w.oats	March	4.0	1.9
	Grand mean					3.3
Tractor (12 m tramlines)	Warren	Hands-free	w.wheat/black-grass + w.oats	July	2	4.0
	Warren	'Fieldstar'	w.wheat/black-grass + w.oats	July	1	2.9
	Broadmead	Hands-free	W.wheat/black-grass + w.oats	July	6	5.1
	Broadmead	'Fieldstar'	W.wheat/black-grass + w.oats	July	0.8	3.0
	Pike hill	Hands-free	W.wheat/grass weeds	July	10	4.6
	Barley cut	'Fieldstar'	W.wheat/grass weeds	July	13	6.2
	Grand mean					4.3

+ data not included in grand mean as speed affected by periods when the ATV was stationary

3.2.4 How patchy are weeds in fields?

The potential for reductions in herbicide use, with the patch spraying of weeds, depends on the percentage of the field that is infested. It is generally accepted that the five weeds targeted for patch treatment are known to be spatially aggregated. This has been clearly demonstrated by Wilson & Brain (1991) for black-grass and by Rew *et al.*, (1996) for common couch, for example. However, only limited data exists on the actual level of infestation. The % infestation drives the economics of this technology, so it is important to have an estimation of the % of fields infested. The previous project (Lutman *et al.,* 1998) estimated that an average

of 51% of the area of 13 black-grass fields were infested, 18% for wild-oats (four fields) and 45% for common couch (six fields). More data were needed to begin to give a reliable estimation of the reduction in herbicide use that could be expected. This project has again focussed on the most significant annual grass weed, black-grass, but has also collected some data for the others. The weed distribution maps (Table 4.1) were used to estimate % infestations. The data were fed into the 'Surfer' surface mapping software package (Golden Software Inc, Colorado, USA) and 'nearest neighbour' analysis was used to estimate the proportion of the field infested with weeds. In the 11 sites with black-grass the mean level of infestation was 28% and the range was between 5 and 85%, much as for the earlier data set, though the mean was lower. The eight sites with wild-oats generated a mean of 20%, about the same as previously. The means for common couch and for creeping thistle were 30% and 23%, respectively. The two weeds with most sites in the two 'surveys' are black-grass and wild-oats. It is interesting to note that in general the % infestation levels for wild-oats were lower than for black-grass, suggesting that farmers are finding the former less difficult to manage than the latter. This would agree with general weed control perceptions, that indeed it is easier to control wild-oats then black-grass. Appreciable savings seem possible for both these weeds as overall, including data from both projects, only 40% of field areas are infested with black-grass and 17% with wild-oats.

Other research data also shows that weeds are aggregated. For example, Johnson *et al.* (1995) found that in a survey of 12 maize fields that 30% of the field areas were free of broad-leaved weeds and 70% were free of grass weeds. Similarly Gerhards *et al.* (1997, 1999) found that herbicide treatment in two winter wheat fields containing cleavers, black-grass and other broad-leaved weeds were only warranted on 55 and 58% of the area and in a third field only 54% required treatment. So, clearly, weed treatment over the whole field is not required and spatially selective applications do have potential to reduce herbicide use, with consequent economic and environmental benefits.

*3.2.5 How representative are the maps of the 'true' weed distribution?*
The utility of weed maps depend on their accuracy. A weed map can be produced by continuous recording of, for example weed presence/absence, from an ATV. This map is only of use if it reliably reflects the actual distribution of the weeds. The observer may fail to identify important areas of infestation, or the interpolation necessary when mapping observations do not cover the whole field, may not be appropriate. Both situations may result in inaccurate maps. Studies in Denmark (Christensen & Heisel, 1998) indicated that continuous mapping could produce simple maps identifying the areas of high and low infestation, when compared with an intensive grid map (24 x 24 m). Similarly, Barroso *et al.* (*2*001) showed that continuous mapping of wild-oat panicles from a combine harvester, produced weed distribution data similar to that achieved by recording seed rain post-harvest on a 6 x 12 m grid.

The work in this project has tried to establish the accuracy of the visual maps. One hectare areas of the fields identified as Warren and Broadmead were subjected to detailed weed mapping (Table 3.1). These two were marked out on a 5 m x 5 m grid. A 1 m² quadrat was positioned at each grid intersection and numbers of the target weeds (black-grass and wild-oats) occurring within the quadrat were counted several times a year for three years. Continuous presence/absence weed maps were also created in winter 1999 using the ATV. The ATV was driven at 6 m intervals. The areas marked out for grid sampling were geo-referenced, allowing a comparison between the methods to be made. Areas mapped using grid sampling were compared with the same area mapped by continuous sampling methods. The presence/absence of the weed mapped using the two methods was compared using simple correlations, splitting the field into cells (Warren field had 400 cells) and establishing whether the information in each cell was the same or different.

Generally, the maps created from a vehicle were similar to the more detailed maps created using the quadrat grid method. Fig. 3.7 shows a 1 ha area of Warren field mapped for black-grass. At a quadrat threshold of 5 plants/m² there is a correlation of only $r = 0.60$ between the quadrat grid map (3.7a) and the ATV map (3.7c). If the threshold is increased to 20 plants/m² (3.7b), the correlation between the two mapping methods increases to $r = 0.82$. From this it can be concluded that black-grass seedlings can be detected using continuous sampling methods at a threshold of 20 plants/m². At lower plant densities there is a failure to record all plants. The same field was also mapped for wild-oat seedlings (Fig. 3.8). The larger seedlings of wild-oats could be seen at a lower density (2 plants/m²) (correlation between quadrat and ATV map 0.74).

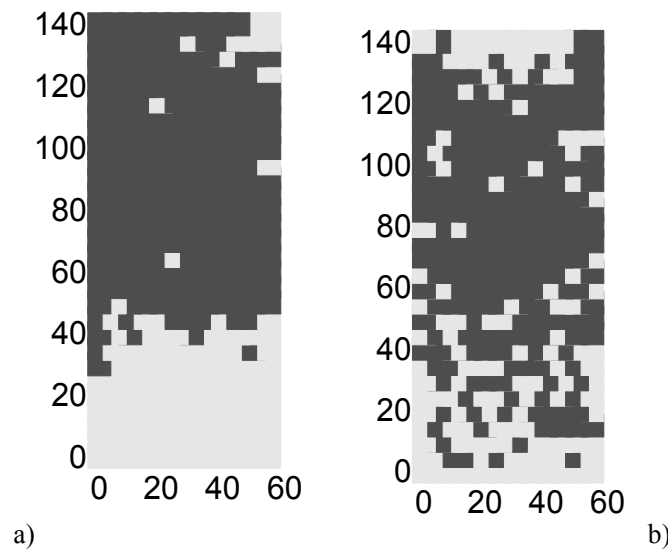a)   b)   c)
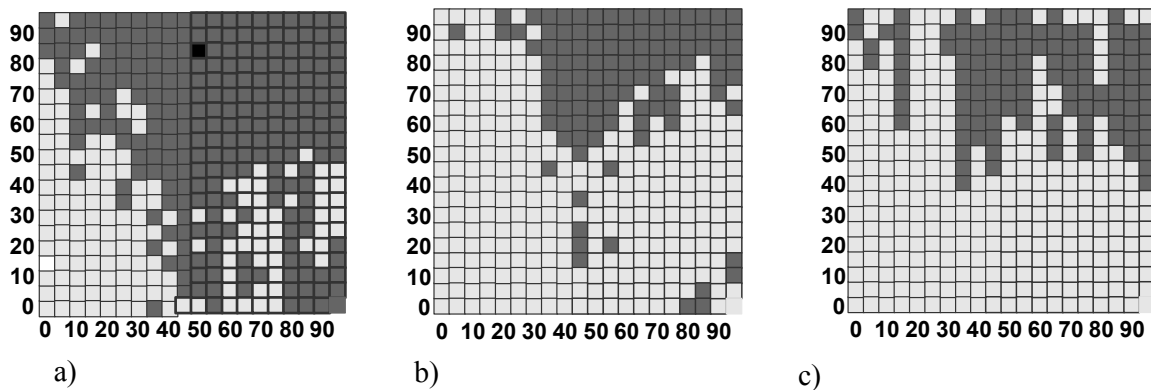
Fig. 3.7   Comparison of black-grass distribution on a 1 ha area mapped with a quadrat on a 5 m x 5 m grid a) threshold 5 plants/m² b) threshold 20 plants/m² and c) mapped using continuous sampling method from an ATV. (black areas = infested)
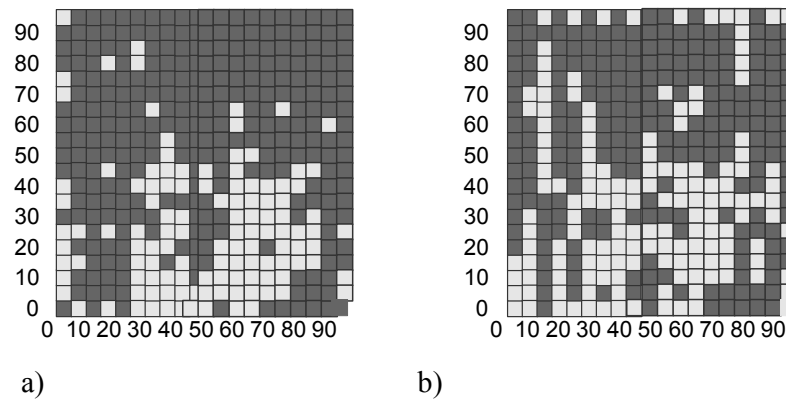
Fig. 3.8 Comparison of wild-oats distribution in Warren field mapped with a quadrat on (a) 5 m x 5 m grid - threshold 2 plants/m^2 (b) using continuous sampling method from an ATV (black areas = infested)

Care must be taken when mapping weeds, particularly grass weeds from a vehicle. Figure 3.9 shows two maps of field where the quadrat map (a) appears to be showing considerable less black-grass than the corresponding ATV map (b). This is because the field also contained a high density of annual meadow-grass seedlings, which were not distinguishable from black-grass seedlings when travelling across the area on the ATV.

We believe that continuous recording of presence/absence of weeds can provide an acceptable basis for the spatially selective application of herbicides.
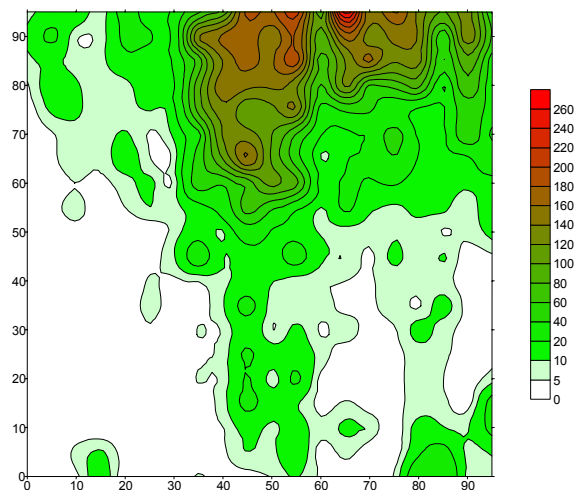

Fig. 3.9 Comparison of black-grass distribution mapped with (a) quadrat on a 5 m x 5 m grid - threshold 5 plants/m^2 (b) using continuous sampling method from an ATV
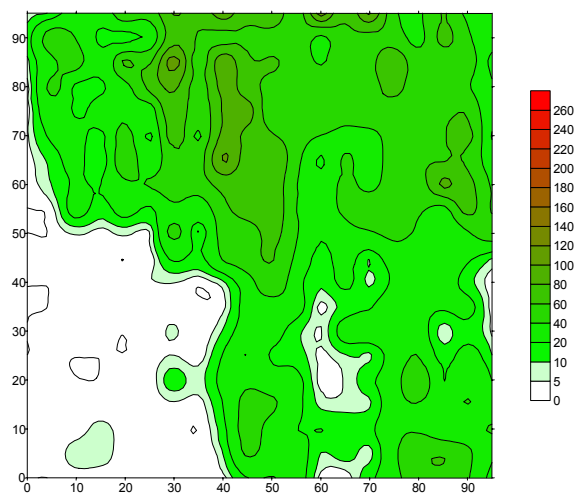
February 1999
Warren field
black-grass
quadrats 5m grid
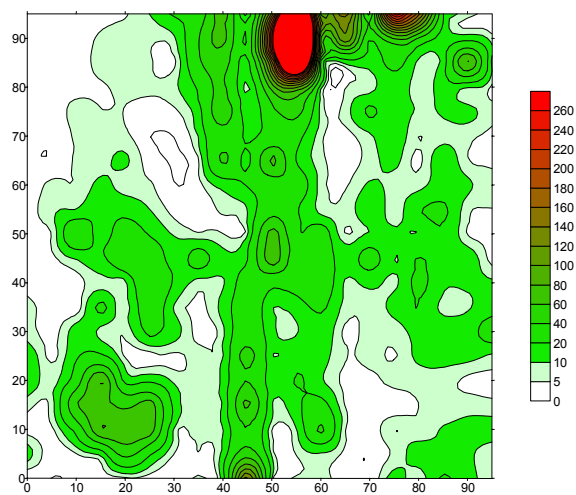
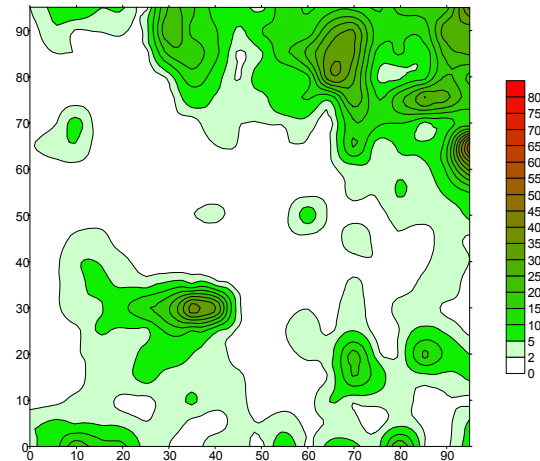December 1999
Warren field
black-grass
quadrats 5m grid

April 2001
Warren field
black-grass
quadrats 5m grid

Fig. 3.10   Changes in the distribution of black-grass in a 1 hectare area of Warren field in seasons 1998/1999, 1999/2000 and 2000/2001

February 1999
Warren field
cleavers
quadrats 5m grid

December 1999
Warren field
cleavers
quadrats 5m grid
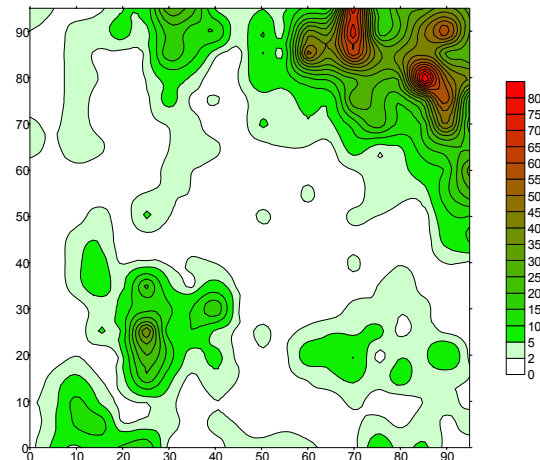
April 2001
Warren field

cleavers
quadrats 5m grid

Fig. 3.11 Changes in the distribution of cleavers in a 1 hectare area of Warren field in seasons 1998/1999, 1999/2000 and 2000/2001

February 1999
Warren field
wild-oats
quadrats 5m grid

December 1999
Warren field
wild-oats
quadrats 5m grid

April 2001
Warren field
wild-oats
quadrats 5m grid

Fig. 3.12   Changes in the distribution of wild-oats in a 1 hectare area of Warren field in seasons 1998/1999, 1999/2000 and 2000/2001
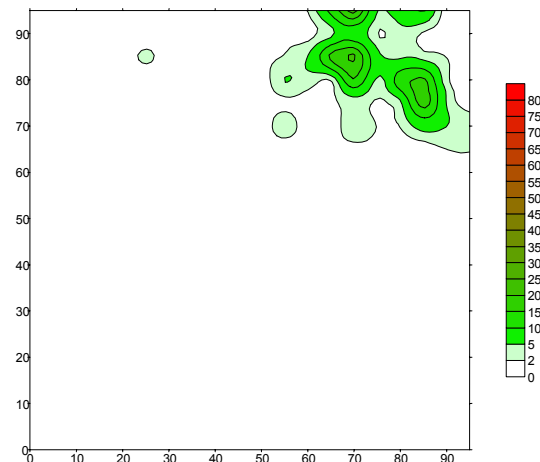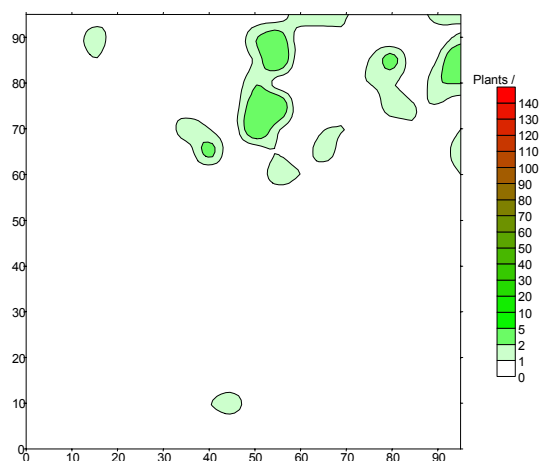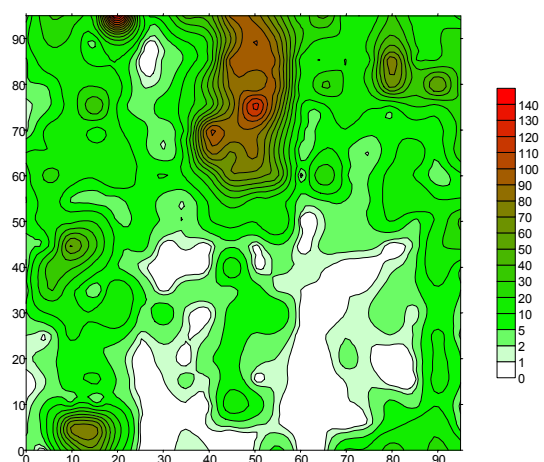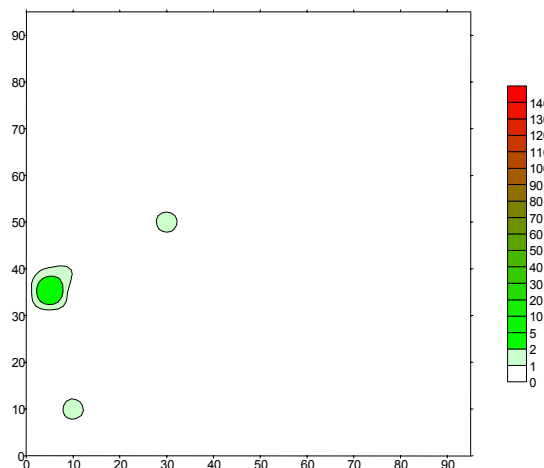
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3.2.6 How does the distribution of weeds change with time?

The need to re-map depends on how much the weed patches change over time, especially how fast they can expand. It is certainly true that weed levels in one year will not be identical to those in the next, as the success in establishment varies from year to year. This was clearly shown in the surveys on black-grass done by Wilson in the 1980s (Wilson & Brain 1991), where infestation levels varied from year to year. Although the positions of the weedy areas tended to remain constant the sizes of the patches 'waxed and waned'. The critical points that have to be established for the target weed species are: do the patches move and do the patches expand? The former would require frequent re-mapping but the latter could be accommodated by using appropriate buffers to account for patch expansion. The basic biology of seed dispersal and patch movement is summarised in Chapter 2 on weed biology. However, some data on patch movement has been collected from the quadrat counts done between 1999 and 2001 on Warren, Broadmead and Cashmore fields, using the 5 m sampling grid. In these fields weeds were counted within 1 m^2 quadrats placed on a 5 m grid over defined sections of these fields.

Warren field

Wild-oats, black-grass and cleavers were recorded in the quadrats on Warren field in the seasons 1998/1999, 1999/2000 and 2000/2001.

Black-grass - As can be seen in Fig. 3.10 the black-grass infested most of the surveyed area and was most dense in the top centre of the one hectare area. This was apparent in all three years. Black-grass was most abundant in December 1999, and in general the more dense areas were as recorded the previous February, although there were few plants in the lower left corner of the map in the December count. The weed was more widespread in April 2001, probably because the poor control achieved in 2000, despite applications of several herbicides, allowed the existing weed infested area to expand. The % infested area recorded from the presence/absence maps increased from 42% in 1999 to 86% in 2001 (Table 3.1). Evidence from other research in this field in 2000 confirmed the presence of herbicide resistant black-grass. However, the overall densities were lower in 2001, probably reflecting the extremely wet autumn that inhibited weed establishment.

Cleavers - The cleavers were more restricted in their distribution, occurring mainly in the top right corner (Fig. 3.11). The maps in February 1999 and December 1999 were very similar, but in spring 2001, after the very wet winter, densities were lower and the patch in the bottom left had apparently gone. This probably reflects the waxing and waning of patches in good and poor germination years, as the bottom left corner was not the core of the infested area in this test hectare.

Wild-oats - The wild-oats were more erratic as few were present in February 1999 and April 2001, whilst an appreciable infestation was present in December 1999 (Fig. 3.12). Later presence/absence maps generated from a tractor in July 1999 indicated that there was a greater degree of infestation, especially in the bottom left of the map at that time, suggesting that appreciable emergence of the wild-oats had occurred after the February map had been recorded. The centre of the infestation in 1998/1999 season in the top centre of the map re-appeared in the 1999/2000 but not in the last season. The very wet winter of 2000/2001 seems to have restricted wild-oat emergence.

Broadmead

The predominant weed in this field was black-grass and again, as in Warren field, the presence of herbicide resistance was confirmed in 2000. Some wild-oats were also present but only occurred at low levels and were only recorded in season 1999/2000 (<10% area infested Table 3.1).

Black-grass - Black-grass was present on the majority of the surveyed area. A high density area was recorded in the first season in the middle of the mapped area, with none present at the bottom of the field (Fig. 3.13). Following herbicide treatment in April which failed to control all the black-grass, a new high infestation area was recorded in the top left of the assessment area in summer 1999. This was closest to the recorded area of herbicide resistant types. This new area was confirmed as the highest density area in December 1999. Poor control in 2000 meant that the black-grass area had expanded in 2000/2001, although because of the wet conditions in the autumn, the densities of black-grass were lower. The main application of herbicides did not occur until after the April assessment. Because of the presence of herbicide resistant plants and the late application of the herbicides, the infested area increased in size over the three seasons.

Cashmore

This field was partially infested the black-grass. There was a clear division in the soil type, the upper part of the field being lighter soil than the lower. The black-grass was mainly present in the lower part of the field (Fig. 3.14).

Black-grass - The main infested area remained at the bottom of the field, although low densities were present elsewhere in January 1999 and February 2000, prior to herbicide treatments. This was particularly apparent in February 2000. Little remained in April 1999 after application of the herbicide. This map does highlight that herbicide treatment makes the patches contract towards the densest areas, as even with high activity from the herbicide not all plants will be killed where densities are particularly high.

Broadmead Quadrats 1 m^2 on 5 m grid

Black-grass

December 1998
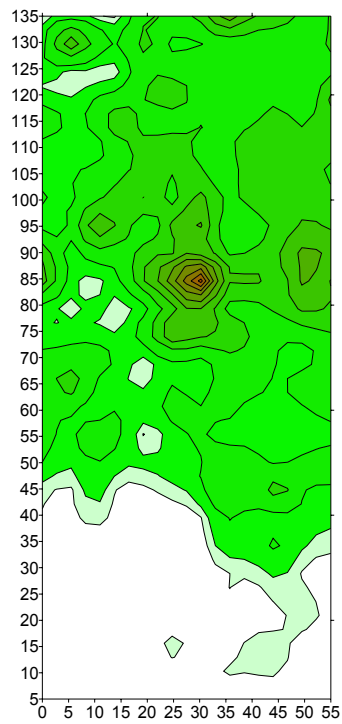
June 1999
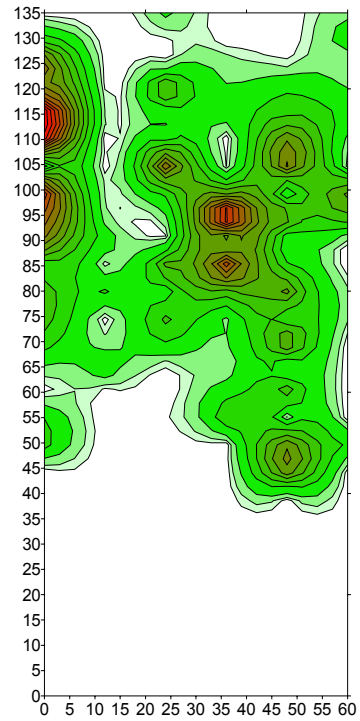
December 1999
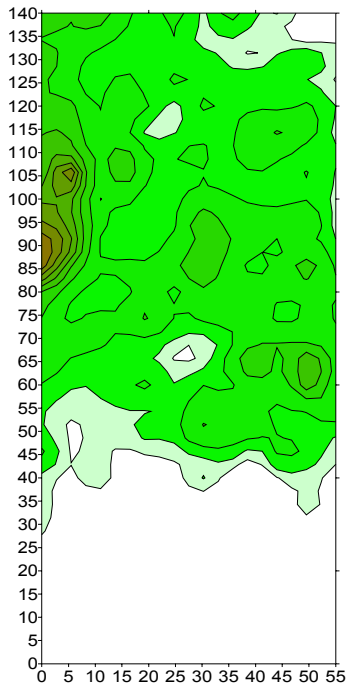
April 2001
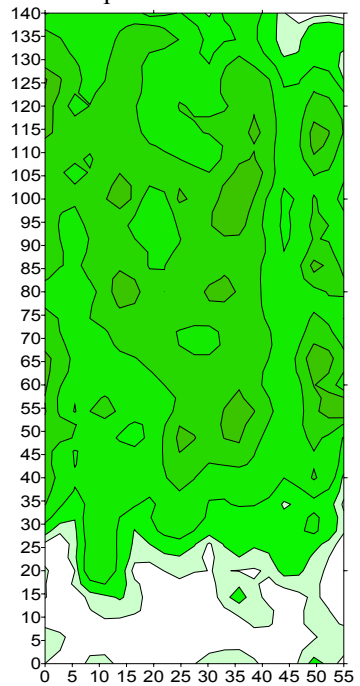
Fig. 3.13 Changes in the distribution of black-grass in an area of Broadmead field in seasons 1998/1999, 1999/2000 and 2000/2001

Cashmore Quadrats 1 m^2 on 6 m grid
Black-grass

January 1999
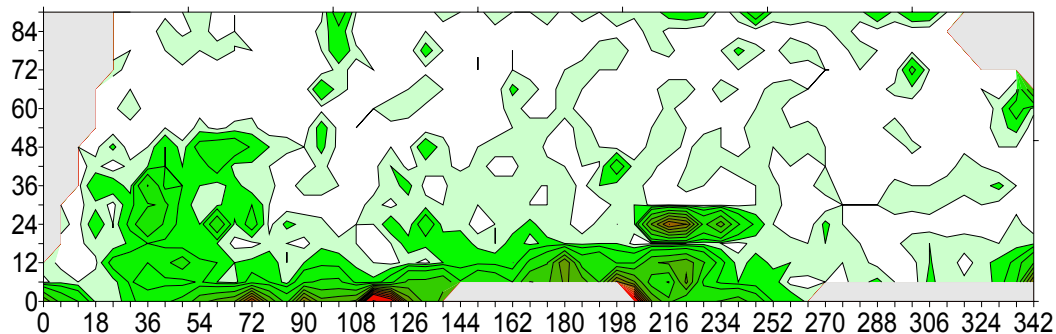
April 1999
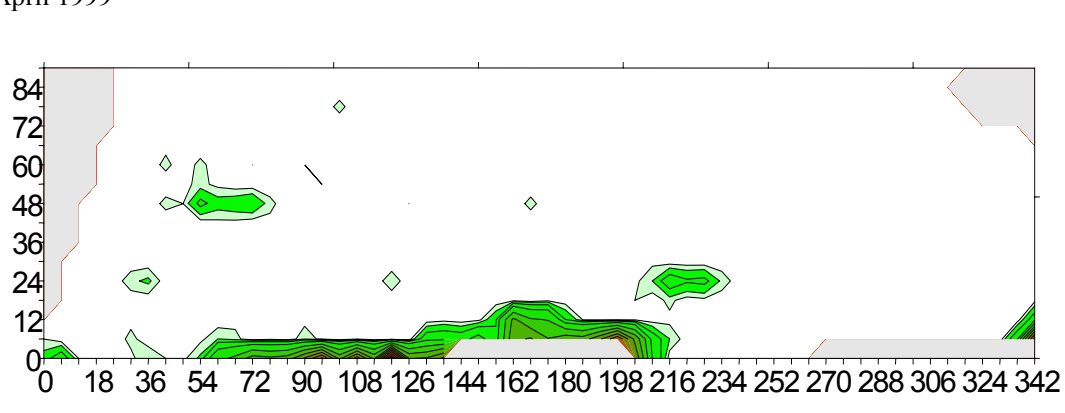
February 2000
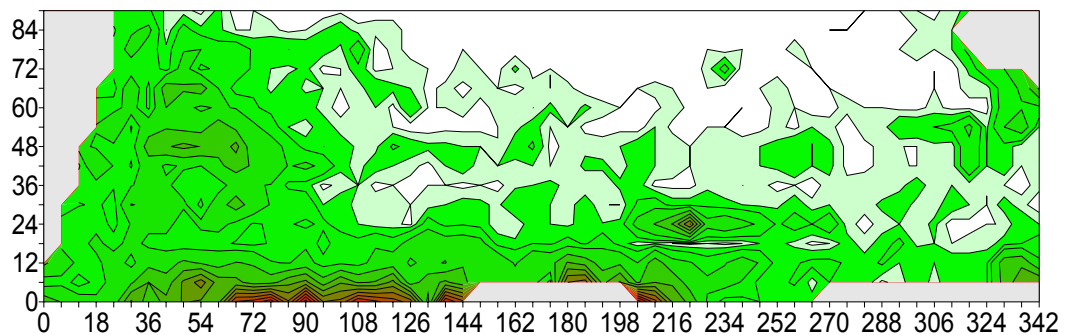
Fig. 3.14   Changes in the distribution of black-grass in Cashmore field in seasons 1998/1999 and 1999/2000

Up to now it has not been possible to do further detailed mathematical analysis of these maps to investigate their relationships. However, simple correlation analyses on the Warren data showed correlations of 0.42 - 0.59 between the February 1999 and December 1999 maps of all three species and between 0.54 and 0.62 for the black-grass and cleavers for December 1999 and April 2001. The correlation between the wild-oat maps, for this period is much poorer, as can be seen from Fig. 3.11. These maps would benefit from much more detailed spatial analysis as was done in the MSc project of Harkness in the previous project (Harkness, 1996). Resources have not permitted this in depth analysis.

It is clear that the patches wax and wane with the seasons, depending on the suitability of the season for weed germination. This was also shown by Wilson & Brain, 1991. The data tends to suggest that the most reliable maps are generated in years when emergence is greatest. Thus, it would be prudent when starting to map weeds with the intention of using the map in one year to control the herbicide application in subsequent ones, to map fields for several years. This is not a problem if the map is to be used to control the sprayer in the current crop. Once a good map is established there is no need to map every year and the frequency of re-mapping depends on the stability of the patches (see Section 2).

3.2.7 How easy is it to convert the treatment map into an application map
This part of the process of controlling the sprayer is covered in more detail in Chapter 4 (below). Appropriate software has been written to process the weed map, so that it can be used to control the sprayer (application map).

3.2.8 Conclusions of work on visual mapping
The work has shown that visual mapping from an ATV, tractor or combine harvester is possible. Different weeds are easier/harder to maps at different times of the year. It is difficult to map more than two species at a time, though more are possible, provided the operator has good 'concentration'. Similarly, although it is possible to map more than one level of infestation, it is easier to simply map presence and absence. This still leads to appreciable reductions in herbicide use (see Section 6). The use of the original touch-sensitive 'Fieldstar' screen to map weeds was not satisfactory but this has been overcome by using the voice recognition system and more recently by the development of toggle switches by AGCO. When mapping from an ATV, mapping is the only operation possible and so has to be fully costed into the cost-benefit analyses. However, we believe it is possible to map from a tractor or combine whilst carrying out other operations, thus discounting the cost. We had limited experience of this and so further testing is needed. The weed maps correlated acceptably with the quadrat maps on Warren and Broadmead, but the comparisons showed for example that when small it was not easy to map low densities of black-grass. Therefore, for such conditions the philosophy of spraying high doses on patches and low doses on the rest of the field, is preferred to a spray/no spray decision. The precision of the map improves the closer the mapping transects

are. Thus, with the ATV it was possible to map between the tramlines, whilst later in the season the operation is restricted to tramlines which can be 12-30 m apart, or even more with some current machinery. In compensation, the observer can scan a wider swathe from a tractor than is possible from an ATV, where mapping generally encompasses only the area immediately adjacent to the ATV. The wider the transects the less accurate is the map and the greater the degree of interpolation needed to create the map. Transects based on 12 m tramlines are clearly acceptable but, depending on the nature of the patch distribution, maps based 24 m tramline transects may not optimise herbicide reductions. The detail of the map needs to be linked to the spatial application potential of the sprayer. A sprayer able to patch spray from different sections of the boom needs a more detailed map to optimise herbicide use, than a sprayer that has an unsegmented boom.

Overall, wild-oats infested only 20% of the area of the mapped fields and black-grass 28%. Therefore the potential to reduce herbicide use is appreciable. These may be an underestimate of national levels of infestation, as the project tended to target fields with clearly patchy infestations and avoided those with higher more uniform distributions. This aspect of the project is reviewed again in Chapter 6 – cost/benefit analysis.

Weed maps appear to reflect the total distribution of the weeds in the field most accurately in years that encourage high germination from the weeds. So, unknown fields should be mapped for 2-3 years initially to obtain a sound map of the overall distribution. Thereafter weeds need to mapped less often, depending on the intrinsic stability of the patches, which is species dependent (Chapter 2).

3.3 Semi-automated weed mapping

3.3.1 Basic concept

It was recognised that manual weed detection, particularly when part of an initial field survey, represents a substantial cost (financial and time) and is a major factor influencing the commercial uptake of patch spraying approaches. While fully automated weed patch detection is regarded as the most desirable situation, work as part of this project has shown that for grass weeds in cereal crops, this is not likely to be technically feasible for at least the next five years – see Section 3.4 below. One possible approach to aiding manual weed patch detection is to measure some form of vegetation index so as to identify areas of a field where such indices may differ. Targeted manual surveying and identification can then be directed to such areas of a field so that the reasons for anomalies in the vegetative canopy can be identified and, where these anomalies are due to the presence of weeds, then these can be noted together with the weed species present. An advantage of this approach is that where vegetation differences are due to the presence of weed patches, then a map of a vegetation index can be used to define the boundaries of the patch without the need for further detailed surveying.

Methods of measuring crop canopy characteristics based on spectral reflectance techniques have been developed as part of research studies and for commercial applications. Such developments have particularly aimed at establishing a basis for the application of nitrogen fertilisers to winter cereal crops but have also related to the application of fungicides and growth regulators, the monitoring of soil conditions and the detection of weed patches. A review of the uses of spectral reflectance for cereal crop protection and nutrition (Scotford & Miller, 2002) indicated that such techniques had been used for weed patch detection in the following ways:

(i)   in nominally bare soil situations where the presence of green leaf against the soil background was detected (e.g. Felton, 1995; Biller, 1998);

(ii)   by using a vegetation index to show the presence of weed patches in a crop (e.g. Rew *et al*., (1999); Lamb *et al*., (1999)) – results from such studies indicating success only at relatively high weed plant densities of circa 30 plants/m^2;

(iii)   by using a spectral reflectance characteristics to differentiate between plant species and hence detect weed from crop plants (e.g. Vrindts *et al*., (1999)) – this approach has yet to be developed such that it can be applied in realistic field conditions – see also Section 3.4 of this report.

Work reported by Godwin *et al.* (2002) measuring spectral reflectance characteristics as an aid to crop management also noted that differences in a vegetation index due to the presence of weeds could be established from aerial surveys supported by a ground survey.

The approach taken in this project work was not to solely rely on the measurement of a vegetation index to detect weed patches but to use such measurements as the basis of a targeted field manual survey and to aid the definition of weed patch boundaries.

3.3.2 Experimental approach

To examine the potential for using spectral reflectance measurements and a vegetation index as an aid to the manual detection of weed patch positions, a series of field experiments was set up as summarised in Table 3.4. It was decided to establish weed patches at the time of drilling rather than rely on natural infestations because of improved reliability with this approach. Simulated "weed" seed was spread onto patch areas at the time of drilling using either an oscillating spout type fertiliser spread or by hand.

Table 3.4 Summary of experiments conducted measuring a Normalised Difference Vegetation Index (NDVI) as a means of detecting weed patch positions

Field name	Crop	Weed		Densities, plants/m^2	NDVI measurements	Manual mapping	Comments
		Species	Date drilled				
Sawyers field Rothamsted	Rape	Barley	13/8	50 and 200	12/9 and 27/9	25/9	
Meadow field Rothamsted	Wheat	Oats	14/9	20, 80 and 320	19/10 and 7/11	21/11	
Summerdell field Rothamsted	Wheat	Rape	14/9	20, 40 and 120	19/10 and 19/11	21/11	High natural background weed population
Clover hill Silsoe	Wheat	Rape		50	NR	NR	Established for visual assessment and demonstration only

depending on patch size and weed plant density within the patches. Applied "weed" seed rates were calculated assuming 80% establishment.

For each field area in which simulated "weed" patches had been established, maps of a Normalised Difference Vegetation Index (NDVI) were generated using an array of six two-band radiometers mounted on a boom following procedures described by Stafford & Bolam (1998). It was originally intended that measurements would be made on up to four occasions in each field but in practice, weather conditions limited the potential for measurements to twice in each field (see Table 3.4). On each measurement occasion, the radiometers were mounted equally spaced along a sprayer boom (24 m wide for the measurements made on 12/9 and 12 m wide for all other measurements) and with a GPS unit also mounted on the tractor/sprayer combination. A compensating radiometer fitted with a cosine correcting filter was fitted on the boom and directed upwards so as to provide data for correcting for variations in ambient light conditions. All radiometers were connected to a signal conditioning unit mounted in the tractor cab with the outputs from the sensors and GPS position monitored at 1 Hz using a laptop computer also mounted in the tractor cab. Details of the sensors and the main signal processing methods were as reported by Stafford & Bolam. The analysis of the data included a routine that separated the values from each sensor and adjusted the recorded vehicle position to account for the distribution of sensors along the boom. In this way a detailed map of NDVI for the test fields was obtained with a spatial resolution of less than 5 m.

In addition to the measurements of NDVI, established simulated "weed" patch positions were also recorded manually from an ATV using the techniques described in Section 3.2 of this report. This enabled results of this approach to be compared with the measurements of a vegetation index and both to be referenced against the positions of the simulated "weed" patch positions as established.

3.3.3 Results of measurements of vegetative indices as indicators of weed patch positions
The map in Fig. 3.15 shows the established simulated "weed" patch positions in Sawyers Field at Rothamsted where barley was used as the simulated weed in a crop of oilseed rape. Also shown on this map are the manually mapped "weed" patch positions logged from the ATV. The agreement between these two approaches is very good. The measured NDVI values recorded on two separate occasions are shown in Fig. 3.16 together with an overlay of the established patch positions onto the NDVI map recorded at the earlier timing. The results generally showed a good correlation between areas of higher vegetative index and the positions of weed patches particularly at the earlier measurement date (Fig. 3.16 (a) and (c)). The correlation was less pronounced along the northern edge of the field and a further inspection showed that rape was very thick with some arable drilling in this part of the field and the low density barley patch was poorly established. Field walking after the second vegetative index measurements showed that the barley
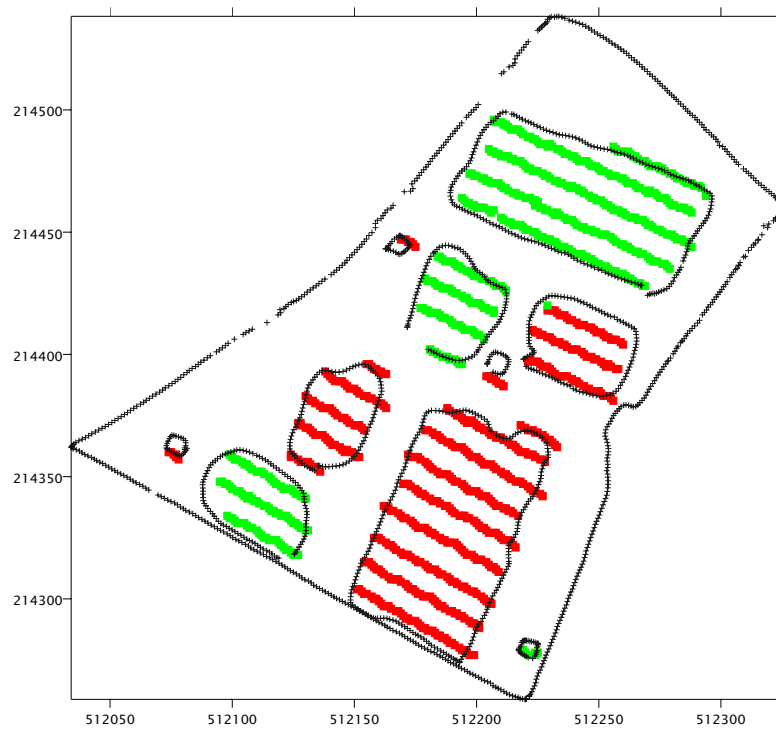
Fig. 3.15 A map of Sawyers Field showing established simulated weed patch boundaries (crosses) and the results of a manual survey recording high (red) and low (green) weed densities within the patch

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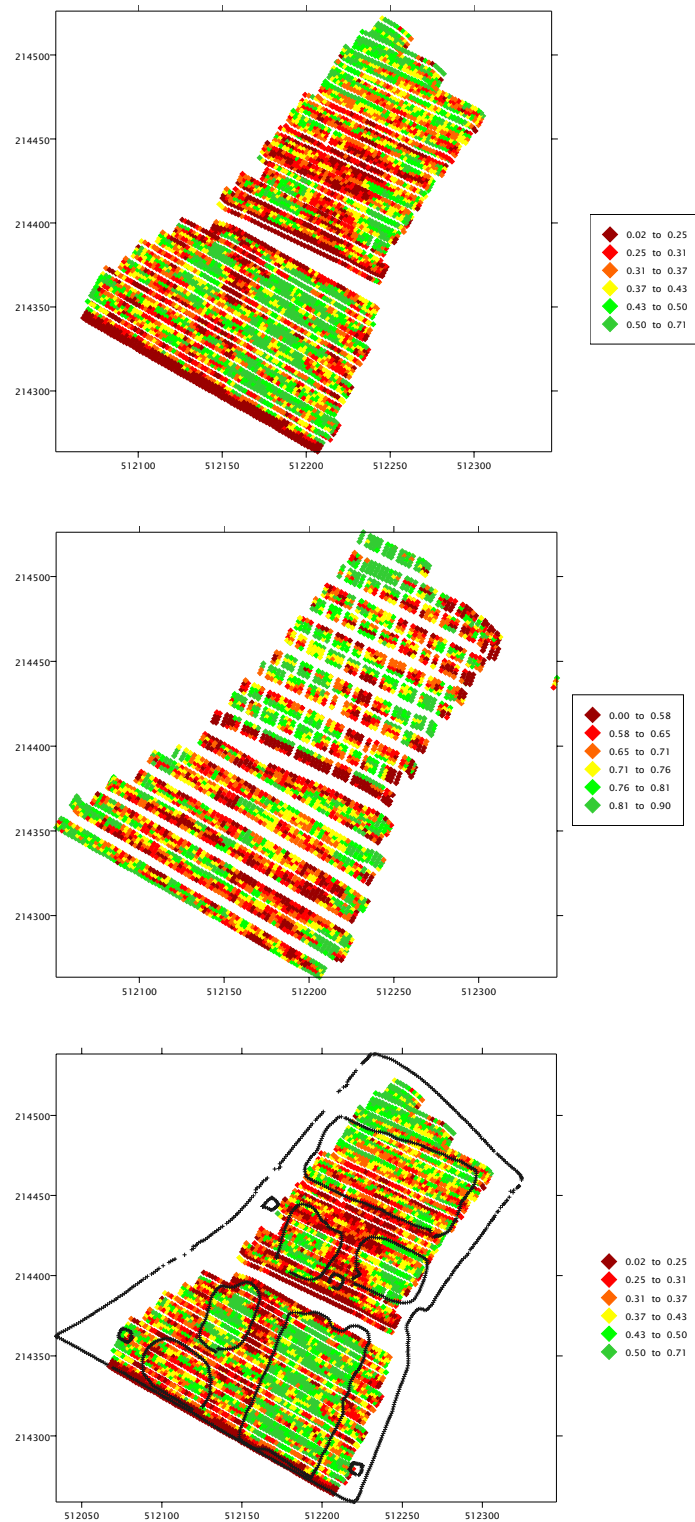
Fig. 3.16   Maps of the measured Normalised Difference Vegetation Index (NDVI) generated for Sawyers Field at Rothamsted

    (a) Top - Map generated on 12/09/2001
    (b) Middle - Map generated on 27/09/2001
    (c) Bottom - Map generated on 12/09/2001 with positions of established patches overlaid

plants were a visibly lighter green colour and this would give a lower NDVI value in comparison with that from the rape leaves. The establishment of the rape was also noticeably patchy by the second assessment date. The white areas across the map in Fig. 3.16 (b) are due to a failure in the operation of one of the spectrophotometric sensors. Results have therefore been omitted from the maps.

Fig. 3.17 shows the established patches of oats in a crop of wheat (Fig. 3.17 (a)) with the results from a manual mapping from an ATV (Fig. 3.17 (b)). The square area in the centre of the southern area of the field contained a separate trial and was not included in the study reported here. The agreement between established and mapped weed positions shows some correlation but has probably been influenced by:

- the difficulty of visually distinguishing grass weeds at an early stage of growth; and
- the presence of some natural wild-oat plants in the field.

The results from the radiometry measurements of NDVI in this field show relatively good agreement between the results obtained on the two measurement dates (Fig. 3.18). There is some correlation with the simulated "weed" patch positions shown in Fig. 3.17 and field walking subsequent to making measurements of vegetation index did show that there were oats in the areas identified as having a high vegetation index. However, it is difficult to use the radiometry results for NDVI to aid the definition of patch positions or the edges of patch boundaries in this field condition. There was some evidence of slug damage in this field that also influenced the values of NDVI used to generate the map.

The field used to examine the detection of rape as simulated "weed" patches in a field of wheat (Summerdells Field) had high background populations of other weeds including chickweed, field speedwell and cranesbill (*Geranium* spp.) and this substantially influenced the results obtained. The manually detected simulated and natural weed patch positions did not show a good correlation with the maps of NDVI (Fig. 3.19) and it is difficult to relate any of the mapped weed patch positions to those that were established in this field. There was again good agreement between the measurements made of the distribution of vegetative index across the field on the two occasions, but the level of natural weed in the field, and the poor vigour of the rape, was such as to mask any linkage between measured vegetation index and the established weed patch positions.

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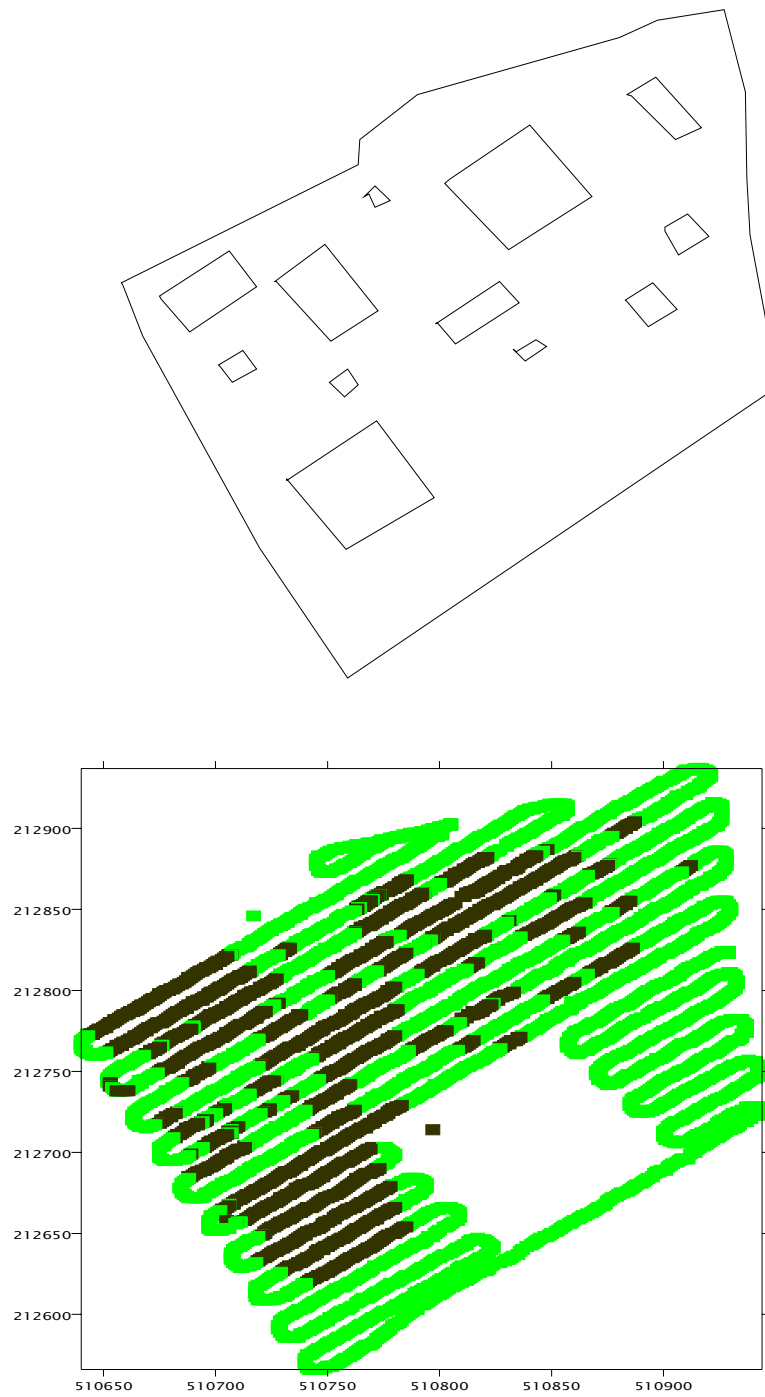
Fig. 3.17   Simulated oat "weed" patches in a crop of wheat in Meadow Field, Rothamsted.

(a) Top – the plan for establishment

(b) Bottom - results from manual mapping from an ATV

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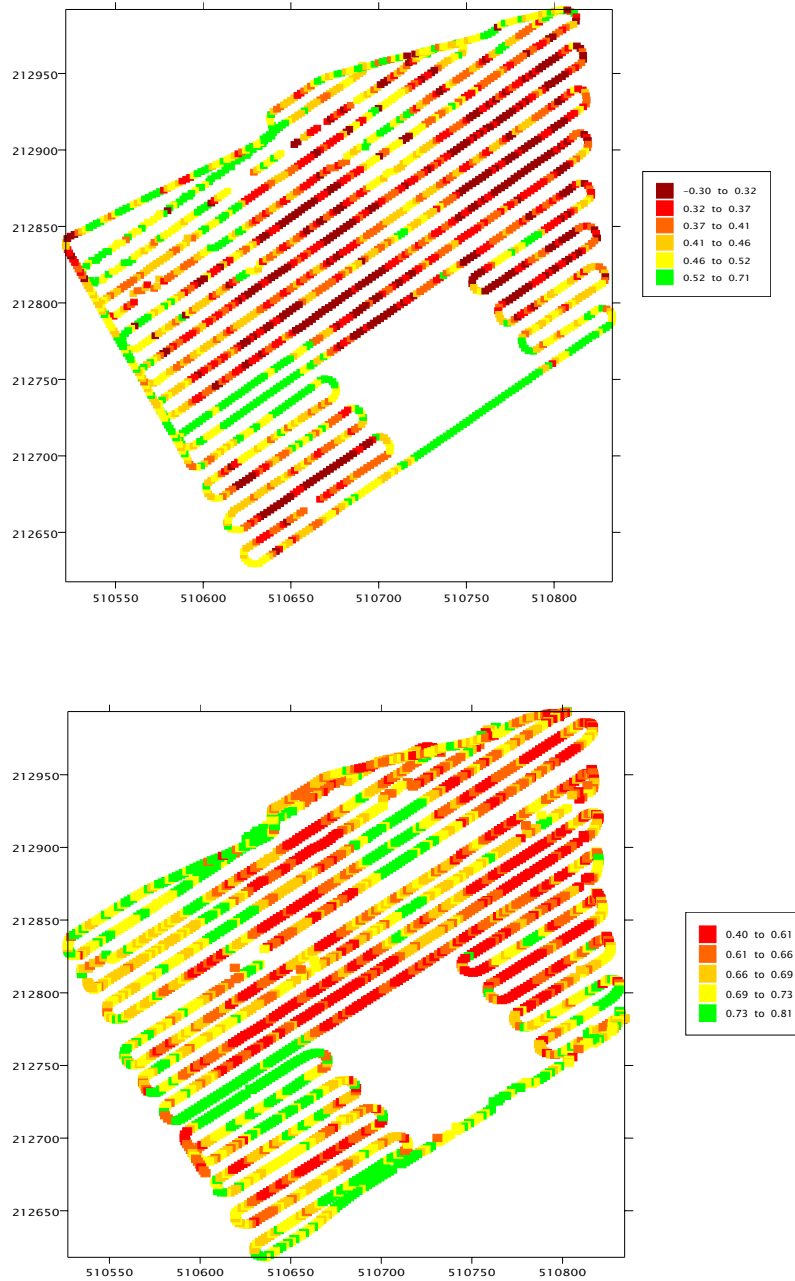
Fig. 3.18 Maps of the measured Normalised Difference Vegetation Index (NDVI) generated for Meadow Field at Rothamsted.

(a) Top – as measured on 19/10/2001
(b) Bottom – as measured on 07/11/2001
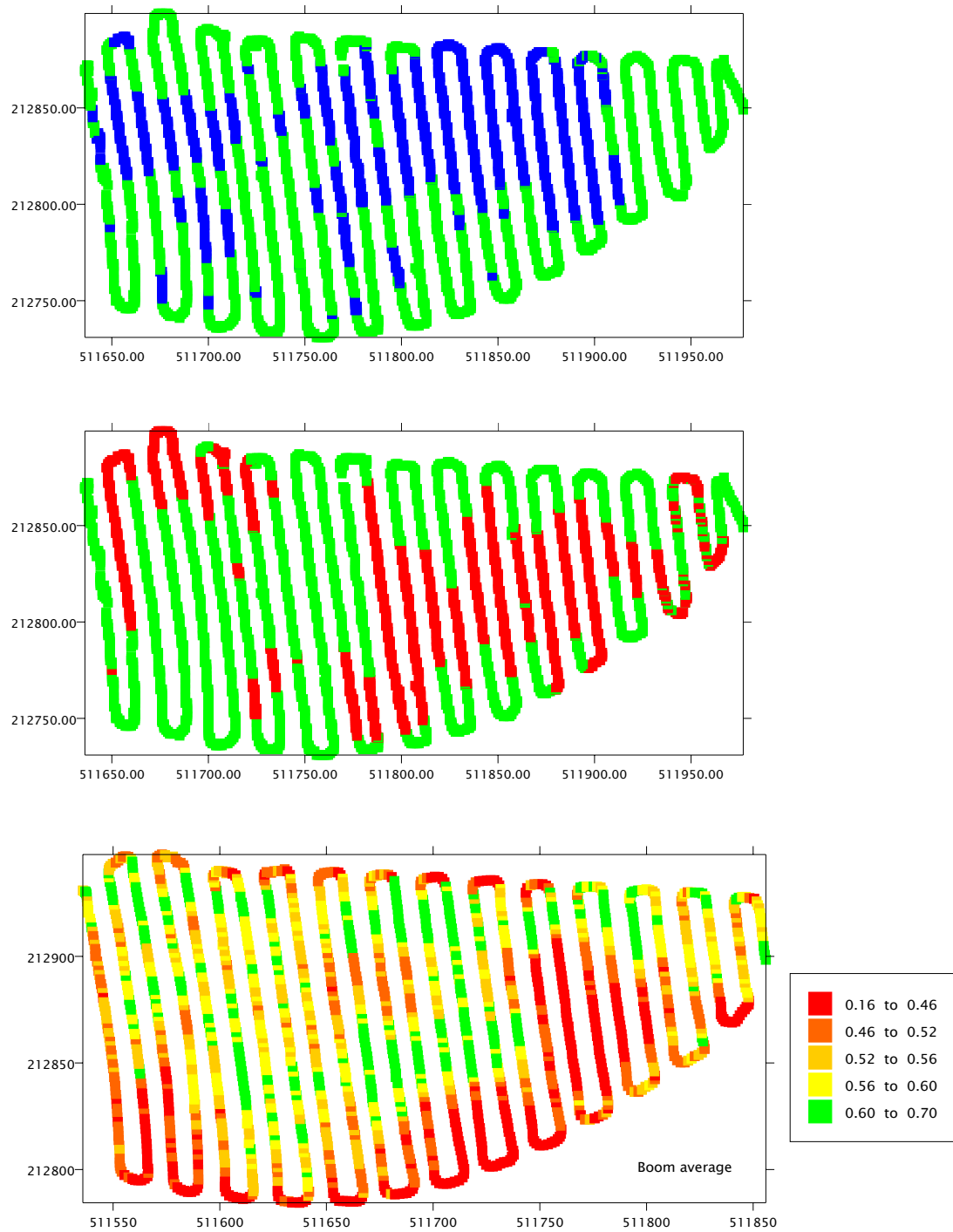
Fig. 3.19   Simulated "weed" patches of rape in a wheat crop in Summerdells Field at Rothamsted.

(a) Top – manually mapped rape patches

(b) Middle – manually mapped patches or other weeds

(c) Bottom – measured NDVI values on 19/11/2001

3.3.4 Conclusions and implications for using measurements of a vegetation index to aid weed patch detection

The results from this study show that in some circumstances the use of a measured vegetation index map will provide a useful aid to weed patch detection. Such measurements are most likely to be useful:

- when made at a relatively early stage of both crop and weed development as with the experiments reported in Section 3.3.3 above: - the response characteristics of spectral response measurements made above a crop canopy are such that the largest discrimination will be obtained at growth stages up to approximately 3.1 for conventionally grown cereal crops in the UK (Scotford & Miller, 2002);

- when the crop condition is reasonably uniform: - the large variations in crop canopy will give variations in the measured vegetation index and if this variation overlaps with weed patch areas, then the definition of patch boundaries based on such measurements will be complex;

- where the main weed present is to be targeted in some form of patch treatment.

In one of the experimental field conditions used in this study (Sawyers Field at the first measurement date) there was clear evidence that the use of a measured vegetative index map would have aided the manual mapping of weed patch positions. It should be noted that this was also the condition for which the most reliable maps were generated by manual survey. The vegetative index map would have enabled field areas to be targeted during the manual surveying and the time for such manual mapping to be reduced in proportion to the weed area in the field. For the other two field conditions, the advantages gained by having a vegetative index map when mapping weed patch distributions was less clear. In the case of Summerdells Field, even after the establishment of simulated "weed" patch positions, the weed distribution was not definably patchy and therefore not amenable to patch treatment. The detection of patches in this condition is difficult and not directly relevant to any patch treatment. For the oats in wheat in Meadow Field, the vegetation index provides some indications of the parts of the field to survey but insufficient detail to aid patch boundary definition.

Based on this set of results, it is unlikely to be economic to generate a vegetative index map solely to aid the detection and definition of weed patch positions. However, it is likely that such data will be collected as part of precision farming approaches involving the management of a cereal crop canopy (Godwin *et al.*, 2002) Scotford & Miller, 2002; Wollring *et al.*, 1998). Under such conditions, it would be appropriate to use vegetative index maps as a basis to aid weed patch detection.

Our study used radiometers mounted on a boom to give a spatial resolution in the NDVI map of less than 5 m. Vegetation indices can also be determined from measurements made from aircraft or from satellites and a resolution of this level will be required if such maps are to be used to aid the definition of patch boundaries rather than just the presence of weed patches.

3.4 Automatic weed patch detection

3.4.1 Background to automated weed detection

At the beginning of the project it was accepted that the potential for adopting patch spraying approaches would be substantially higher if weed patches could be detected and mapped automatically. Weed detection has been the subject of considerable research and development effort with a number of different approaches taken to the problem. These can be classified as follows:

Discrimination on the basis of colour

Work by a number of authors has shown that different plant species exhibit different spectral reflectance characteristics (e.g. Zwiggelaar, 1998; Vrindts *et al*., 1999) and recognised that this difference may form a basis for the discrimination between crop and weed plants. However, it has also been found that for a given species of plant, the measured spectral reflectance characteristics are also influenced by growing conditions, by viewing angle and by ambient light characteristics. A possible approach to accommodate this dependence on conditions would be to use a measure of spectral reflectance that is calibrated in the field to account for the reflectance characteristics from clean crop and weed patch areas within a crop.

Discrimination on the basis of shape

Leaf and plant shapes collected by image analysis can be analysed and compared with reference shape characteristics as the basis of a plant species discrimination routine. Many such approaches are still at the early stages of development and are not yet capable of dealing with overlapping leaves from different species.

Discrimination on the basis of position

Work in rowcrops (Tillett *et al.*, 1998; Miller *et al*., 1997) has used information about row structure and plant spacing within the row to detect both row orientation for machine guidance and plant positions within the row. Having detected plant positions within the crop, spectral reflectance was then used to distinguish plant material from the soil background and plants that were not crop assumed to be weeds. Such an approach is only relevant where a crop is grown in widely spaced rows and with discrete crop plants spaced along the row.

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Thompson *et al*. (1991) used image analysis to examine the inter-row region in conventionally drilled cereal crops and used a colour analysis to determine the ratio of green material in the row and between the row. The hypothesis here was that in a clean weed free crop there would be a clear region between the rows that had a low level of leaf occurrence whereas within a weed patch the level of green leaf material in this inter-row space would be much higher. This was shown to be an effective method of automated weed patch detection at a defined early stage of crop development but that the time over which many crops were at this growth stage could be very short so as to make practical exploitation of the approach non-viable.

Combinations of the above basic approaches have also been taken with a wide range of data collection and analysis techniques employed. For this project work we chose to use colour as the main basis for weed/crop discrimination recognising that we were always likely to be operating with overlapping crop and weed leaves in a relatively dense crop canopy. We planned to use in-field calibration techniques to account for differences in spectral reflectance characteristics arising from factors such as variety and growing conditions.

3.4.2 Experimental approaches to image collection and analysis

A digital camera (type: Sony Digital Video Camera DCR-TRV900E) was used to collect images of grass weed patches in cereal crop canopies by mounting the camera statically above the crop and with the camera attached to a tractor that was then driven through the crop. Emphasis was directed at image collection in the summer period when grass weeds such as wild-oats and black-grass were clearly visible above the crop canopy, and results from the visual mapping study had shown that they could be readily detected at this stage. Pictures were taken in a wide range of crop and weed conditions, from a range of viewing angles and in a range of ambient light conditions.

For a sub-set of the weed/crop images obtained, a colour threshold analysis was conducted with the aim of discriminating between weeds and crop. For nearly all of the images obtained with a low horizontal viewing angle, weeds and crop could be distinguished by such a colour threshold analysis (see Fig. 3.20). This form of analysis was not successful when there was a mixture of weed species within the image frame.

The robustness of the weed/crop discrimination on the basis of colour was examined by taking images of a given weed/crop condition in a range of lighting conditions and viewing angles particularly with respect to plant orientation, as influenced by the wind and the position of the sun, even if it was behind cloud. The results from our analysis of these images showed that the colour thresholds used to discriminate between crop and weed varied with all of these conditions such that within a given field at a given time the threshold values for colour discrimination depended on crop orientation and viewing angle – see Fig. 3.21.

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3.4.3 Implications from results of image analysis to discriminate between crop and weeds

The dependence of spectral reflectance from surfaces such as plant leaves on the characteristics of the ambient illumination is a well recognised problem and is the subject of on-going research at Silsoe Research Institute (Marchant *et al*., 2001; Marchant & Onyango, 2002) and elsewhere. Such research would have been outside of the scope of this LINK project and although results relevant to the analysis of crop/weed images have been produced over the lifetime of this project, further developments of the research is needed before it can be related to practical uses for weed patch detection in cereal crops.

The variability of the colour discrimination analysis for distinguishing weeds from crop was such that the frequency of in-field calibration needed would have been too high to provide a practical approach to grass weed patch detection in cereal crops. Each change of direction, for example, at the end of each tramline, would require at least the use of a different calibration dataset depending upon travel direction and changes in ambient light conditions with both time of day and degree of cloud cover would also mean that frequent re-calibration of the analysis routine would be required.

The option of combining measurements of spectral characteristics (colour) with leaf shape as a means of weed detection was not pursued in this project because of the large computing requirements needed for such an approach and the need for the further research to develop leaf shape routines such that they may be able to accommodate overlapping leaves and work in realistic crop canopy conditions. If such an approach can be developed then this may have implications for the way in which field areas are sampled. The approaches taken in much of this project have involved assessments of the whole area to be treated. An alternative strategy may involve detailed surveys of smaller areas, for example using an image analysis technique and then some interpolation to determine weed patch boundaries.

Fig. 3.20   Image of wild-oats in a crop of wheat (top) with the wild-oats false coloured on the basis of a colour discrimination analysis (bottom).

Fig. 3.21   Images of black-grass in a wheat crop showing the effect of viewing position in relation to the sun on the apparent colour difference between weed and crop.

4.0 Creation of a Treatment Map

4.1 Introduction

This project has based the spatially selective application of herbicides on the creation of weed and treatment maps. The use of a map-based control system enables weed patch detection to be undertaken at a time when it can be conducted effectively to give relatively accurate maps both in terms of weed species/density and also position, (Perry *et al.*, 2001). This approach also has advantages associated with the selection of both product/formulation and dose rate and this could in the future be via an interface with a decision support system. Defining those materials that are needed for the treatment of a particular field also limits the loading and transport of herbicides to that required for the field concerned.

The basic information on the distribution of weeds is held in the weed map, but in its initial form, as shown in Fig. 3.1, it is not appropriate for instructing the sprayer controller, as to what herbicide dose to apply to each unit (pixel) of the field. Computer programs have been developed that enable spatial data to be input, manipulated and written out as treatment maps in a range of formats using different transfer media to suit the available hardware. One such program, 'Patchwork', (Patchwork Technology, Pontypool, UK) was used as the basis of our development work in this project. The aim of the work was to define the components of a weed patch to treatment map transform. The platform under which such a transform will be undertaken needs to be easy to manage such that data can be safely and effectively manipulated by a non-specialist computer user.

4.2 Weed patch map to treatment map transforms

The generation of a treatment map involves the following main steps:

(i)   the reading into an appropriate software package of the recorded data relating to weed patch positions - species and/or densities;

(ii)   the generation of a weed patch map involving an interpolation of the recorded data to define discrete weed patches and the recognition of outlying weeds away from a defined patch. Note that results from previous studies have shown that application strategies based on multiple dose levels are more likely to give reliable control over a number of seasons (Paice & Day, 1997; Lutman *et al.*, 1998) and therefore weeds or small weed patches outside of a main patch need to be treated with herbicide but at a lower dose than in the main patch;

(iii) the extension of patch boundaries to account for factors such as weed and seed movement in the period between detection and treatment and uncertainties relating to the performance of the in-field location system;

(iv) the definition of treatments to be applied to the extended patch and intermediate areas in terms of:
- the type(s) of formulation and/or tank mix;
- the dose rate;

(v) the writing of the treatment map to the appropriate output media and in an acceptable format.

Plots of the recorded weed patch presence/absence in an example field, its input into a map-based data management program ('Patchwork') as a weed patch map and the output treatment map are shown in Figs. 4.1(a), 4.1(b) and 4.1(c), respectively. The raw data plot, Fig. 4.1(a) reproduces the combine track in the field and tags each position as either having weed (black) or no weed (grey). When this was read into the data management package, the standard interpolation routine correctly recognised the presence of two main weed patch areas on the left hand side of the map and merged these into a single large weed patch area as expected. Weed patch areas on the right hand side of the map area were less well represented on the interpolated map and it was considered that there was scope to adjust the interpolation parameters to improve the fit in this area. This was confirmed by analysing weed patch distribution data for a number of other field conditions. Small outlying areas and single weeds were again ignored by the interpolation routine.

The form of the treatment map (4.1(c)) closely resembles that of the interpolated weed patch map (4.1(b)). This was expected since the standard 'Patchwork' software package did not include a specialised weed patch to treatment map algorithm. Work during this project defined methods by which such treatment maps could be generated both in terms of the areas to be treated and the treatments to be applied. Where weed patch mapping was to be conducted in the season prior to treatment, a buffer zone would need to be added to account for factors such as weed seed movement and location errors. There is strong evidence to indicate that the width of such buffers should be greater in the direction of harvesting and cultivation, but this leads to additional complexity in the operation of any transform program and was not considered to be justified for the programs that would be delivered as part of this project.
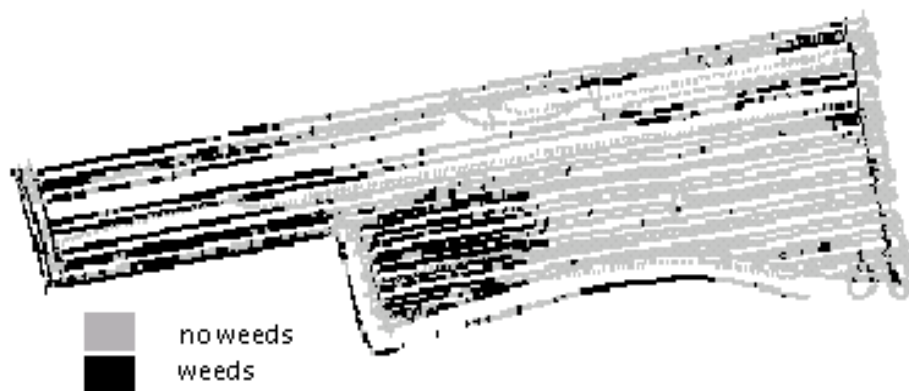
(a) Weed patch map as recorded
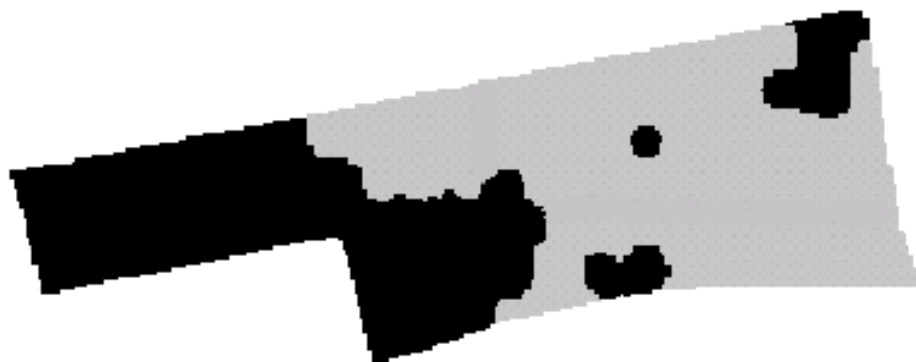
(b) Weed patch map after initial interpolation

(c) Treatment map

Fig. 4.1   Weed patch map (a) as recorded; (b) when read into a data management package as a weed patch map and (c) as an output treatment map

Work in previous project studying black-grass and reported by Rew *et al*., (1997) recommended that a buffer zone 4.0 m wide be added around the outside of mapped weed areas to account for the majority of positional and detecting errors incurred while mapping and the movement of seeds by agricultural machinery. Results from the work in this project with cleavers and wild-oats (see Section 2) also concluded that this would be an appropriate width of buffer zone although the movement of individual weed seeds of wild-oats was recognised as a factor influencing the required frequency of re-mapping.

Further work was undertaken using the 'Patchwork' software to:

- examine the adjustment of parameters within the interpolation routines so as to improve the smoothing of mapped weed patches; and
- to add a variable width buffer zone around smoothed weed patch areas.

It was recognised that there would be some interaction between the performance of interpolation routines and the width of buffer zone areas that would need to be added to weed patch areas as part of a weed map to treatment map transform. During the development of the interpolation routine within the 'Patchwork' software, comparisons were also made with the outputs from other interpolation routines such as those used in the 'Surfer' software package (Golden Software, USA).

Plots of the recorded weed patch presence/absence for the same example field as in Fig. 4.1, a smoothed map with a 6 m buffer zone and the output treatment map with the additional buffer zone, are shown in Fig. 4.2(a), 4.2(b) and 4.2(c) respectively. Figure 4.3 shows a similar transform for a weed map of wild-oats in a wheat crop and with the interpolated and treatment maps shown in 'Patchwork' and 'Fieldstar' formats. In this case no additional buffer zone areas have been added around the weed patches.

It was originally envisaged that the weed to treatment map transform would be delivered as a series of relationships defining treatment areas to which the required treatments could be applied. These would be available to be incorporated into different precision farming software packages, with the 'Patchwork' programs used to demonstrate the approach. Experience gained when implementing the planned approaches showed the importance of the characteristics of the interpolation routines within the software packages and therefore the main delivery of the outputs from the project in relation to weed to treatment map transforms is via the 'Patchwork' software package. The methods could however be incorporated in other software packages taking account of the characteristics of interpolation routines and the way that data is handled.
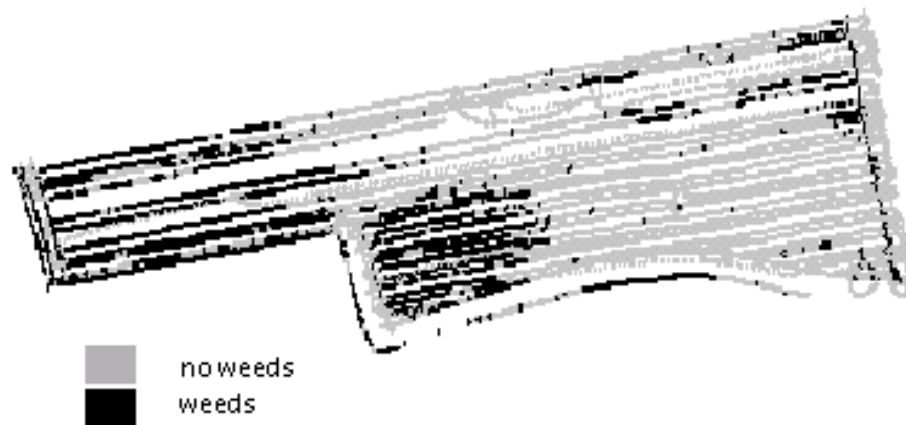
(a) Weed patch map as recorded
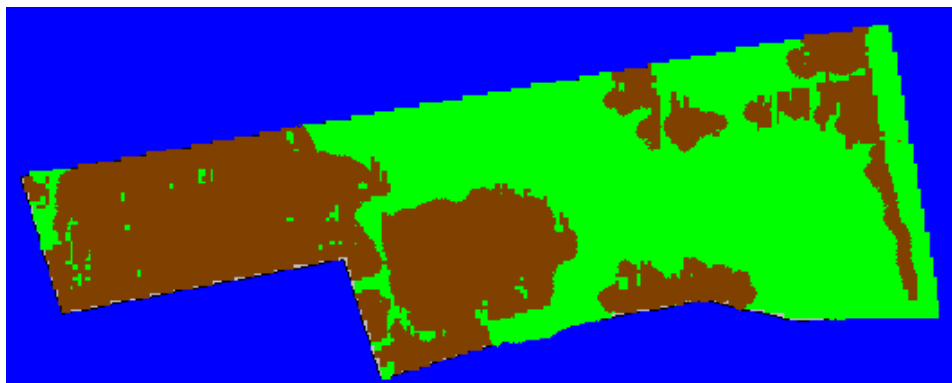
(b) Weed patch map after refined interpolation
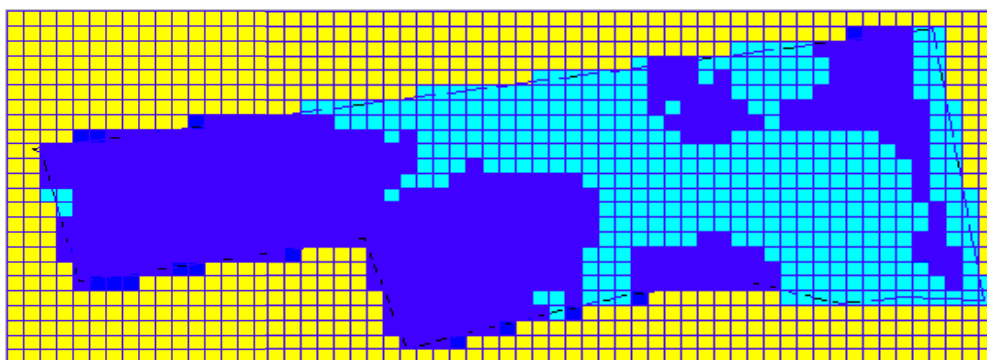
(c) Treatment map

Fig. 4.2   Weed patch map (a) as recorded; (b) when read into a data management package as a weed patch map with a 6 m buffer zone and (c) as an output treatment map
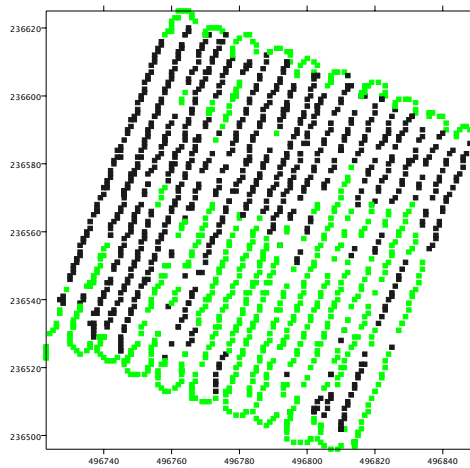
(a)Weed map as recorded – mapped from an ATV
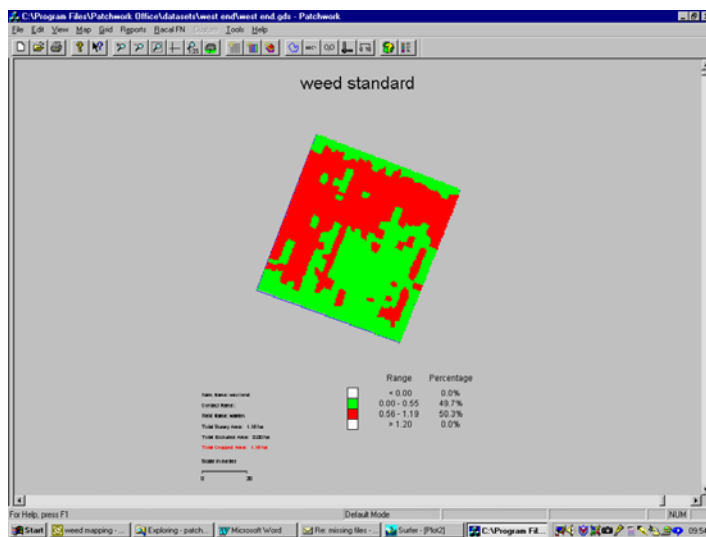
(b) Interpolated map in the 'Patchwork' software – no added buffer.
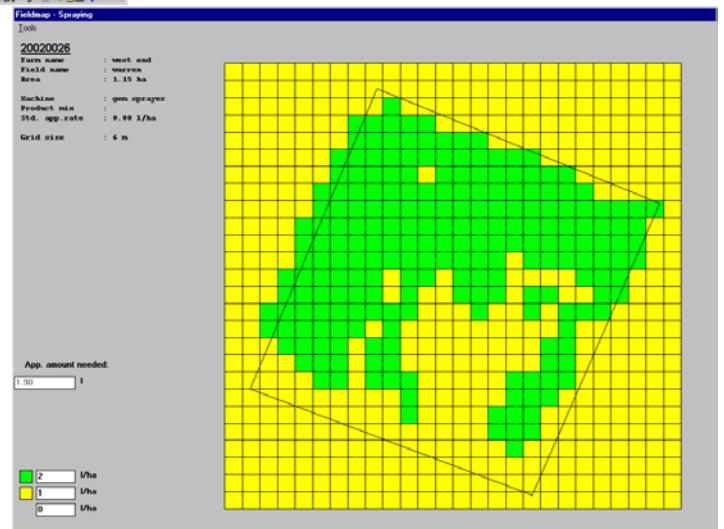
(c) Treatment map in the 'Fieldstar' software.

F**ig. 4.3** A further example of a weed to treatment map transform

Weed patch maps are commonly stored in a raster format (e.g. Fig. 4.1) whereas the movement of boundaries is more effectively conducted in a vector format. The treatment map generation programs are therefore likely to include a raster/vector transform such that the addition of a buffer zone area can be efficiently added to identified weed patch areas.

It was recognised that a weed to treatment map transform when complete would include:

(i)　　　methods for interpolating and modifying weed patch areas to account for characteristics of the positioning system (both during mapping and treatment application), of the detection systems (particularly in terms of threshold levels) and weed seed movement as discussed above; and

(ii)　　　the dose rates and/or herbicide mixtures to be used.

The selection of a herbicide or tank mix treatment was not considered in detail as part of the project work reported here but would need to consider:-

- the dose response characteristics of the herbicide/mixture particularly in relation to the low dose treatment areas;
- the characteristics of the weed patch detection system in terms of threshold densities, reliability and positional accuracy;
- the competitive status of the weed;
- the cost and environmental characteristics of the herbicide/mixture.

Many of these factors may be effectively included by an appropriate interface with a decision support system such as the weed management system currently being developed as part of a different Sustainable Arable LINK project (Parker & Clarke, 2001). Data on which such assessments are made would come primarily from the agricultural chemical manufacturers together with publicly funded studies examining factors such as dose response characteristics and resistance. A collation of such data and recommendations of herbicide dose rates to be used was beyond the scope of the work reported here. Similar thought processes are evident in a recent paper by Faechner *et al.* (2003), where they have developed a computer programme that links herbicide dose response and the competitive effects of weed infestation on yields, to estimate appropriate doses for areas of fields with different levels of weeds.

5.0 Herbicide application and system testing

5.1 Introduction

One of the key parts of the project has been to establish the ability of the application system to apply herbicides, as directed by the spray/treatment map, on a spatially variable basis. Earlier sections in this report have described how to create the map and how to convert the weed map into a treatment map. This section reports the application of herbicides as controlled by the treatment map. Thus, it covers the performance of the sprayer and of the system as a whole.

5.2 Sprayer development and performance

5.2.1 Micron PatchSpray sprayer

The original sprayer developed at Silsoe Research Institute to patch spray weeds was based on an injection metering system which injected concentrated herbicide solutions into the spray lines that were linked to 2 m sections of booms. This very elegant technique to achieve spatially variable application, with a very fine level of precision, was used in the previous patch-spraying project (Lutman *et al*., 1998). However, there were some practical limitations to the technique. Firstly, the formulations of a number of key herbicides were not appropriate for the injection metering system and secondly, the combination of both injection metering and spatial variability would result in a level of complexity that could limit commercial up-take. Thus, it was decided that the commercial prototype should move away from injection metering to more 'conventional' application systems. During 1997-1999 a prototype patch spraying system was developed at Silsoe Research Institute, which was compatible with standard spraying equipment and could be retro-fitted to existing equipment if required. This is now being marketed as the Micron Sprayers Ltd Patchspray system.

With any given nozzle type, output can only be altered by changing pressure. But, as pressure also influences droplet size and spray distribution patterns, there is a limit to how much output can be changed by simply changing pressure. Application rates could be changed by +/- 20% by changing pressure, but there is need to change application rates by as much as 300%, to accommodate the requirements of patch spraying. The solution to this problem was to build a sprayer with multiple boom lines or multiple feeds from the same line and different nozzle sizes on each boom. By switching nozzle lines and adjusting pressures, it was possible to create an application system where flow rates could be changed over a wide range without changing spray quality thus providing appropriate dose flexibility. The original concept used three nozzle orifices at each boom location such that a dose rate range of more than 5:1 could be achieved over a continuous range, Miller *et al.,* (1997). In the development of a practical prototype system that was used for

the work in this project, it was found that by careful nozzle selection, a two-nozzle cluster could achieve the 300% dose rate range required with only small gaps (less than 10%) in the operating range – see Fig. 5.1. The switching of the nozzles and the control of the spray pressure was controlled by a compressed air system. Each nozzle on the line was fitted with a pneumatic on/off valve, activated by air lines (Fig. 5.1).

Fig. 5.1 Details of the spray boom of the PatchSpray sprayer, showing the valves that control the nozzles

As shown in the report of the previous project (Lutman *et al.* 1998) this configuration provides adequate flexibility and a fast response, generating minimal 'lag times' between receipt of an instruction from the computer controller to change dose and the response at the nozzle. A key aspect of the performance of this system is the opening and closing response times of the valves controlling the liquid supply to each nozzle set. Measurements of the sprayer output over a series of nozzle set changes were made by supporting strips of chromatography paper at ground level aligned in the direction of travel. These were then sprayed with a tracer dye solution ("Green S" – Merck Chemicals) with the sprayer travelling at a speed of 8 km/h and using a simulated control treatment map that include a sequence of nozzle set changes. The positions corresponding to the nozzle set changes were studied on the chromotography paper strips, initially using visual assessments to ensure that there were no gaps or areas of overlap and then by using dye recovery techniques to check that the applied dose agreed with that specified on the treatment map.

One engineering constraint that generated some discussion was the need to divide the boom into smaller sub-units. The previous experimental sprayer with injection metering functioned with 2 m sub-units but the current sprayer only changed application rates across the whole boom. From the theoretical patch-spraying standpoint the greater the resolution and the smaller the 'pixel' (the minimum area sprayed with a given dose) the greater the reduction in herbicide use. This has been clearly demonstrated in papers by

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Wallinga (Wallinga, 1995; Wallinga *et al.,* 1998) where he showed that the finer the spatial resolution the lower the amount of herbicide used to control a patchy weed infestation. The bigger the spray unit the more 'weed free' area is treated. Rew *et al.,* (1997) recommended that a resolution of 4m x 4m was the most appropriate for treating patches of grass weed in a cereal crop. From a biological standpoint therefore it would have been better to split the spray boom into perhaps 4 x 6 m sub-sections, but the engineering complexities this would have caused were believed to be greater concern. Each sub-section would require its own control system, thus creating a sprayer with four-times as much complexity as a full boom control system. It was concluded that commercially, the added cost of the increased complexity, outweighed the potentially greater herbicide saving. Any future redesigning of the sprayer may need to review this decision, balancing the extra cost and complexity of a split boom system with the reduced herbicide saving of the single boom system.

AGCO's 'Fieldstar' controller controlled the sprayer. This was installed in the sprayer tractor and the treatment map could be simply loaded into the controller. The 'Fieldstar' screen provided an image of the field to be sprayed and the doses to be applied to each section of the field (Fig. 5.2). Each section of the field receives its own designated herbicide treatment. This can be automatically provided by the spray map to treatment map software, or can be inputted or changed manually. When the application is completed 'Fieldstar' will generate an application record map of where the herbicides were applied and at what rate.
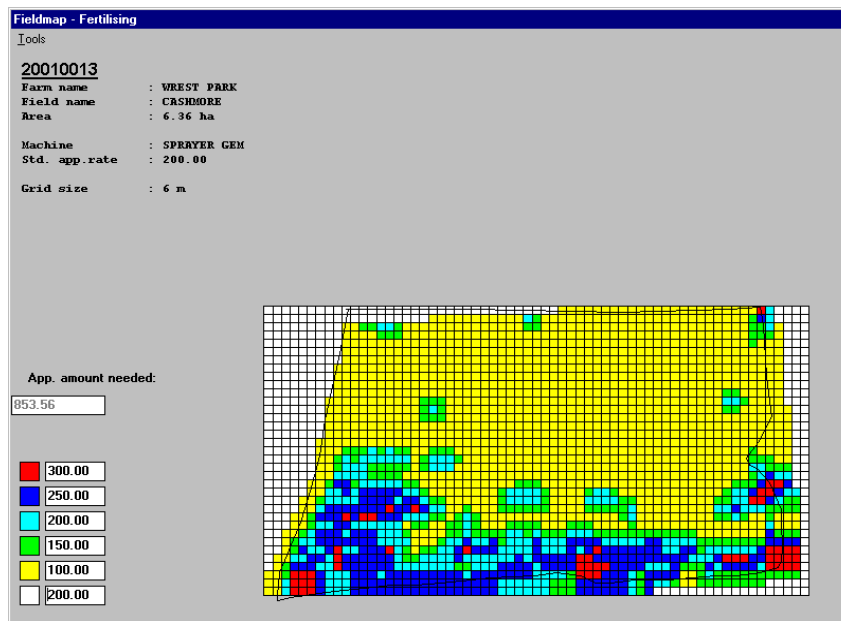
Fig. 5.2 Spray application map for Cashmore field: herbicide application for the control of black-grass

5.2.2 Spra-Coupe injection sprayer

During the course of the project, Silsoe Research Institute had access to a Spra-Coupe injection sprayer. This was set up to inject herbicides into the entire spray boom (as one unit), but had the advantage over the Patch Spray system as it was possible to apply a uniform herbicide and then inject a second product when needed. This avoids the need for low dose/high dose strategy, as the carrier (cheaper) product could be sprayed over the entire field and the more expensive patch application product could be applied only to the patches. The unit was again controlled by a Fieldstar unit mounted in the cab and this incorporated both monitoring and control functions of the sprayer. The injection elements of the Spra-Coupe were experimental as the sprayer system was primarily set up to validate the effectiveness of the electronic controls. Preliminary studies were made using this sprayer to characterise the range of doses that could be delivered by both the pressure control strategy and the injection metering unit. The response times of the injection metering system were of particular relevance to this project work and measurements were made by injecting a tracer dye solution of:

(a)   the delay from the injection point to delivery to the central feed on the boom (primary delay);

(b)   the delay from the boom centre to the outer nozzles (secondary delay).

Results, expressed as a distance travelled when applying 100 l/ha, gave values of 45 and 26 m for the two delays respectively. These values would be reduced pro-rata by operating at higher volume rates. There was also some scope to move the injection closer to the boom and this would reduce the primary delay by some 15%.

A component of the primary delay can be accommodated by effectively looking forward on the treatment map. However large delay distances such as those measured with this system will cause problems particularly when priming the system and starting work in a field, even if a defined spraying path is to be followed. The secondary delay effectively needs to be accommodated by the size of buffers around patch areas (see Section 4) and again the large values measured in this study would have implications for the magnitude of herbicide savings that could be achieved by patch spraying.

There is a scope for reducing these values depending on the details of the design of the spraying system. In the Spra-Coupe the use of a centrifugal pump driven directly from the engine does give problems with the primary delay due to the use of long pipe runs of a large bore pipe. However, the use of this pump design does avoid the need for a by-pass loop around the pump as part of a pressure control system. Commercial developments outside of those within this project but undertaken at the same time and demonstrated early in 2002 used injection points on the spray boom and a re-circulating system on the boom.

This then reduces the primary delay to a very low value and changes the form that the secondary delay takes. With a conventional arrangement, the step dose change effectively moves along the boom (outwards from the feed point) as liquid is output from the nozzles. In the re-circulating design, the change in dose level is effectively ramped across the full width of the boom and therefore would be a preferred control strategy when patch spraying with a high dose/low dose control algorithm.

While some spraying trials work was done with the Spra-Coupe unit operating in on/off mode, relatively little work was done with the injection metering system.

5.3 Field spraying

During the project six fields were treated with herbicides, to check the effectiveness of the application system. The weeds were mapped, the treatment map was created and the herbicides were applied with the Micron PatchSpray patch sprayer (Table 5.1). The fields with the exception of Norfolk were treated with a low dose/high dose strategy, whereby the patch area received a high dose (the recommended rate) and the non-patch are received a lower dose. Norfolk was treated with a spray/no spray strategy, as the patches of thistles were particularly easy to see. The low dose/high dose strategy reduces the saving in herbicide but avoids the problem of weed patches regenerating from low density infestations not included in the patch areas, when the map was created. Decisions on doses to use were made on the nature of the patch distribution and on the characteristics of the herbicides chosen. Thus, a wide span of doses was used in the field application of fluroxypyr, which has appreciable activity at low doses on cleavers, whilst clodinafop doses were only reduced marginally, as its effectiveness on black-grass is known to be poor at low doses. The issue of the dose to use and the merits of low/high versus spray/no spray have already been discussed by Paice (Paice & Day, 1996; Paice *et al*., 1998) and again in Chapter 2, here. Ideally, the dose would be linked directly to the infestation level and its anticipated impact on crop yield, but such an approach requires detailed knowledge of the impact of the weed on the crop and on the herbicide doses required to control/suppress those effects. At the moment such detailed approaches are not available but the recent paper by Faechner *et al.*, (2003) explores a suitable model to define the optimum dose for a given weed infestation, linking yield effects and herbicide performance. The treatment doses used on the fields patch sprayed in this project were based on 'expert opinion'.

Table 5.1 Details of the spray treatments applied in the project

Weed	Field	Crop	Herbicide used	Date	Dose range (L product/ha)
Wild-oats	Warren 1	W. wheat	Tralkoxydim (Grasp)	Mar 2000	0.6-1.4 l/ha
Wild-oats	Warren 2	W. wheat	Clodinafop (Topik)	May 1999	0.083-0.125 l/ha
Cleavers	Warren 3	W. wheat	Fluroxypyr (Starane)	May1999	0.4 – 1.0 l/ha
Black-grass	Broadmead	W. wheat	Clodinafop + trifluralin(Hawk)	Mar 2000	2.0-2.5 l/ha
Creeping thistle	Norfolk	Sugar beet	Clopyralid (Dow Shield)	May/June 2000	0-1.0 l/ha
Black-grass	Cashmore	W. wheat	Isoproturon	Dec 2000	1.7-5.0 l/ha

'Fieldstar' generates a map of the actual application, which can be retained for future use. An example is given in Fig. 5.3.
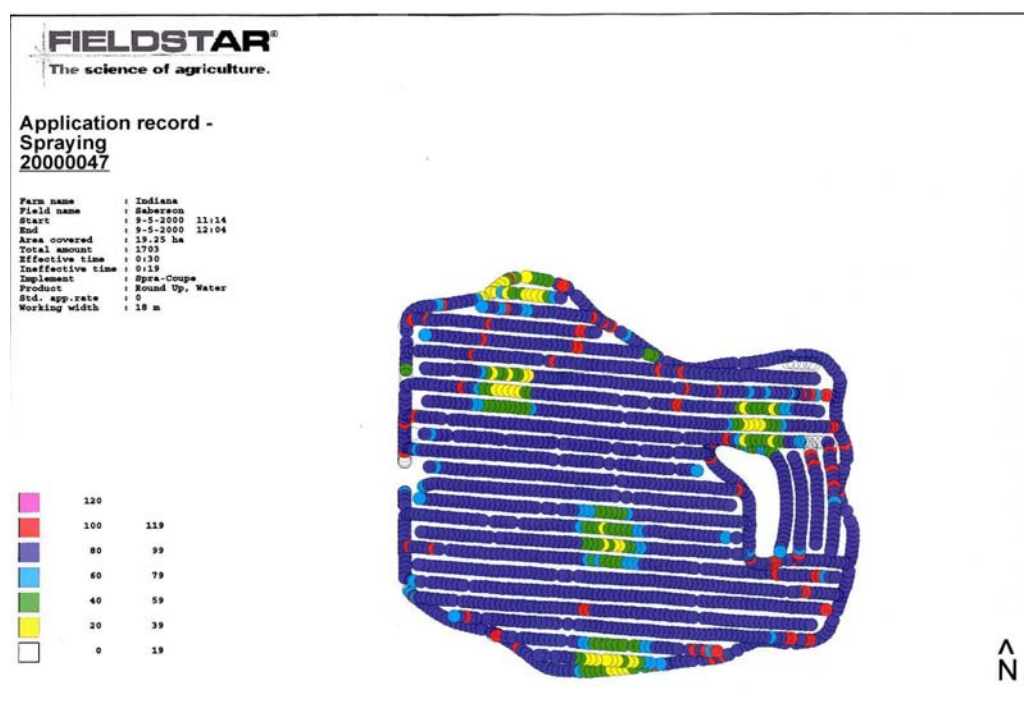
Fig. 5.3 Example of a spray application record generated by 'Fieldstar'

All the treated fields were checked for the effectiveness of the products used and all achieved reasonable levels of control although some surviving weeds were recorded, especially in Cashmore field treated with isoproturon and Broadmead treated with clodinafop. This was not surprising, as it is notoriously difficult to achieve complete control of black-grass, especially as in Broadmead, where the treatment was to

large plants in March, which subsequently were found to have a degree of resistance to this herbicide. Although the overall level of control in the fields was not 100%, there was no evidence that variations in the level of control were linked to the spatial variations in doses. Post-spraying assessments simply noted low and high levels of partly controlled weeds, as even the areas treated with the full product rate had not always achieved full control. The cautious approach adopted with the doses used and the low dose/high dose strategy does seem to have avoided failures due to the spatially variable treatments.

5.4 Project demonstration

In February 2002 the consortium set up a demonstration of the achievements of the project. As well as a series of talks about the various components necessary to patch-spray weeds, the meeting also included a demonstration of how to do it. An artificial weed infested area was set up on a grass field at Silsoe; weed areas were marked with plastic pegs. The weed patches were mapped using the voice recognition software and the weed map was generated. This was then converted into the treatment map using the software developed by Patchwork Technology. This treatment map was installed in the 'Fieldstar' controller in the tractor cab of the sprayer and 'herbicide' was applied on a spray/no spray basis onto the patch areas, as directed by the map. The demonstration was attended by 50-60 people representing all sections of the industry, including research, chemical industry, sprayer manufacturers, contractors, farmers, and government.

Because of the foot and mouth outbreak in 2001 no practical demonstrations were possible and this was one of the main reasons for the special February 2002 demonstration. However, further publicity for the project was felt justified and so a demonstration of the 'system' was included in the Silsoe contribution to Sprays and Sprayers (June 2002). In this demonstration a video camera showed how the sprayer responded to the presence of weeds as recorded on a weed/treatment map.

6.0 Economics

6.1 Introduction

The success of this technology will depend to a considerable extent on the economic balance between the reduction in variable costs as a result of the reduction in herbicide use and the costs involved in implementing the technology. Other factors such as the need for a spray application map to identify where pesticides have been applied, to confirm compliance with environmental and regulatory requirements such as 'Local Environmental Risk Assessments for Pesticides' (LERAPs) may become of greater significance in future. But, currently the main driver relating to the uptake of the technology is the cost/benefit analysis. As the technology of patch spraying weeds is still at its early stages, it is difficult fully to explore all the financial aspects of the technique, but it is possible to generate estimates of cost savings in herbicides and balance this with the equipment and manpower costs associated with their use. The recently published HGCA report on precision farming, primarily in relation to fertiliser management (Godwin *et al*., 2002) endeavours to estimate the economic benefits of exploiting the technology and concludes that the costs of equipping a farm to be capable of adopting precision farming techniques range from £5 ha^{-1} to £18 ha^{-1}, depending on the system chosen and farm size. They also conclude that financial benefits from spatially optimised nitrogen management could be in the region of £22 ha^{-1}. Clearly, the set up costs of patch spraying will be much lower on a farm that is already involved in yield mapping and the spatially variable application of fertilisers, than it will be on a farm with no such involvement. This has to be borne in mind when endeavouring to assess the cost-benefit of patch spraying.

6.2 Herbicide savings

6.2.1 Sprayed fields

During the project several fields have been 'patch sprayed' and it is therefore possible to identify the reduction in herbicide use achieved and hence the reduction in costs. An example of a weed map and conversion to a treatment map is given in Fig. 6.1. Details of fields treated during the project are reproduced below (Table 6.1). Percentage herbicide savings were lower than the % infested areas because of the need to link where the weeds were to the spray boom position and to include buffers (as discussed in Section 4). Also the majority of fields were sprayed using a low/high dose strategy rather than the apparently simpler spray/no spray system, whereby the main patch areas received a full dose and the area outside the patches received a reduced dose. The level of reduction in dose varied between products, as some have greater dose 'flexibility than others. This has been discussed in Section 5.3.
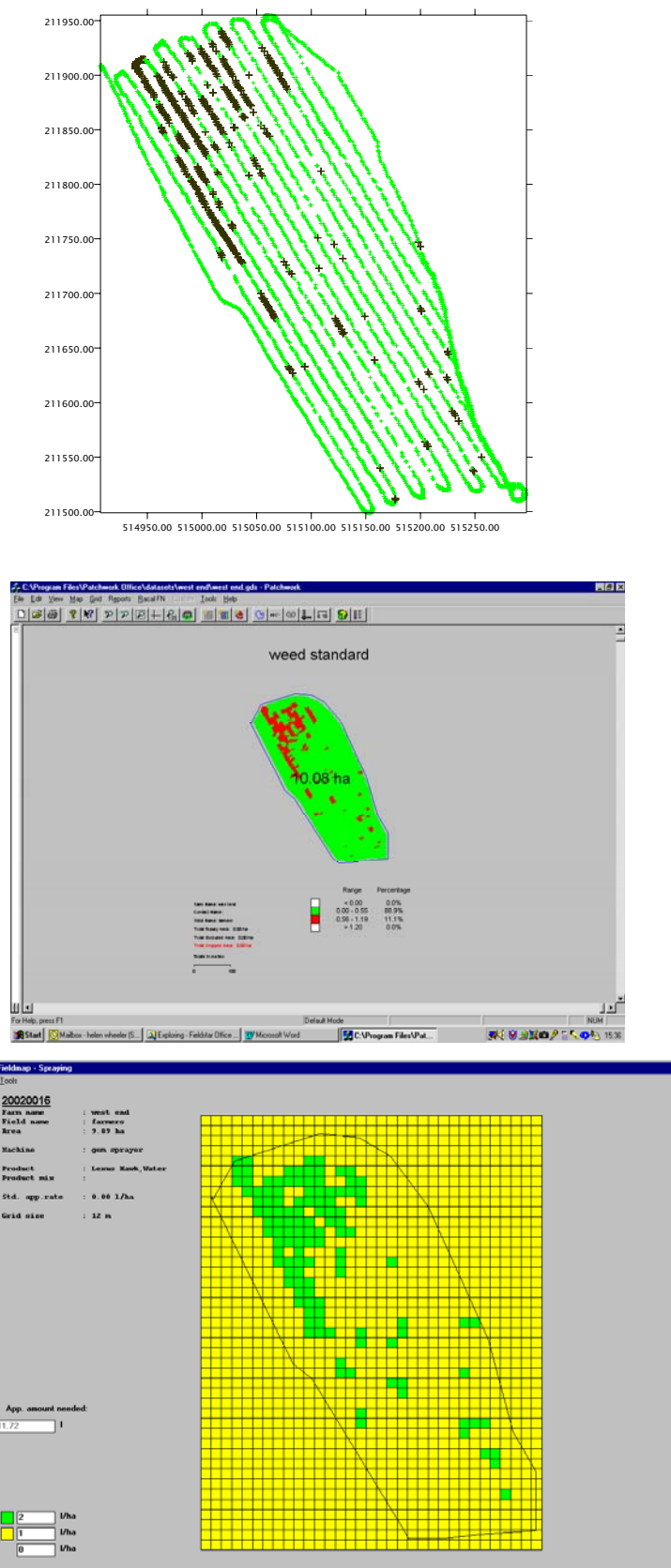
Fig. 6.1 Details of (a) initial weed map, (b) 'Fieldstar' interpolated map and (c) spray application map for Farmers Field (onion couch mapped July 2000)

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Table 6.1 Potential herbicide savings from patch spraying

Weed	Crop	% area infested	Herbicide used (doses in product/ha)	% herbicide saved	Cost saving £/ha
Wild-oats	W. wheat	51	Tralkoxydim (Grasp)	27	9.57
Wild-oats	W. wheat	19	Clodinafop (Topik)	18	3.44
Cleavers	W. wheat	27	Fluroxypyr (Starane)	30	5.68
Black-grass	W. wheat	65	Clodinafop + trifluralin (Hawk)	9	2.00
Creeping thistle	Sugar beet		Clopyralid (Dow Shield)	31	19.69
Black-grass	W. wheat	58	Isoproturon (IPU)	33	3.63

NB full details of application rates etc are given in Table 5.1

Herbicide savings varied from 9-33%, giving cost savings, dependent on the herbicide used, of up to £20/ha. The savings were greatest on the field of sugar beet where a spray/no spray programme was adopted for the control of creeping thistle (*C. arvense*). The weed was easy to see in the beet crop and the operators were confident that the map fully represented the infested area. In contrast, with the grass weeds and cleavers in cereals it was felt prudent to adopt a low dose/high dose treatment, as lightly infested areas were not easy to map (see Section 3) and so herbicide savings are lower, £2-10 ha^{-1}. Dose ranges varied according to the perceived flexibility of the products concerned. When only a small proportion of the field was infested, as with cleavers, the % reduction in herbicide use was much smaller than one might expect from the % area infested. This was because the 'uninfested' area was treated with a low dose of fluroxypyr (40% of full dose), thus decreasing the herbicide savings. Even so, there was still a 30% reduction in herbicide use. The need to apply a low dose over all the uninfested areas would decrease with experience of the weed distribution in the field, and the application map can be easily adjusted to remove herbicide application from certain parts of the field, if desired. Similarly, greater experience with the product could lead to greater reduction in doses applied to the 'uninfested' areas. Least herbicide was saved in the field sprayed with trifluralin + clodinafop, because the field had a 65% infestation and it was decided that the products had only limited dose flexibility. With the basis of the cautious low dose/high dose approach it seems likely that herbicide savings will not exceed £10 ha^{-1} unless the weed patches are restricted to small parts of the field and some uninfested parts can confidently be left untreated. The effect of the two contrasting spraying strategies on herbicide reductions is explored further in the succeeding section.

6.2.2 Modelled patch spraying treatments

As the number of fields where it was practicable to use the patch sprayer was limited, we have also simulated cost savings on a further eight fields. These fields were mapped during the project to assess our ability to create weed maps (Chapter 3) and these maps have been processed in precisely the same way as the maps used in the fields actually treated. The weed map has been converted to a treatment map that would have

controlled the herbicide application. We created two contrasting scenarios: a) where the patches were sprayed and the rest was untreated (spray/no spray), and b) where the patches received a high dose and the non-patch areas a low dose (low/high). In the latter scenario the high dose was the recommended rate and this rate was reduced by 50% for the low dose (non weed patch) areas. Cost reductions were related to application of the full rate to the whole field. Such a scenario would be particularly relevant to the control of black-grass (as for fields 2-5 & 8 (Table 6.2)), as users tend to keep to the recommended rate for the control of this weed. These data show that appreciable reductions in herbicide use are possible. As with the treated fields (Section 6.2.1) the cost saving is appreciably greater when the spray/no spray application system is used, especially when the infested area is relatively small. This is clearly seen if the costs of treatment using the two systems are compared with the relatively little infested field (2) and the more heavily infested field (7b). They also demonstrate that the absolute cost benefit is markedly influenced by the price of the herbicide. This is most clearly seen if tralkoxydim is used for the control of wild-oats instead of clodinafop (field 7b). Overall, the spray/no spray option saved £12 ha^{-1} and the low/high dose option £6 ha^{-1}.

Table 6.2 Calculated herbicide savings based on created weed spray application maps generated from weed patch maps

Site	Weed	% area infested	Herbicide used	Herbicide cost/ha (£)	% area treated (spray/no spray)	Amount of herbicide saved £/ha (% saving)	
						Low dose / high dose[*]	Spray / no spray
1	Onion couch	11	Glyphosate	15.2	17.0	£7.28 (48)	£14.55(96)
2	Black-grass	5	Clodinafop	19.1	13.2	£8.30 (43)	£16.60 (87)
3	Black-grass	13	Clodinafop + trifluralin	22.3	12.6	£9.72 (44)	£19.44 (87)
4	Black-grass	58	Clodinafop	19.1	65.1	£3.33 (17)	£6.67 (35)
5	Black-grass	32	Flupyrsulfuron + pendimethalin	39.4	52.4	£9.37 (24)	£18.73 (48)
6	Creeping thistle	2	Metsulfuron	9.2	5.4	£4.34 (47)	£8.69 (94)
		2	Glyphosate	15.2		£7.19 (47)	£14.39 (94)
7a	Cleavers	14	Fluroxypyr	19.0	25.7	£7.06 (37)	£14.13 (74)
7b	Wild-oats	50	Clodinafop	19.1	68.7	£2.99 (15)	£5.99 (31)
		50	Tralkoxydim	35.2		£5.52 (15)	£11.03 (30)
8	Black-grass	58	Topik	19.1	79.1	£2.00 (11)	£ 4.01 (21)

* 'low dose' = 50% of full rate and 'high dose' = 100% of full rate

It should be noted that comparison of an overall recommended rate application with the application of a recommended rate to the patches and 50% rate to the rest of the field, is rather artificial, although it served as a possible practical response to the need to patch spray, for this financial analysis. In reality the user might not ever use full rates and so the comparison should be between low rates overall and higher rates

on the patches and lower rates on the non-mapped areas. This scenario could lead to more herbicide being used on the patch treatment, albeit applied in a more targeted way. The herbicide saving will vary according to the intended overall treatment, compared to the proposed doses to be applied to the patches and the rest of the field. A series of possible outcomes based on choice of doses is given in Table 6.3. these are abstracted from an 'Excel' spreadsheet that can explore a wide range of alternative scenarios. It was not the role of this project to devise a dose selection system but it is very relevant to calculating cost savings. The choice of appropriate doses for weed control is one of the main aims of the Sustainable Arable LINK Weed Management Support System project (Parker & Clarke, 2001).

Table 6.3 Examples of a 'calculator' to estimate potential savings depending on % of fields infested and dose selection for patch areas and non-weed areas

Herbicide Product	Price £/ha	Overall treatment % full rate	Weed patch treatment area		Non-weed patch area		Patch treatment Average rate (%)	Difference between patch and overall (%)	Financial consequences £/ha
			% Area	% of Full rate	% Area	% of Full rate			
Topik + oil	19.12	100	60	100	40	80	92	8	1.50
		100	40	100	60	60	76	24	4.59
		100	**65**	**100**	**35**	**70**	**89.5**	**10.5**	**2.00**
Starane	19.00	60	60	80	40	40	64	-4	-0.76
		60	60	60	40	40	52	8	1.50
		100	60	100	40	60	84	16	3.04
Roundup	15.20	100	40	100	60	50	70	30	4.56

Taking as a further example the most widespread weed included in this project, black-grass, one can assume that approximately 50% of each field area is infested (see Lutman *et al.,* 1998; Chapter 3, this report). If 50% of the field is infested, approximately 65% of the field will need treatment. The standard treatment would be based around clodinafop, but as this herbicide has only limited dose flexibility the 'low' dose would be only in the region of 70% of the recommended rate. It is highly likely that both the patch areas and any overall treatment would be at the full rate. In such a scenario one would expect to save only £2 ha^{-1} (see Table 6.3 grey underlined values). However, if the clodinafop was replaced by the more costly flupyrsulfuron + pendimethalin, in order to combat herbicide resistance in the black-grass, savings would increase to approximately £7 ha^{-1}. Thus, with a combination of cheap herbicides, low dose flexibility and relatively high levels of infestation, cost savings will be small. Conversely, expensive products, high dose flexibility and lower levels of infestation, will generate higher cost savings. An interactive 'calculator' like that shown in Table 6.3, could be used to assist the user to estimate possible cost benefits from using the system.

6.3 Cost of treatment

There are several aspects of the cost of treatment that have to be factored into the cost benefit analysis of patch spraying. The primary costs are related to the equipment needed to patch spray and the cost of creating the map. The costs of the equipment depend on the users existing commitment to precision agriculture. If the user is already creating yield maps and perhaps is applying fertiliser on a spatially selective basis, then he/she will already possess a lot of the basic equipment. For example the GPS receiver and the control system, such as that provided by AGCO's 'Fieldstar' can be removed from the combine harvester and mounted on the patch sprayer, requiring minimal work and expense. In this scenario the main outlay in equipment costs would be the cost of creating a sprayer with potential to spray patches, which could either be a 'retro-fitted' patch spraying modification to an existing sprayer, or a new sprayer. If the user was 'content' only to apply herbicides on a spray / no spray basis there would be no need to include the cost of conversion of the sprayer, but as discussed elsewhere a low dose / high dose strategy is preferred to a spray / no spray one.   In both situations some new software would be needed to process the weeds maps and create the spray application map.

The second area of expenditure, is the cost of creating the weed map. As automated detection is not yet a practical option (see Section 3) the map has to be created by an observer. This has been discussed in some detail in Section 3 and the conclusion was that it would cost in the region of £2/ha, but this cost could be discounted over several years, depending on the stability of the patches of each weed species and hence the frequency of re-mapping.

The third area of costs is the provision of software that will convert the weed distribution maps into treatment maps that will control the sprayer. This may need some specialist software, such as that provided to this project by Patchwork Technologies. These costs are relatively small, compared to the 'hardware' costs.

6.4 Cost/benefit analyses

Two alternative scenarios will be discussed. The first relates to a farmer/contractor with no previous involvement in precision agriculture and the second to one who already has GPS equipment and yield mapping capability on the combine harvester. Both users are assumed to be arable farmers, or contracted to arable farmers, with winter wheat as the main crop and with infestations of grass weeds. This assumes herbicide applications will be on a low dose / high dose or spray / no spray basis.

6.4.1 Farm with no previous use of precision agriculture

In this scenario the farmer would need to purchase all the necessary GPS equipment and computer controls. The recent report on the HGCA funded Precision Farming project (Godwin *et al*., 2002) suggests that the costs of equipping a farm to benefit from the techniques of 'precision agriculture' will vary from £4,500 to £16,000. Information from the commercial partners in this 'weed' project suggests that if the user had no existing equipment, the costs to patch spray weeds would be between these extremes,. Thus, the cost of GPS location and control systems would be in the region of £4,500. The second equipment element is the patch sprayer. The cost to provide the ability to patch spray using the Micron PatchSpray System would be in the region £3,000. This could be retro-fitted to a current sprayer or fitted to a new machine. It must also be remembered that the system would also be able to spatially vary liquid fertiliser treatments. The cost of converting an injection metering sprayer, such as the Spra-Coupe, which would also have the potential to patch spray, would be somewhat higher, but this machine would have the potential of spraying two products at once, a feature not possible on the PatchSpray system.

6.4.2 Farm already generating yield maps

If a farmer or contractor is already equipped to yield map, the cost of equipment to patch spray weeds is less. The user still has to buy or convert a sprayer so that it is capable of patch-spraying, as did the user with no experience of 'precision agriculture'. The GPS and computer control systems, such as AGCO's 'Fieldstar', would not need to be purchased and so their costs could be set against both fertiliser application and patch spraying weeds. Thus, the actual outgoing costs of starting to patch spray weeds could be less than £2,000. This low cost would assume that the farmer was purchasing a new sprayer and equipping it to patch spray (the cost of the new sprayer is not included). If the patch sprayer was created by modifying an existing machine the set-up costs would increase to about £4,500.

6.4.3 Overall costs

In the absence of any previous involvement in Precision Farming, the costs of setting up to patch spray weeds would be approximately £8,000 (£4,500 for GPS and control systems, £3,000 for spatially variable application technology, £500 for relevant weed mapping software). If the user is already yield mapping this cost could be reduced to less than £2,000. There are no extra spraying costs as the system is simply applying a product that would have been applied anyway, to parts of fields, instead of whole fields. There was no evidence that patch spraying was slower than conventional practice particularly since the control actions are taken automatically.

6.4.4 Preliminary conclusions of cost benefit analyses

Assuming the costs outlined in 6.4.2 are realistic, herbicide savings have to exceed the cost of the equipment and software, and the cost of mapping (when it is done as a special operation). Thus, a conservative cost of

£8,000 for the equipment and £1.00 ha^{-1} for mapping (assumes mapping only one year in two and/or summer mapping being done as part of another operation) has to be balanced with a saving of *c.* £6 ha on the control of patches of grass weeds. After removing the mapping cost from the herbicide saving, it would suggest that the sprayer has to be used on approximately 1600 ha to recover the costs (conservative conclusion = approximately 2000ha). This cost could be retrieved over several years, so the farmed area of winter wheat infested with spatially aggregated grass weeds needs to be around 7-800 ha. If the farm outlay to set up a patch spraying system is lower, as it would be if elements of precision agriculture such as fertiliser application were already being used, then less than 1000 ha needs to be treated and so the area of wheat treated each year need only be *c.* 300 ha.

This scenario depends on herbicide savings being around c. £4-7 ha^{-1} (mean £6), which according to the sprayed fields in this project and in the modelled maps seem possible. However, if extreme caution is used in selecting doses to apply to the non-patch areas of fields, and/or the weeds infest a high percentage of the field, the savings would be lower. This can be seen in some of the scenarios modelled in Table 6.3. Conversely, with greater confidence from experience in using the system encouraging more spray/no spray decisions and greater dose reductions in the non patch areas, where low/high systems are used, saving of greater

7.0 Conclusions

The overall aim of the project was to optimise herbicide use by developing a spatially selective weed control system for arable crops. This meant integrating all the component parts of the system: GPS location and weed mapping, creation of a treatment map and application system.

It was concluded that weed species which tended to be: a) aggregated in distribution, b) were expensive to control and c) which received specific herbicides, were most appropriate for patch treatment. The most appropriate targets were thought to be the annual weeds black-grass, wild-oats, bromes and cleavers, and the perennial weeds creeping thistle and common couch. Almost all the work in the project was aimed at these species, though fields with some other weeds (e.g. onion couch) were also mapped.

7.1 Weed biology

The biological studies included in the project were aimed to build on existing data on the spatial behaviour of patches. It was targeted at improving our understanding of why weeds are aggregated in distribution and quantifying how stable the patches were. This information is needed to estimate how often fields need to be re-mapped.

7.1.1 Stability of patches

Research in the previous project has shown that black-grass patches were relatively stable, though cultivations would move seeds about 3 m. In this project we investigated the stability of patches of wild-oats and cleavers. The latter seem to behave like black-grass, as movement of the patches was limited. However, wild-oat patches are clearly more unstable. This was not because the core of the patches moved great distances, because they too only moved 3 m or so, but rather it was the appearance of isolated plants as far as 30 m from the original patch. These were presumably trapped inside the combine harvester and eventually were returned to the soil some distance from their origin where they could start to form new patches. Consequently, in the absence of some control in the non-patch areas, new patches would have the potential to form quite frequently. Natural dispersal only moved seeds a maximum of 2 m.

The overall conclusion was that patches of cleavers and black-grass, once properly mapped, need only be re-mapped every three years, whilst the less stable wild-oats and brome would probably need mapping every other year. Perennial weeds would need mapping less frequently. When converting weed maps to treatment maps, it would be prudent to include a 4 m 'buffer' around the patches to allow for errors in detection, GPS drift and the movement of seeds by cultivations, natural dispersal and harvesting operations.

7.1.2 Why do patches occur

Work in the project, coupled with extensive study of the published literature, concluded that there are many reasons for weed patches occurring in fields. Basic research has shown that random events occurring in a field uniformly infested with weeds will generate aggregated weed distributions. However, there is also evidence both from the work done in this project and from other published data that variation both in soil characteristics and topography can influence weed distribution. This was most clearly seen in this project on Cashmore field where the black-grass was concentrated in the bottom part of this sloping field, where the soil had a high clay content. Other, agronomic events, such as a serious spray miss and poor crop establishment may result in new patches of weeds. Similarly old hedge lines in newly amalgamated fields can be the focus for weed infestations. Thus, there are many reasons for the occurrence of patches in fields, some under the control of the farmer and some not.

7.2 Mapping

Map-based patch spraying has a number of advantages over real-time treatment. The availability of the weed map prior to treatment provides an opportunity for the user to reflect on product choice and dose prior to use, and to estimate precisely product requirements so that the risk of putting too much herbicide solution in the sprayer is minimised. Real-time treatments have none of these advantages, but do have the benefit of not having to carry out a separate operation to create the weed map. In the project it was decided that a map-based approach was most appropriate for 2002.

7.2.1 Visual mapping

The project aimed to deliver a system that could be used by farmers in 2002. This meant focussing on visual mapping of weeds. The work showed that it was possible to create maps of weeds from presence/absence records collected by recorders travelling up and down tramlines in tractors or all-terrain vehicles, depending on the time of year. Such presence/absence maps did not fully match the more time consuming weed quadrat counts taken on a grid basis, as it was not always possible to see low densities of weeds, especially when small. Additionally, an element of extrapolation (kriging) was needed to fill in the gaps in the assessment areas between the tramlines that could not be assessed from the mapping vehicle. Despite these shortcomings the maps generated correlated well with the quadrat counts. However, their shortcomings especially with difficult to see small weeds, emphasises our preferred option of spraying high rates of herbicide on the weed patches and a low rate on the rest of the field (low dose/high dose system). Although, this reduces the herbicide saving compared with a spray/no spray system, it ensures that low weed densities, that may have been missed when mapping, are treated. This 'conservative' approach could be relaxed once the user was satisfied, perhaps after 2-3 year's experience that the maps really did fully define the infested area. Another biological feature of the weed patches that also reinforces the low dose/high dose approach is

the fact that the weed patches 'wax and wane' each year depending on the weather and soil conditions at emergence. Patches will appear larger in years with a high % weed emergence and smaller when emergence is lower. Because of this, 'new' fields should be mapped more frequently in early years.

During the course of the project we explored several methods of recording the data. Initially the 'Fieldstar' touch sensitive screen was used to record weed presence/absence, but this was difficult to use, especially on the ATV. As a consequence the possibility of using voice recognition was explored. This worked well but it must be remembered that the software has to be trained to recognise each user's voice. A third method, using a bank of toggle switches was developed in the final year of the project. Both this and the voice recognition system seemed practical, though the latter requires the use of a robust portable computer that may not always be available.

Obviously creating a map takes time and by recording the time taken to map fields we concluded that visual mapping from an ATV can be done at 3 ha/h and from a tractor at a faster rate of around 4 ha/h. This would mean that mapping would cost around £2/ha. It seems possible to map from a tractor whilst doing another operation and from the combine when harvesting. In which case the cost of mapping drops to nearly zero. We only had limited experience of doing two operations at once in the project (e.g. mapping and fertiliser application), but those involved thought it feasible.

Weeds varied as to the time of year when it was possible to create a map. Common couch, for example, was only really visible at harvest, whereas black-grass was most evident in mid summer. The timing of mapping in winter depended on sowing date, as the weeds such as black-grass and cleavers needed to reach a minimum size before they were sufficiently visible to be mapped.

7.2.2 Automated detection

A number of those consulted on the project believe that patch spraying will only be successful if mapping can be automated. There is a dichotomy of view as to whether automated detection should create a map for later use or whether it should be linked to real-time treatment. At the moment both are theoretical concepts, as neither is possible in narrow row crops such as cereals and oilseed rape. However, as part of the project work was done to assess whether visual imaging could create sound weed maps. Studies with a video camera indicated that it was extremely difficult to achieve reliable weed maps. It was not possible for the camera to discriminate between green weeds in a green crop, especially in the changing light conditions that often occur under the variable UK climate. Other researchers in Europe are finding it equally difficult to achieve good discrimination between crops and weeds, but progress is being made, and automated detection may become a reality before the end of the decade. Spectral reflectance and other related methods using specific wavelengths of light, including infra-red, also offer some possibilities for automated weed

identification. Although laboratory research indicates that discrimination between crops and weeds is possible, field tests have failed, because of weather induced variability in reflectance. However, the project has explored the possibilities for semi-automated detection, using reflectance systems, combined with field walking. In this part of the project NDVI sensors mounted on a tractor were used to create maps of 'greenness' of fields in the first few weeks after crop emergence. The study in autumn 2001 explored whether areas of high green were associated with weed patches. This worked reasonably well, but users must walk the field with the map: a) to identify which weed species are present and b) to determine whether increased greenness is due to weeds and not to other agronomic factors (e.g. double drilling). Once the causes of the differences in greenness have been identified the vegetation index map can be used to delineate the weed infested areas. Further testing is needed to establish the full potential of the technique.

7.3 Conversion of the weed map into a treatment map

The 'raw' weed map showing where the weeds are within the field cannot be used directly to control the sprayer. Computer programs have been developed that enable spatial data to be input, manipulated and written out as treatment maps in a range of formats using different transfer media to suite the available hardware. One such program, 'Patchwork', (Patchwork Technology, Pontypool, UK) was used as the basis of our development work in this project. The aim of the work was to define the components of a weed patch to treatment map transform. This involved:

i)   reading the weed data into the software package
ii)   interpolating the recorded data to define discrete weed patches and recognise outlying weeds
iii) extend the patch boundaries to account for weed and seed movement and the accuracy of the in-field location system
iv)   defining treatments to be applied (products and doses)
v)   writing the treatment map to the appropriate output media

This task was successfully accomplished but it must be noted that the actual selection of appropriate doses for different areas of the field was not part of the project, although a key issue. Choice of doses was based on 'expert opinion' though in future such choices may be possible from the LINK Weed Management Support System project.

7.4 Herbicide application and system testing

A number of fields were treated with the Micron PatchSpray sprayer, using the weed and treatment maps created in the project. The maps were installed in the 'Fieldstar' controller and this instructed the

sprayer to apply herbicides to the weedy area of the field. The sprayer has a double boom with different nozzles in each boom. Variable dose rates are achieved by changing volume rates which is achieved by switching between booms and changing pressure. The two together give the potential for a 300% change in application rates. The 'system' worked reliably and herbicide applications were as required by the treatment map. Most fields were sprayed with a low dose/high dose system, whereby the patch area received a high dose and the rest of the field a low dose, although one field (infested with thistles) was sprayed on a spray/no spray basis, with the non-patch areas being untreated. Herbicide doses were decided by the staff at Silsoe and Rothamsted, and the range used varied according to the perceived dose flexibility of the product concerned. The patches were generally sprayed at the recommended rate and the 'low dose' was between 30% and 80% of the full rate. The low dose/high dose approach was used to ensure that unmapped low level infestations were at least suppressed by the herbicide and could not form the focus of new patches in subsequent years, as discussed in the earlier section on mapping. Weed control was acceptable but in some fields weeds, especially black-grass, survived. Survivorship was not associated with the variable rates, but was related to other factors.

In February 2002 the project was demonstrated to more than 60 delegates, representing all sectors of the industry. As well as formal lectures there was a 'live' demonstration of weed mapping, creation of the treatment map and spray application.

7.5 Economics

The financial benefits of patch treatment were calculated for the six sprayed fields and, in addition, application maps were created for eight further fields that had been weed mapped. These eight application maps effectively replicated what would have occurred if the fields had been sprayed. The overall conclusion was that in the winter wheat crops sprayed for the control of grass weeds, using a low dose/high dose strategy, savings of £2-10/ha could be expected. This was a cautious approach and if a bolder approach of spray/no spray had been used savings in herbicide would have increased to £4-20/ha. Such a bold approach may not be appropriate in the first year or so of patch spraying a field, but once sound records and maps of the weedy areas are available, this technique may be more appropriate. It must be remembered that the amount saved will depend on the % of the field infested and on the cost of the herbicide. The low savings tended to be on fields where over half the area was infested and where treatment was with a cheap product (e.g. isoproturon for black-grass). Greatest savings were achieved in a field of sugar beet treated twice with clopyralid to control thistles. This field was treated on a spray/no spray basis and savings were nearly £20/ha.

These savings have to be balanced against the cost of application using the patch spraying technique. Firstly, if the map has to be created as a separate operation, for example from an ATV, this will cost in the region of £2/ha. This cost can be discounted over 2-3 years, depending on the frequency of re-mapping. Also there would be no cost, if mapping was done as part of another farm operation. Equipment costs to allocate to patch spraying are difficult to estimate because they depend on the level of involvement of the farm in other aspects of precision agriculture. If the farm was already yield mapping and applying fertiliser on a spatially variable basis, costs of the equipment should be shared between the different activities. Overall, costs of the GPS and control systems would be in the region of £4,500 which could be used for a range of precision farming activities. The other cost that must be included is the cost of the sprayer. The conversion of a sprayer so that it will patch spray will cost approximately £3,000 and the software to create the treatment maps about £500. Overall a conservative cost would be £8,000 in total, which would be reduced to approximately £2,000 if the farm already owned equipment for yield mapping and fertiliser application.

If herbicide savings are in the region of £6/ha, mapping costs overall are £1/ha and the equipment to patch spray costs £8,000, then the sprayer has to be used on approximately 2000 ha to recover the costs of treatment.

7.6 Environmental implications

The technique of patch spraying weeds has other benefits apart from those involving finance. The reductions in herbicide use that can be achieved with the technique also have environmental benefits, helping to reach Government objectives of ensuring that pesticide use is kept to the minimum necessary. If herbicide use is reduced by 20% on those farms employing the technique, as seems possible (mean herbicide saving on sprayed fields in this project = 25%), then an appreciable reduction in the 8 million ha of cereals treated with herbicide in 2001 (Crop Protection Association, 2002), could be achieved. However, the imponderable factor is the level of uptake by the users. Although currently only a very limited number of farmers are patch spraying, in future greater availability of spray controllers with automatic controls and the anticipated decline in cost of geo-referencing computer systems, coupled with the absence of the need to pay for a differential signal, will make the technology cheaper and more attractive to users Although patch spraying is more complex than blanket treatments, this complexity has to be balanced with economic benefits and with environmental and regulatory requirements. The application record map produced by 'Fieldstar' provides a written record of where and how much herbicide has been applied to each treated field. This clearly complies with requirements of crop assurance schemes and the demands of those purchasing the crops. Currently this applies particularly to those selling direct to supermarkets but in the future is likely to be

equally relevant to commodity products such as cereals and oilseed rape. It also provides evidence of compliance with regulatory requirements such as LERAPS.

7.7 Relevance to levy papers

The main message for levy payers from this project is that there are financial savings to be made from using this technology, especially where grass weeds and cleavers are a problem. But, if the fields have high levels of infestation, the savings with the current sophistication of the technology will be small. All the component parts of the system are in place and it would not be difficult for a farmer already yield mapping to start patch spraying weeds, as much of the location and computing technology is the same. However, expenditure on a spatially regulated sprayer, or a retro-fit kit for a current sprayer, would be essential. The cost of equipment to achieve patch spraying is not insignificant (see above) and so the sprayer will need to be used on an appreciable area to recoup the initial outlay. The other constraint is that the user has to have the time to create the maps, either when doing other activities or as a 'stand alone' task in the winter/early spring.

The other benefit to levy players is that the technology provides a tool to help meet the increasing environmental goals of agriculture. The technology will provide printed evidence of compliance with environmental regulation, in relation to herbicide application. In the future this may be required by DEFRA or by those purchasing the crops, as part of crop assurance schemes.

8.0 Technology Transfer and Publications

8.1 Technology transfer

The following activities and publications, aimed at increasing the awareness of the industry to the work of project, were done/produced between 1998 and 2002.

8.1.1 Demonstrations

Demonstrations took place at Cereals 1999 and at Sprays & Sprayers 1999, 2000 & 2002. A specific demonstration of the project was held at SRI in February 2002 (see Section 5).

8.1.2   Dissemination of information to potential users

Articles in the farming press:

Farmers Weekly 7 Jan. 00 – Is patch spraying worth investment?

Farmers Weekly 7 Jan. 00 – Patch sprayer gives costs a good soaking

Crops 27 May 00 – Precision moves ever closer

Farmers Weekly 16 Feb. 01 – Maps and detection key to patch spray progress

Crops 17 Mar. 01 - Thistle up ahead, couch left

Crops 31 Mar. 01 – Cutting-edge time savers

Crop Production April/May 01 - Patch-spraying – a route to herbicide savings

Crops 23 June 01 - Satellite spraying sees big savings

Agrow Supplement Autumn 2001 – Precision agriculture – the future of crop protection

Farmers Weekly 23 Nov. 01 – Patch spraying waits to take off commercially

Farmers Weekly 1 Mar. 02 - His master's mapping voice

Crops 2 Mar 2002 - Patches offer potential

Arable Farming 9 Mar. 02 - Patch dynamics

Newsletters:

SRI News Summer 98 - success for patch sprayer

HGCA Topic Sheet 13 spring 98 - developing a weed patch spraying system

Agriculture Link Newsletter March 99 – Patch spraying develops

SAPPIO Programme Fact Sheet 00 – Exploiting weed patch dynamics

ARIA Newsletter Dec. 01 – exploiting weed patch dynamics

8.2 Published papers

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