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DEVELOPMENT OF A 'PATCH SPRAYING' SYSTEM TO CONTROL WEEDS IN WINTER WHEAT

by

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Contents

1. EXECUTIVE SUMMARY

Weeds are not uniformly distributed within fields but are spatially aggregated, occurring in patches. In principal there is no need to treat the areas of the field where the weeds are not present. Recent advances in technology now offer possibilities for the spatially selective application of herbicides. This could result in reductions in herbicide use and thus in the cost of weed control and in the environmental impact of the products used. This LINK project has investigated the potential for spatially selective treatment and developed methodologies for weed mapping and for the spatially selective application of herbicides.

1.1 Weed patch ecology

A basic understanding of the ecology of weed patches is essential for the development of successful patch spraying systems of weed control. As these systems will depend on the production of historical maps to describe the distribution of weeds within fields, information is needed on the extent and speed of change of the patches and the factors causing these changes. Three important aspects of patch dynamics have been investigated in the project: seed movement resulting from soil cultivation, seed movement by combine harvesters and pollen movement in black-grass. This work has shown that the movement of seeds by cultivation is relatively limited, most seeds would not move more than 2m. Combine harvesters have the potential to cause greater movement of a small percentage of seeds. The amount of movement depends on the proportion of seeds shed prior to harvest and the nature of the seeds. Our experiments have shown that the majority of black-grass seed is not moved very far by combines. However, observations on other species such as brome grasses indicate that a greater percentage of seeds could be moved further. Studies on pollen movement of black-grass confirmed a very rapid decline in pollen density away from the weed patches but this was not reflected in a similar steep decline in seed production, indicating that isolated plants only required small amounts of pollen to fertilise the seeds.

Modelling studies have also been carried out with black-grass to predict how patches might be expected to behave under contrasting management systems, with and without spatial selectivity. The studies indicated that intra-specific competition between weeds will tend to decrease patchiness. In contrast, patchiness will be maintained if weed seed dispersal is limited. Annual variability in weed seed production will tend to cause the patches to expand in years of high production and contract in years of low production.

As far as can be judged from the limited field evidence and from the specific studies carried out in this project, the patches of many common key arable weeds will remain relatively static. Further work is needed to confirm patch stability.

1.2 Weed mapping

This aspect of the programme was aimed at the production of field maps, identifying the areas infested with weeds. These would subsequently be used to control the application of herbicides with the patch sprayer. When the project started mapping techniques were poorly developed and initial maps were created by simply walking round patches, marking weed positions with canes and measuring their position with a tape measure. As the project developed, a new, more automated mapping system was developed. A high clearance vehicle was used to provide a good viewing platform from which weed occurrence was recorded onto a computer by means of a simple key pad. At first, navigation was by recording the wheel revolutions to establish distances along tramlines. Later, Global Positioning System (GPS) technology was used to locate weed positions. Differential GPS systems are now being widely used for a range of spatially based agricultural operations. Some problems were experienced with the reliability of the GPS systems but the technology is rapidly improving.

The work concentrated on mapping the following species: black-grass (*Alopecurus. myosuroides*), wild-oat, (*Avena fatua*), barren brome, (*Bromus sterilis*) and common couch grass (*Elymus repens*). These species were selected because of their economic importance, their spatially heterogeneous distributions within fields and their visual presence at times of year and in crops that permitted visual mapping of their distributions. A total of 25 fields were mapped, some several times to record different weeds. The best time to map the distribution of grass weeds within the farm rotation is natural regeneration set-aside, when the full extent of the weed patches should be visible. It is also possible to map after spray application from June-August, when the weed seed heads are above the crop and easily visible. The six populations of common couch which were mapped showed a range of distribution patterns, the areas infested ranging from 3 to 79% (mean = 37%). Thirteen fields of black-grass exhibited infestation levels of 4-85%, with a mean of 51%. Thus, for the two main surveyed weeds more than half the field area required no treatment for weed control.

Further work showed that the precision and repeatability of the weed maps was high and that it was possible to map weeds whist walking along tramlines and from combine harvesters. Some issues remain to be resolved such as: how easy is it to map from a tractor, how do you map weeds satisfactorily when tramlines are 18 or 24m apart?

In this project, we have developed techniques for mapping weeds on a whole field scale using systems that are fully compatible with the patch sprayer.

1.3 Creation of treatment maps

The weed map has to be converted into a map that can be used to control the sprayer. In order to ensure that all the weeds in the patch were treated, to take account of any small navigation errors and to allow time for the sprayer to switch on and off, buffers (surrounding areas around each identified patch) were added to the weed maps. It was concluded that each patch should be increased by 4m.

1.4 Patch spraying

The project used an experimental patch spraying rig which was designed and constructed at Silsoe Research Institute as part of project work funded by the Ministry of Agriculture, Fisheries and Food. The system had been designed to use a novel injection metering system developed by the Institute The experimental patch sprayer was based on an existing 12 m mounted design, modified to accommodate the injection metering system. The system was designed to operate with clean water in the spray tank and concentrated chemical formulation was metered into the spray delivery lines at a rate which depended on the speed of the spraying vehicle and the required dose. The system was designed to achieve the highest practical spatial resolution with a rapid and uniform response time characteristic along the boom, which was divided into 2.0 m sections, giving a treatment resolution of 2x1m.

The patch sprayer was controlled by the treatment map which was stored on a personal computer mounted in the tractor cab that was connected to the control system of the sprayer. In-field location was initially determined from the distance travelled down tram-lines but subsequently by using the GPS system described in Section 1.3.

The objectives of this part of the project were to: demonstrate the operation of the system with a range of active herbicide formulations, to examine the performance of the system in large scale field trials and to carry out further development of the system, as needed. The field performance of the sprayer was tested using a tracer dye and a desiccant herbicide (diquat). Following some modifications to the system as a result of this developmental work, the tests indicated that the injection metering and sprayer control systems functioned effectively. The sprayer was used to apply herbicides to seven fields, using the weed maps to control the sprayer. As the sprayer has a twin boom, it was possible to apply one herbicide as a uniform treatment and to apply the second one in a spatially selective way. A range of different aspects of the spatial application technology were explored during these studies. The work demonstrated that the prototype sprayer was capable of applying the herbicide where instructed by the map. As the project reached its conclusion, the development of a commercial patch spray system was started in collaboration with Micron Sprayers.

1.5 Economics of patch spraying

The uptake of patch spraying practice is likely to depend on its ability to show real long term economic benefits. Preliminary analyses showed that financial benefits attributable to patch treatment of weeds can be calculated for the two weed species, which were studied most intensively in this work, black-grass and common couch. Using the standard herbicides available for the control of these weeds, the single year economic savings were estimated to be in the region of £5-10/ha/yr, depending on the spray strategy adopted. Further estimations of the economic benefits have been obtained from calculations of the amount of herbicide used on the patch sprayed fields. Savings were appreciable, being in excess of 40% in 6 of the 7 tests, with a mean financial value over the seven experimental treatments of £15/ha.

Modelling studies with black-grass over a ten year period also indicate that savings would be between £3 and £20/ha/year, depending on the level of infestation. This work also indicates that costs of control over ten years are likely to be lower if the areas outside the defined patches are treated with a low herbicide dose rather than not being treated, as the dual-dose system is less sensitive to weed seed dispersal.

1.6 Conclusions

The work carried out over the last four years has clearly identified the potential of this technology for the treatment of weeds. Using computer and satellite location technologies it is possible to map weeds at certain times of the year to an accuracy of 2-4 m. This information can then be used to control the application of the herbicides. The requirement for a sprayer with a definable and rapid on/off response time has been met by the work at Silsoe Research Institute, based on an injection metering control system. The simplified analysis of the economics of patch spraying shows substantial benefits but further work is required to assess the economic benefits more fully. Thus, this project has progressed the patch spraying of weeds from a theoretical concept to a reality. There are still a number of unanswered questions but the basic information to develop commercial, practical, spatially selective weed control systems is now in place. The commercial development of the system is the next phase of the project and the collaborative work between Micron Sprayers and Silsoe Research Institute is already laying the groundwork for such progress.

2. INTRODUCTION

The distribution of weeds within fields is not uniform and they are generally spatially aggregated in "patches" (Marshall, 1988; Mortensen *et al.*, 1993; Rew *et al.*, 1996a). This is most easily seen in fields infested with tall weeds in late summer, when patches of thistles (*Cirsium arvense* L.), wild-oats (*Avena fatua* L.) and black-grass (*Alopecurus myosuroides* Huds.) are a common feature of the arable landscape. Lower growing weed species are more difficult to see but many of them are also patchily distributed. The only generalisation we can make is that aggregated distribution is very common but there is little detailed information to support this conclusion. This spatial heterogeneity has clear implications for weed control. In principle it is only necessary to control weeds in the areas of the field where they occur. In practice this has been impossible to achieve up to now, except in a very coarse way. Farmers will turn off spray booms on certain tramlines if they are certain that the weeds are not present in that part of the field. More carefully targeted applications of herbicide to weed patches offers the potential to reduce herbicide use significantly, giving both economic and environmental benefits. Recent technological developments have made it possible to contemplate the development of such spatially selective treatments.

Spatially selective treatments for narrow-row arable crops are likely to be based, for the foreseeable future, on visually created weed maps that are used to control the sprayer. Automated detection is not yet an option for closely spaced crops such as cereals and oilseed rape. On fallow land and in wide-row crops such as maize and soybeans automated detection is possible because it is based on either spectral reflectance or image recognition to identify green weeds (between the crop rows) against the brown soil (Felton, 1995; Stafford & Benlloch, 1997). Such a system will not function in narrow-row crops as the detectors are not able to separate green crop plants from green weeds. Research is in progress to use differences in leaf shape and cover (Gerhards *et al.*, 1995) or spectral reflectance (Brown *et al.*, 1994) to distinguish weeds from crops but commercial systems are unlikely in the near future. Consequently, weed detection has to be done by eye. The creation of the map has been simplified by the availability of Global Positioning Systems (GPS). Prior to this, weeds could only be mapped by using a tape measure or by some method using dead-reckoning, such as recording the distance travelled from the number of wheel revolutions. This was not very practical, and GPS, assuming it was sufficiently accurate, would provide a technique that would overcome these problems.

The second issue needing to be studied was the development of a spatially controllable sprayer. Research at Silsoe Research Institute indicated that injection metering could provide a technique ideal for subdividing spray booms into the smaller independent sub-units required to provide the resolution needed to optimise the benefits of patch spraying (Paice *et al.*, 1995, 1996) Simply organising the sprayer to turn on or off would only provide spray 'cells' at least 12m wide. There was a need to subdivide the boom so smaller 'cells' could be treated.

Thus, a spatially selective system of weed control seems to require four elements: a computer-based navigation system coupled with visual observation to generate weed maps, a system to convert the maps into instructions for controlling the sprayer, a sprayer designed to apply the herbicides to the mapped patches and expert knowledge of the herbicide doses required to control the varying infestation levels. The fourth element was not included in the specific tasks of the project but would be needed in a practical spatially selective weed control system.

As spatially selective treatments need to be based on historic weed maps, information on the stability of weed patches becomes of considerable importance. Knowledge of the stability of patches is essential because very stable distributions need only be mapped occasionally whereas, rapidly changing patterns of distribution would either be impossible to patch spray or would need regular re-mapping. Evidence for the stability of weed patches is scarce. The only detailed UK study is that reported by Wilson & Brain (1991) which monitored the distribution of black-grass in a field in Oxfordshire over a 10 year period. This work concluded that the weed patches were quite stable, but as the sampling grid was quite coarse (36 x 40m) local changes, relevant to more precise patch treatment, would not have been identified. Detailed studies of two fields in Nebraska containing several broad-leaved weed species over four years (Gerhards *et al.*, 1997) also showed that weed patches were stable, indicating that seedling distributions in one year were good predictors of future distributions.

The overall objectives of the programme were to develop technologies for patch spraying weeds, including mapping, sprayer design, weed spatial dynamics and economics, that would form a sound basis for the subsequent commercial development of patch treatment of weeds.

Project Objectives

1. Mapping the distribution of weed populations on a field scale to create maps which can be used:
    - i) as treatment maps for spatially selective herbicide application
    - ii) as records of the scale and pattern of patchiness on different sites and, thus, the potential savings in herbicide use.
    - iii) as evidence for the degree of stability of weed patches over time

2. Studying the engineering requirements for the sprayer to achieve the control of delivered material.

3. Studying some of the biotic and abiotic factors controlling weed distribution that influence the balance between stability and movement.

4. Development of a computer model of spatial dynamics of black-grass incorporating known information and new data from this project.

Information on all four aspects outlined above is required to establish the potential economic benefits of patch spraying. The programme has examined alternative methodologies to create maps of weeds, incorporating recent advances in satellite location technologies. It has also explored the engineering requirements for effective spatially selective herbicide applications. The biological studies have included a range of weed species but most effort has been concentrated on common couch (*Elymus repens* (L.) Gould) and black-grass (*A. myosuroides*). This is justified by the economic importance of these weeds in cereal crops and because there was clear evidence of their aggregated distribution. Additionally, the model of the spatial dynamics of black-grass being developed would benefit from the biological data generated in other parts of the project and could be re-parameterized in the future for other annual species. In contrast, a wide-spread effort on a greater range of weeds could result in both the specific and general objectives being poorly served. The economic consequences of spatially selective treatments have been investigated, in order to determine the potential savings that are possible with this system.

3. PATCH ECOLOGY AND DYNAMICS

A basic understanding of the ecology of weed patches is essential for the development of successful patch spraying systems of weed control. As these systems are likely to depend for the foreseeable future on the production of historical maps to describe the distribution of weeds within fields, information is needed on the extent and speed of change of the patches and the factors causing these changes. Both biotic and abiotic factors will influence patch behaviour and a number of perhaps conflicting factors may be involved. For example, agricultural practices are intended to ensure homogeneity but weeds seem to be aggregated in distribution, despite years of uniform treatment. Why? In contrast, we would expect from basic plant ecology that new weed patches would appear and existing ones would expand. Seeds must be moved by human activity and seed production per plant is likely to be greater at the edge, than at the centre of dense patches, where it is restricted by density dependent weed/weed competition. The success of the isolated plants at the edge of an expanding patch will depend on their success in establishing and producing seed. These isolated plants may be more vulnerable to predation by vertebrate and invertebrate predators and the seed set of out-breeding species will be reduced in the absence of sufficient amounts of viable pollen from other plants. Agricultural operations such as combine harvesting and soil cultivation could be also expected to expand and move patches, transporting seeds and vegetative propagules within and, in some cases, between fields. Yet it seems from field observations, farmer experience and limited scientific data that weed patches are relatively stable. The ten-year study reported by Wilson & Brain (1991) on black-grass in a cereal/grass rotation showed that the weed grew in well-defined patches that remained relatively static over the ten year period. The black-grass was less abundant in some years than in others, and in the years with lower infestations the patches appeared smaller. Clearly, a better understanding is needed of factors controlling the dynamics of weed patches.

During the course of this programme three important aspects of patch dynamics have been investigated:

i) seed movement resulting from soil cultivation
ii) seed movement by combine harvesters
iii) pollen movement in black-grass

Additionally, modelling studies have been carried out to predict how weed patches might be expected to behave under contrasting management systems, with and without spatial selectivity. This work was aimed at reducing the amount of field work needed to predict patch behaviour.

3.1 Seed movement

3.1.1 Soil cultivation

Horizontal movement of seeds by different cultivators was investigated in three experiments during 1994, 95 and 96. Seeds of barley (*Hordeum vulgare*), field bean (*Vicia faba*) and oilseed rape (*Brassica napus*) were positioned on the soil surface or buried 0.1 m deep prior to cultivation. The soil was then cultivated with several different implements (plough, flexi-tine cultivator, spring-tine cultivator, power harrow) once, twice or three times. Seed movement was assessed by counting germinating seedlings (0.01 m^2 grid). More details of experimental procedures are given in Rew & Cussans (1997)

The type of tine implement used significantly affected mean seed movement Primary cultivation with flexi- or spring-tine moved seeds further than a straight-tine or power harrow. However, there was no overall difference between plough and flexi-tine mean seed movement. A single pass with a tine attached to a seed drill moved seeds less than two passes with tine plus seed drill, but the first pass had the greatest effect. Small oilseed rape seeds moved significantly further than larger barley or field bean seeds. The size of rape seeds equated more closely to weed seeds and therefore they could be expected to travel the slightly greater distances shown by the rape. Overall, more than 84% of seeds moved ≤ 1 m from the source (Table 3.1). No seeds were observed > 4.8 m in forward direction or > 0.2 m backwards from the source. Surface sown seeds were moved significantly further than buried seeds (Table 3.2).

Table 3.1 Mean percentage movement of seeds when cultivated with different cultivation implements, sowing positions and plant species combined. RPH = rotary power harrow; t = tine; D = drill; x2 = two passes.

		Experiment 1				
% movement	Overall mean	Straight-t, RPH & D	RPH x2 & D	Spring-t, RPH & D	Flexi-t, RPH & D	Implement S.E.D
Within 1m	93.4	95.9	91.0	92.7	93.8	1.42
>1 m	6.6	4.1	9.0	7.3	6.2	
Backward	5.7	7.3	8.5	2.5	4.4	2.31
		Experiment 2				
		Flexi-t, RPH & D	Flexi-t x2, RPH & D	Plough, RPH & D		Implement S.E.D
Within 1m	84.1	87.6	78.9	85.8		7.60
>1 m	15.9	12.4	21.1	14.2		
Backward	3.5	7.2	2.3	1.4		3.79
		Experiment 3				
		RPH	RPH & D	RPH x2 & D	Flexi-t & D	Implement S.E.D
Within 1m	93.1	95.2	94.4	89.4	93.5	1.54
> 1 m	6.9	4.8	5.6	10.6	6.5	
Backward	3.2	3.1	2.8	5.8	1.0	1.64

In a fourth experiment plots containing seeds of charlock (*Sinapis arvensis*) were cultivated in alternate directions in successive years. The results broadly validated the findings of the previous experiments, as seeds on tined cultivated plots moved a mean distance of 0.43m and those on ploughed plots 0.87m.

Table 3.2 Effect of seed position (surface, buried) on the movement of seeds by cultivation implements (mean of cultivation treatments and species). Data = % movement

	Experiment 1			Experiment 2			Experiment 3		
	Surface	Buried	S.E.D	Surface	Buried	S.E.D	Surface	Buried	S.E.D
Within 1m	91.2	95.7	1.00	79.2	90.3	7.91	88.3	97.9	1.09
> 1 m	8.8	4.3		20.8	9.7		11.7	2.1	
Backward	7.42	3.94	1.63	5.1	13.7	9.19	4.5	1.9	1.16

Thus, we have concluded from this work that soil cultivations are unlikely to cause substantial movement of seeds, and 2m per year is the maximum likely spread by cultivations.

3.1.2 Combine harvesting

Combine harvesters have the capability to move a small proportion of the seed a long distance. This contrasts with cultivations which potentially move all the weed seeds in a population a small distance. Following some preliminary studies on seed movement in *L. multiflorum* in 1994, an experiment was done in 1994/95 to study the distance moved by black-grass seeds from 10 x 10 m plots by a Claas combine harvester. The area beneath the swath was removed in 1 m^2 sections with a vacuum cleaner (on 2 plots) and the resulting samples sorted and germinated. The remaining plots were cultivated (in the same direction as combining) and the seedlings counted in the following spring (Fig. 3.1).

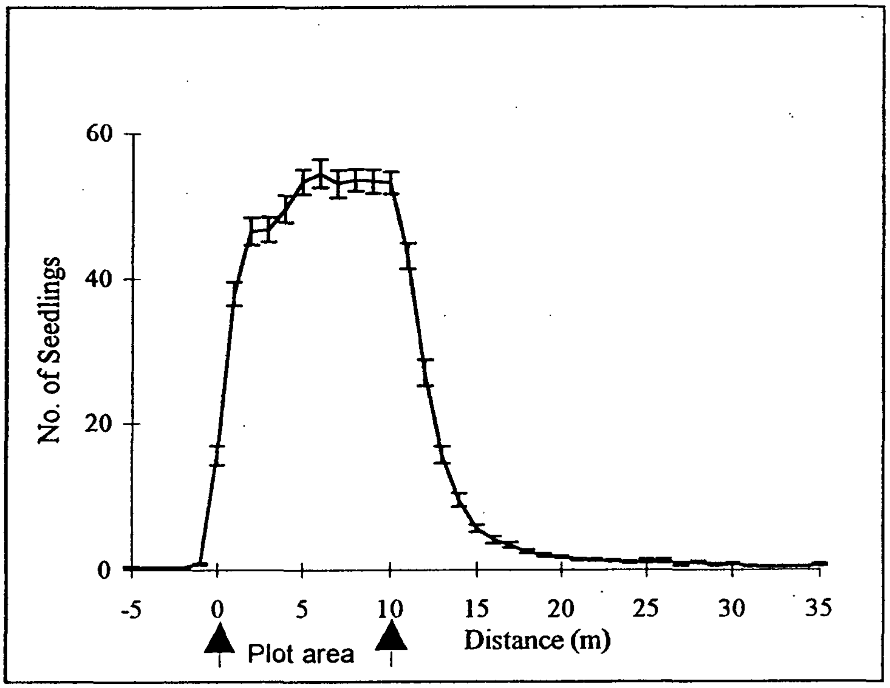


Figure 3.1 Movement of black-grass seeds following natural seed dissemination, combining and cultivation

The results of the work showed that black-grass (*A. myosuroides*) plants shed their seeds naturally prior to combine harvesting, and it was estimated that only 3% of seeds remained on the plants at this time. Between 80% and 84% of seedlings after harvesting and a single cultivation remained within the original plot, although individuals were observed up to 50 m away. Thus for this species movement of most seeds by combine and cultivation occurs over only short distances.

These data on black-grass can be contrasted with earlier studies by Howard, using seeds of brome grasses (*Bromus* spp.) for similar studies. She too found that most seeds moved only a short distance but the proportion moving up to 20m was much greater (Howard *et al.* 1991). These awned larger seeds appear to become trapped within the combine and thus moved further. Consequently, some movement of patches of this species could be expected. These conclusions concur with field experience, as it has been noted the brome grasses can spread quite rapidly from field margins into fields (Rew *et al.*, 1996b). Unpublished data from Peters (pers comm.) also confirms that a small % of brome seeds can be moved at least 20m from their source. Studies of seed shedding in wild-oat (Wilson, 1970) indicated that in many winter cereal crops over 95% of seeds had shed prior to harvest. So generalisations on the effects of combine harvesting on seed movement need to be treated with caution. The degree of movement will depend on the extend of seed shedding prior to harvest, how readily the seeds are thrashed in the drum of the combine and how the seeds behave in the airflow over the sieves. These conclusions emphasise the need for data on combine movement for other species which exhibit apparently aggregated distributions (eg wild oats, cleavers, rye-grasses).

3.2 Dispersal of black-grass pollen and its relation to seed viability

We have observed that black-grass patches appear to be more stable in position than those of barren brome. Part of this difference could be explained by differences in the extent of seed movement by combine but it is notable that barren brome is, to a high degree, in-breeding so that plants establishing in isolation have the potential to establish a new patch. In contrast, black-grass is largely out-breeding and some plants are completely self sterile. Thus, isolated plants might be expected to set little viable seed. We had no evidence of the extent to which this trait inhibits the establishment of new patches of this weed (or, of course, of other out-breeding species). Experiments were done in 1994, 95 and 96. In each year circular patches of black-grass 3 m in radius were established and later in two fields in 1994 and 96, pot grown plants were placed at increasing distances away from this "parent" patch or pollen source, in four lines at 90°, up to 64m (32m in 1994). All the plants outside the pollen source had been produced by cloning from a single plant which proved on subsequent testing elsewhere to be completely self-incompatible. There were no other flowering black-grass plants within 500 metres of the experiments but a few were present at greater distances. Pollen was trapped at 0, 2, 4, 8, 16, 32 and 64 m from the focal area. The pot grown plants were removed before maturity so that the seeds could ripen naturally and be collected as they ripened and shed.

Pollen was produced from mid-May to early July in each year, with the main production period being late May - early June. It was produced at low levels throughout the day but the main period was between 5 and 8 am. Pollen counts dropped exponentially with increasing distance from the source patch, almost halving in the first 2 metres and declining by over 90% at 32 metres. Overall, only between 1.5-3.1% moved 8 to 64 m from the source (Fig. 3.2). Studies in 1996 on the viability of pollen showed that it could remain viable for 10-14 days, a much longer period than was believed to occur (Aphale, 1996). This fact would increase the possibility of pollen fertilising ovules in flower heads of isolated plants.

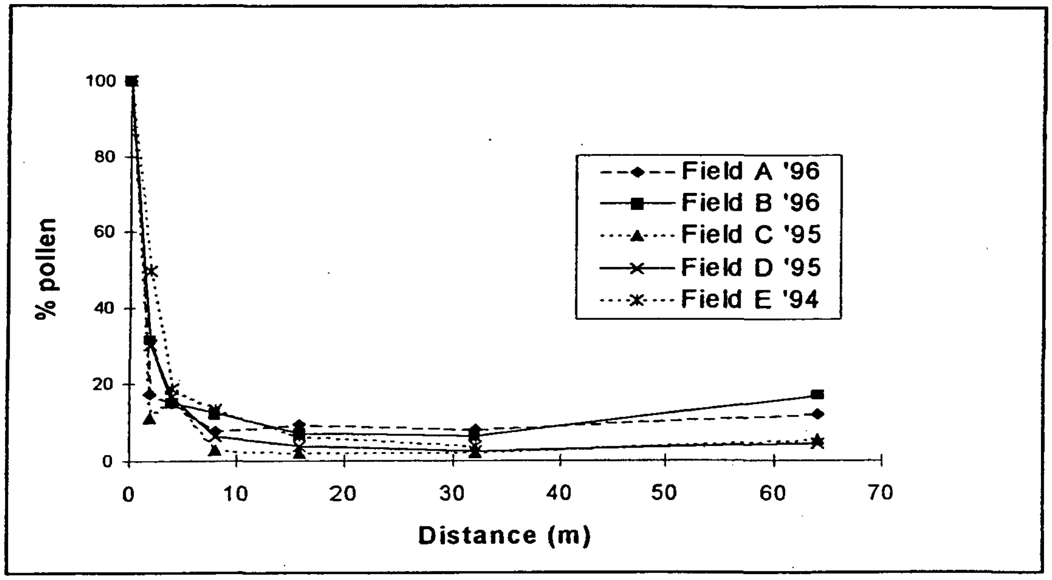


Figure 3.2 Decline in % of black-grass pollen with distance from the weed patch

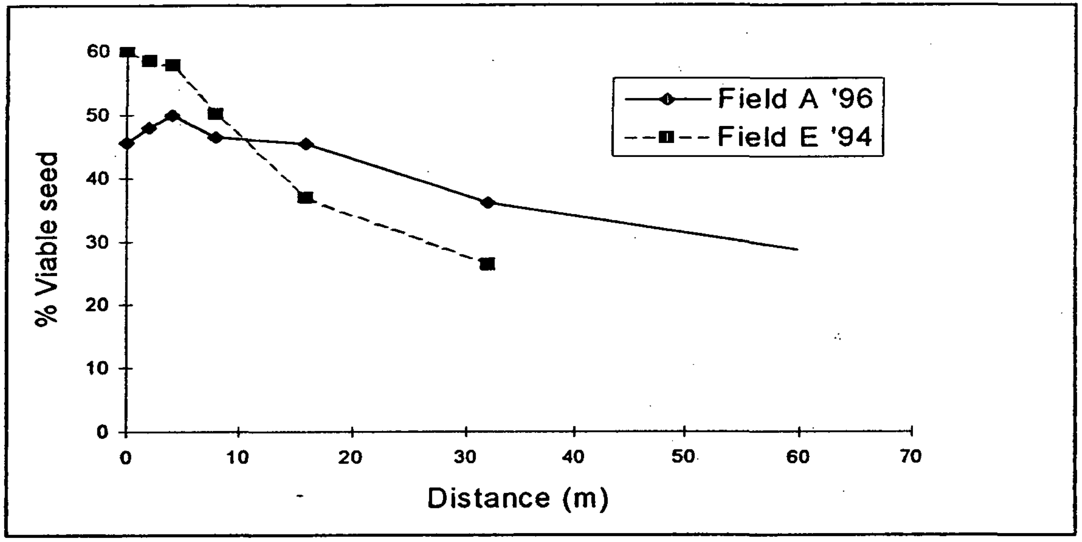


Figure 3.3 Decline in viable black-grass seed production with distance from the weed patch

Seed viability declined much less rapidly than did pollen density, so that 30-40% seed viability was still recorded 32 metres from the pollen source (Fig 3.3). Bearing in mind that the pollen recorded on the traps includes that produced by the outlying plants, which is ineffective in pollination, the pollen density required to achieve fertilisation must be very low. It would appear from these data that the background pollen cloud at Rothamsted in summer, coupled with the apparent long survival of the pollen, is adequate to ensure some fertility even on isolated plants. Nonetheless, the decline in viability of seed from isolated plants is clearly a factor which must contribute in some measure to patch stability with outbreeding species.

3.3 Spatial dynamics model

The development of a generalised understanding of the behaviour of annual weed infestations under a regime of spatially selective herbicide application would require a large number of field-scale experiments, carried out over a long timescale. This degree of experimentation and the delay involved before conclusions could be made were impractical within the scope of this project. We have therefore developed a population dynamics model based on earlier work by Audsley (1993). The weed life-cycle is represented in a similar way to the Audsley model, i.e. as a sequence of stochastic binomial processes. This is based on the principles outlined in Cussans & Moss (1982) and using parameters from Moss (1990) for black-grass. These processes describe weed seed germination, weed plant mortality due to control measures, weed fecundity, mortality of the seeds produced in the current year before they enter the seed bank and mortality of old seeds carried over in the seedbank through dormancy. The main development from the Audsley model is that the area under investigation is considered as a two dimensional array of cells, each having a unique identity and relative position within a Cartesian grid. This arrangement allows spatially dependant and isotropic processes such as seed dispersal (Howard *et al*, 1991) and spatially variable herbicide application to be incorporated in the model and their effects analysed. Outputs from the model include weed seed/plant frequency distribution, spatial weed density maps and annual herbicide and yield costs.

3.3.1 Techniques for characterising weed infestations.

It became clear early in the project that the relative effectiveness of patch spraying compared to homogeneous whole field herbicide application was very sensitive to the initial spatial distribution of the weed seedbank. It is intuitively clear that if all the weed seeds are confined to a small contiguous area of the field, patch spraying will be more profitable than if the weed infestation is more widely distributed. We decided that we needed to define a set of metrics for describing weed distribution. These would then allow us to develop standard initial conditions for simulation and to make general comparisons between model results and field observations. By reviewing the literature and by analysis of the results of our weed mapping exercise (c.f.) and other experiments we have identified three such metrics which have particular implications for patch spraying:-

Frequency distribution: A number of authors (Berti & Mosca, 1989; Wiles *et al.*, 1992) have observed that the occurrence of weeds or weed seed in quadrats or sample volumes can be described by a negative binomial distribution. Other authors (Nordbo *et al.*, 1994) have not observed a negative binomial distribution when sampling whole field infestations. Examination of observed and simulated weed distribution would suggest that the negative binomial will be observed only where there are no major spatial discontinuities within the sample area; either in environmental conditions or in mean weed density. The statistical principles governing this conclusion are discussed by Grafen & Woolhouse (1993).

Patchiness: Several authors have used mean:variance ratio statistics to describe the degree of over-dispersion in samples from animal and plant populations (Berti & Mosca, 1989). In particular Lloyds Patchiness (Lloyd, 1967) has been applied in analyses of weed seedbanks (Dessaint *et al.*, 1991).

Spatial Scale of Density Variation: Various measures have been used to determine the spatial frequency components of weed distributions. Nordbo *et al.* (1994) and Dessaint *et al.* (1991) have used auto-correlation methods. We have developed a technique specifically for this project which is based on fitting an exponential probability function to the discrete fourier transform of the spatially mapped weed distribution. This technique is particularly useful for analysing presence/absence maps as generated by our weed survey vehicle (c.f.).

The three metrics described above were used to compare observations of weed infestation with predictions derived from equivalent model simulations. The 10 year observations of black-grass density in winter cereals fields on the 170 ha Neville's farm (Wilson & Brain, 1991) were used as a basis for this modelling. The original data are based on counts of black-grass plant numbers (after spraying) in quadrats (total area 1m^2 at each sample point) taken at intervals of approximately 40m. For two of the fields we have extracted the data from contiguous sample points in which black-grass presence was observed in 50% or more of the years. The data was selected in this way to approach homogeneity of conditions and constant mean density. In simulation we have shown that if conditions are homogeneous over the modelled area the weed population distribution will always adapt to a negative binomial. In all but one of the years of the Neville's farm data we found that the frequency distribution of the sample points conformed to this negative binomial. The mean values of k of the distribution (which is inversely related to patchiness) would suggest standard deviation of Gaussian seed dispersal range between F=0.15m and F=0.2m. This is close to but somewhat less than would be expected from the results of Howard *et al.* (1991) and Rew *et al.* (1996a) but it should be noted that the standard errors of k were high for each experiment and (as discussed below) residual spatial heterogeneity and temporal heterogeneity of conditions will have tended to reduce k.

Dessaint *et al.* (1991) assessed the seedbank distribution of a number of weed species by taking 300 core samples in a 10 by 7.5m field area. They used Lloyds patchiness (Lloyd, 1967) to quantify the patchiness of the weed seed distribution. We have simulated the conditions of the observation in the model and calculated Lloyds patchiness of the simulated weed seed distribution for comparison. Simulation has shown that patchiness of weed distribution is very sensitive to seed dispersal range. Howard *et al.* (1991) found that the standard deviation of the natural (Gaussian) dispersal range of the two grass weed species *Bromus sterilis* (L.) and *B. interruptus* was 0.187m and 0.312m respectively. We found that for a model dispersal range parameter of F=0.2m, Lloyds patchiness was 2.634 and for F=0.3m it was 1.237. For black-grass in Dessaint's observation the value was 2.041. Although model simulations show that a number of other factors affect patchiness (see below), this is an encouraging result.

A system for mapping weed infestation from a high ground clearance vehicle is discussed in the next section. We have developed a technique which allows us to quantify the spatial scale of weed aggregation from the maps produced by this method. The spatial map data is converted to a power spectrum in the spatial frequency domain using a discrete two dimensional Fourier transform. The 2 dimensional power spectrum is then fitted with an exponential probability distribution to produce two parameters 2 and N. These directly represent the spatial scale of aggregation (in units of metres), parallel to (2) and perpendicular to (N) the field tramlines. We have analysed maps of black-grass presence/absence in two fields using this technique and compared the resulting parameters with those obtained by simulation. The simulation included models for cultivation and harvesting seed dispersal as proposed by Howard *et al.* (1991). We found that in all cases the spatial scale of aggregation was greatest in the direction of the tramlines. For the field data we found a mean value of 2 = 9.3m and N=5.5m and for simulation using Howard *et al.*'s parameters we found 2 = 6.4m and N=4.1m. This suggests somewhat greater actual seed dispersal range than predicted, particularly along the tramlines. As Howard's model was based on secondary cultivation only (by rotary harrow) and only took account of one dimensional dispersal for each process, it is likely that it provides an underestimate of typical total dispersal ranges. This hypothesis is supported by the results of the black-grass seed dispersal experiments described in section 3.1. Since only 3% of the seeds of black-grass are being dispersed by combine harvesting, "phalanx" seed dispersal (Rew & Cussans, 1997) is mainly due to natural shedding and cultivation. Figure 3.1 would suggest that the combined effect of these is of greater spatial scale than that described by Howard *et al.* (1991). This would also agree with the results of 3.1.1 which suggest that smaller seeds are moved further by cultivation.

The analyses above have convinced us that the model is a good generalised representation of the behaviour of black-grass infestations in an arable field. We have thus gone on to use it to assess the effect of various influences on weed patch dynamics in a homogeneous environment and then to look at the likely long term effect of different approaches to patch spraying.

3.3.2 Patch dynamics under spatially homogeneous herbicide application.

Simulation of the behaviour of weed infestations under homogeneous whole field control have highlighted the following generalised relationships:-

Intra-specific (weed-weed) competition: In general this will tend to reduce patchiness as discussed in the introduction. In an arable field however its effect on black-grass seed production is negligible until the weed plant density exceeds 200 plants/m^2 (Moss, 1990). In most cases control measures will restrict the weed population to lower densities.

Weed seed dispersal: Simulation has demonstrated that patchiness is highly sensitive to net seed dispersal range. If the seeds are dispersed only a short distance from the mother plant the distribution will become very patchy over a few years. This is true even if the initial seedbank is evenly distributed over the whole field. If long range seed dispersal mechanisms dominate the weed population will tend towards a random Poisson distribution. In general, the greater the tendency towards patchiness the more effective patch spraying is likely to be.

Annual variability of mean weed population density: There is evidence that the total number of weeds surviving to seed production in each year is highly variable (Wilson & Brain, 1991). In years in which there is little seed return, localised extinctions will occur in the seedbank. The size and shape of these areas of seedbank extinction will be related to the net seed dispersal range. It will take several years of subsequent high seed return for these areas to be recolonised whilst the population in areas in which the seedbank has not been extinguished will rise rapidly. The result will be greater variability of seedbank density (greater patchiness) than would be seen if annual seed return had been constant. This result does not necessarily mean that annual variability of seed return is beneficial to the patch spraying approach, however. Simulation has also demonstrated that if all parameters are constant over the modelled period, and they are selected so that the total weed population is neither increasing or decreasing, weed patches take up a meta-stable state where their area is constant and with a consistent density gradient at their boundaries. In years of relatively high seed return the patches will expand to colonise new areas of the field. Thus a higher proportion of the field is likely to become infested under the influence of variable seed return.

Spatial variability of environment: As might be expected, if there are areas of the field in which the weed species is better adapted or where herbicide efficacy is lower than that in the rest of the field, whole field patchiness will be increased. The spatial scale of this variability is likely to be much greater than that related to seed dispersal mechanisms (as discussed above). Patches defined by spatial discontinuities in the environment are likely to be more stable and will provide a more consistent target for variable dose patch spraying.

The value of this work, simulating the long-term behaviour of patches is clearly demonstrated in Section 7, where the economic aspects of patch spraying are discussed.

4. WEED MAPPING AND DETECTION

This aspect of the programme was aimed at the production of field maps, identifying the areas infested with weeds, which would subsequently be used to control the application of herbicides with the patch sprayer. The work has concentrated on the following species: black-grass (*A. myosuroides*), wild-oat, (*A. fatua*), barren brome, (*B. sterilis*) and common couch grass (*E. repens*). These species were selected because of their economic importance, their spatially heterogeneous distributions within fields and their visual presence at times of year and in crops that permitted visual mapping of their distributions. Additional species have also been mapped in some years. Several different mapping techniques have been evaluated.

4.1 Development of the weed mapping system (1993)

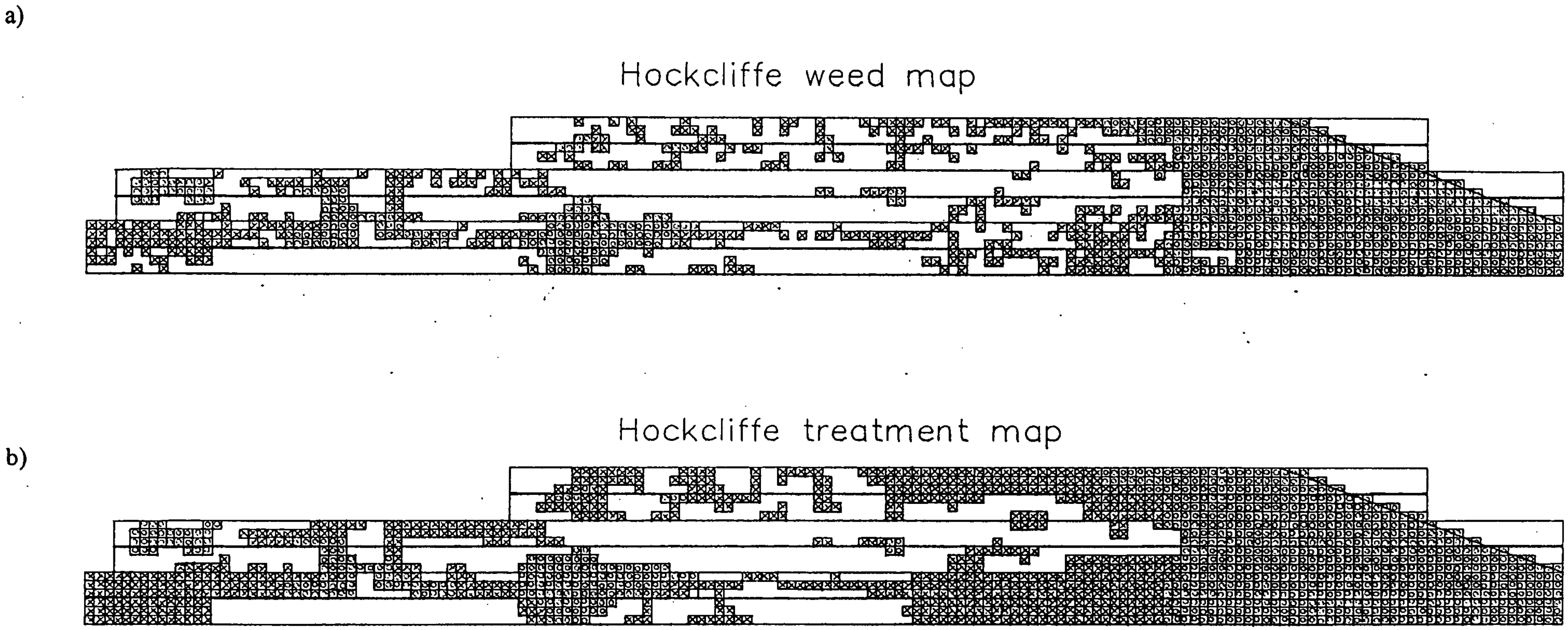
Three tramlines of a winter wheat field (Hockliffe) were walked in March 1993 to detect and map the black-grass plants, which were located and marked with pegs. Where plants were present at densities of > 3 plants/m^2 the area surrounding the plants was pegged out, whilst at lower densities individual plants were marked. These data were then transferred onto a computer field map by manually walking and measuring along each tramline (in 2 m sections) and recording the population density across the six 2 m sections of the 12 m boom. The mapped weed patch positions on the 2 x 1 m grid obtained from the field data were transformed into a treatment map by adding a 2 m buffer to each of the major full-dose patches (see Section 6 for further discussion of the use of buffers).

The three tramlines mapped in March 1993 resulted in a 2x2 m grid field map and treatment map (Fig. 4.1) The distribution of black-grass was accurately recorded without buffer zones or smoothing of the distributions or densities. The experience gained during this exercise showed that this method of field surveying and data manipulation was too time consuming, labour intensive and prone to errors even for experimental purposes. The decision was therefore taken to examine alternative approaches to field map generation that would enable an outline survey of the tramlines, field boundaries and weed patch positions to be recorded simultaneously. It was recognised that the use of a hand-held computer, linked to satellite-based GPS (Global Positioning System), could provide a valuable tool for weed map generation in the future. It was also realised that there was a need for the surveyor to look down on the crop and weed, to improve patch recognition.

As a result of the experiences at the winter wheat field at Hockcliffe, a new mapping system was developed during 1993 based on both a high clearance, self-propelled survey vehicle and a smaller hand-pushed version. Both were fitted with a wheel sensor linked to an on-board computer enabling the distance moved from the start point to be monitored. By incorporating a push button system, weed occurrence and density could be continuously recorded. The push button arrangement permitted a limited number of combinations to be recorded: either a single species at 0, 1, 2 and 3 densities or two species as present/absent. To enable the individual tramlines to be put together as a field map, with minimum prior reconnaissance, two markers were placed in each tramline and at a set distance apart (50 or 100 m). When the whole field had been mapped the data from each tramline were calibrated to line up the markers, thus producing a field map. The accuracy of the system was tested on a set-aside field in which "patches" were marked out by flexicanes. The sizes and distances between patches were measured with a tape measure before being mapped.

Figure 4.1 Map of black-grass created in 1993 by walking round the patches and measuring positions
a) weed map, b) treatment map generated from weed map

x = low density (low dose treatment area)
o = high density (full dose treatment)



Individual components of the mapping system were validated during the summer of 1993. A field with common couch (Field Y) was monitored during crop senescence in July 1993, using the high clearance vehicle (see Fig. 6.7). Other fields were surveyed with the hand-pushed machine. The results identified some of the problems that remained to be resolved, particularly those related to the conversion of the location data points into an accurate weed map. A further problem with the system was that field headlands could not be mapped because of the need to calibrate the system with the 50/100m markers.

4.2 Mechanised mapping using dead reckoning and DGPS (1994 & 1995)

The semi-automated mapping system was further modified during 1994 and 1995 to map infestations of black-grass, barren brome, wild-oats, common couch-grass, onion couch (*Arrhenatherum elatius* ssp *bulbosum* (Willd.) Hyl.), ryegrass (*L. multiflorum*) and creeping thistle (*Cirsium arvense* L.). Special emphasis was devoted to black-grass and common couch-grass, where 15 and 6 fields were mapped, respectively. The problem of 'cryptic patches', where patches in the soil seed bank may not germinate successfully in any one year, was avoided with black-grass by mapping infestations mainly in natural regeneration set-aside. This problem did not affect the perennial weeds like couch grass and creeping thistle. These surveys also provided an opportunity to assess navigational and operator errors in some detail. Alternative methods of establishing the position of weed patches, involving DGPS (Differential Global Positioning System) alone and in combination with ground-based measurements were compared.

Table 4.1 Percentage area of surveyed fields infested with weeds

Weed species	Fields Surveyed (% of field infested)												
A. myosuroides	4	20	34	45	40	46	54	54	59	69	72	84	85
A. fatua	2	14	18	15									
E. repens	3	10	27	48	57	79							
B. sterilis	51												
L. multiflorum	34												
A. elatius	12												
C. arvense	11												

Maps of all sites are included in Appendix 1. At some sites infestations of more than one weed species were recorded. The six populations of common couch which were mapped showed a range of distribution patterns, the areas infested ranging from 3 to 79%. The range of situations encountered is given in Table 4.1 and sample distributions are given in Fig. 4.2. Although fifteen fields were mapped for black-grass, the DGPS (Differential Global Positioning System) failed to work adequately on two fields which had unfavourable geographical positions (e.g. incorporating the base and sides of a valley) and these are excluded from the analysis. A similar distribution of infestation levels to that recorded with common couch was seen, with the remaining 13 fields of black-grass exhibiting infestation levels of 4-85%, with a mean of 51%. The results with wild-oat showed lower infestation levels, with a maximum of 18%. This surprisingly low level of wild oats may simply be due to the small number of fields surveyed but may reflect the attitude of farmers to this weed, which can be removed from the field by hand (roguing). Infestation levels in the single fields surveyed of the other four species are given in Table 4.1. These surveys show that it is possible to map these species as well as the more common wild-oats, black-grass and couch.

Before mapping in 1995, the surveying vehicle was substantially rebuilt to solve steering difficulties. The weed mapping exercise in 1995 identified some further problems. The survey system required two observers each to monitor a 6m width of field as the survey vehicle crossed the fields. This fitted well with the 12m tramlines used by most of the farms where the surveyed fields were. However, it is clear that some farmers are moving towards 18 or 24m tramlines. It is not yet clear how to map such fields. The maps of Fields L and P (see Appendix) exemplify this problem, as strips of unmapped areas alternate with mapped ones. With the former it seems feasible that some form of computer analysis could be used to interpolate the missing data, but for Field P this approach does not seem sensible as the weeds are more randomly distributed. This aspect remains to be resolved.

The effects of incorporating buffer regions of various dimensions around weed patches and the economic benefits associated with only controlling the weed patches were also investigated. Details are given in Sections 5 and 7.

4.2.1 Realtime navigational errors and repeatability

The effects of navigational errors, using dead-reckoning and the repeatability of the surveys was investigated in the 1994 maps of common couch infestations. Mapping errors were investigated in repeated surveys of eight tramlines in one of the couch-grass infested fields (Field A). Three surveys were done over a 24h period. The navigational errors recorded whilst mapping the common couch patches were relatively small. Mapped distances were within 2.5% of the actual distances. However, on some of the fields surveyed, a 2.5% error could be as high as 14m and, although it is unlikely for all the errors to accumulate in the same direction, there was a need to improve navigational accuracy still further. A further contributory factor to inaccuracies in the map is human error. The recorders on the mapping vehicle have to identify the weeds and enter the information on the map. Both activities may result in errors.

There was a high degree of correspondence between the three runs on Field A (Fig. 4.3), pair-wise comparisons giving approximately 85% repeatability on presence/absence data (Rew *et al.* 1996a). More detailed statistical analysis of the data carried out as part of an MSc programme at Reading University (Harkness, 1996) established a 'measure of similarity' between the three runs of approximately 0.1 (0 = identical comparisons and 1 = no similarity). Interestingly runs 1 & 3, which were furthest apart in time were less similar than 1 & 2, and 2 & 3. Further, Harkness was able to show from his analysis that there was more variability down the tramlines than there was at right angles to them. This is what one might expect, as navigational errors and speed of response from the observers would both cause more variation down the tramlines.

A further feature of the ground-based mapping system used in 1994 is shown in the map of Field C (Fig 4.2). This field sloped steeply to the right and as a consequence wheel-slip led to an over-estimation of the distance travelled uphill and an under-estimation down hill, resulting in the 'notched' appearance of the field map. The use of GPS in subsequent years avoided this problem with later maps. However, the accuracy of GPS on steeply sloping ground is still an issue that has to be resolved, as the ground distance is actually greater than the GPS locations would show.

Fig 4.2. Spatial distribution of common couch in three wheat fields (A,C,E) mapped in 1994. solid vertical lines represent the position of reference markers

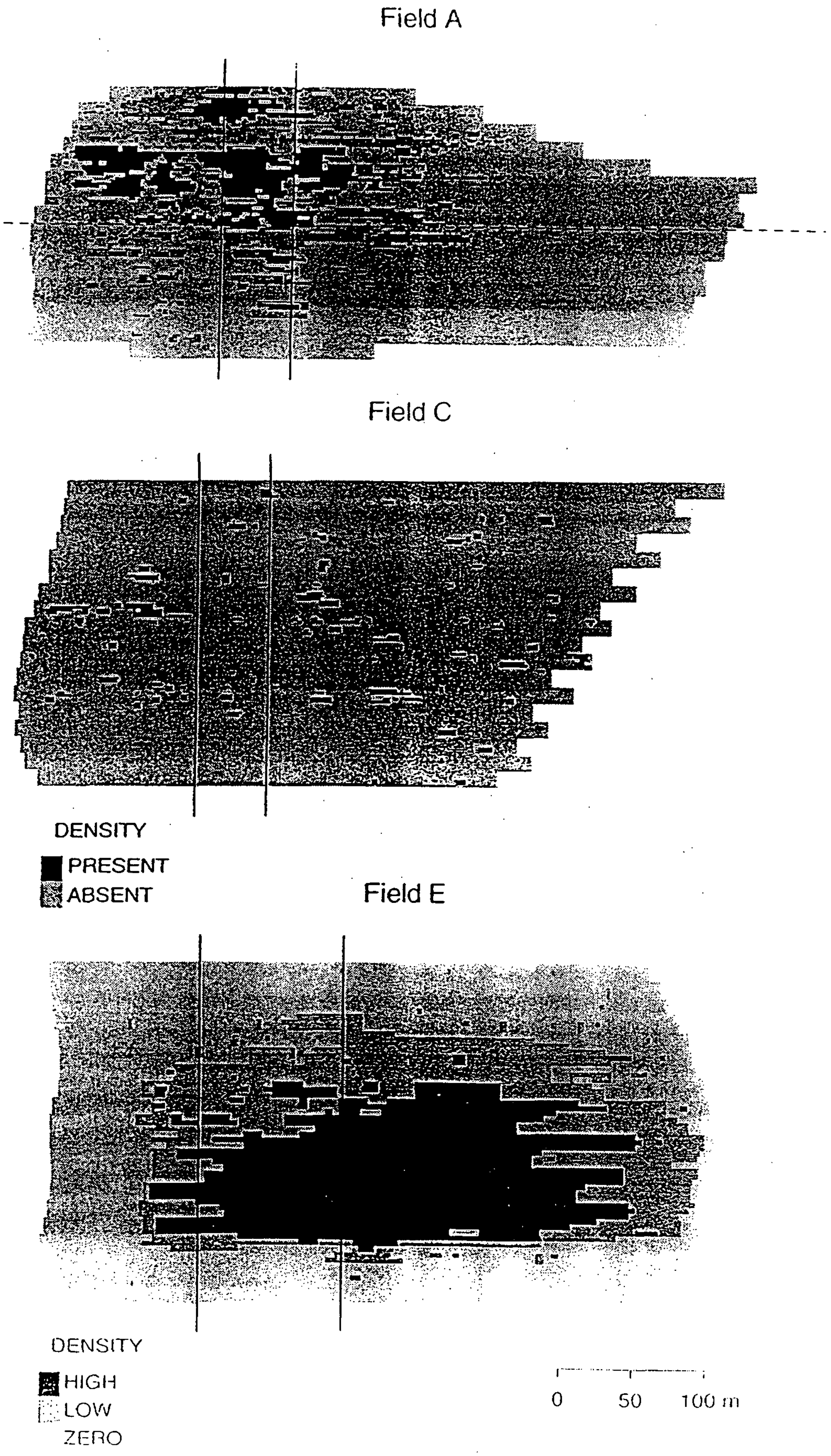
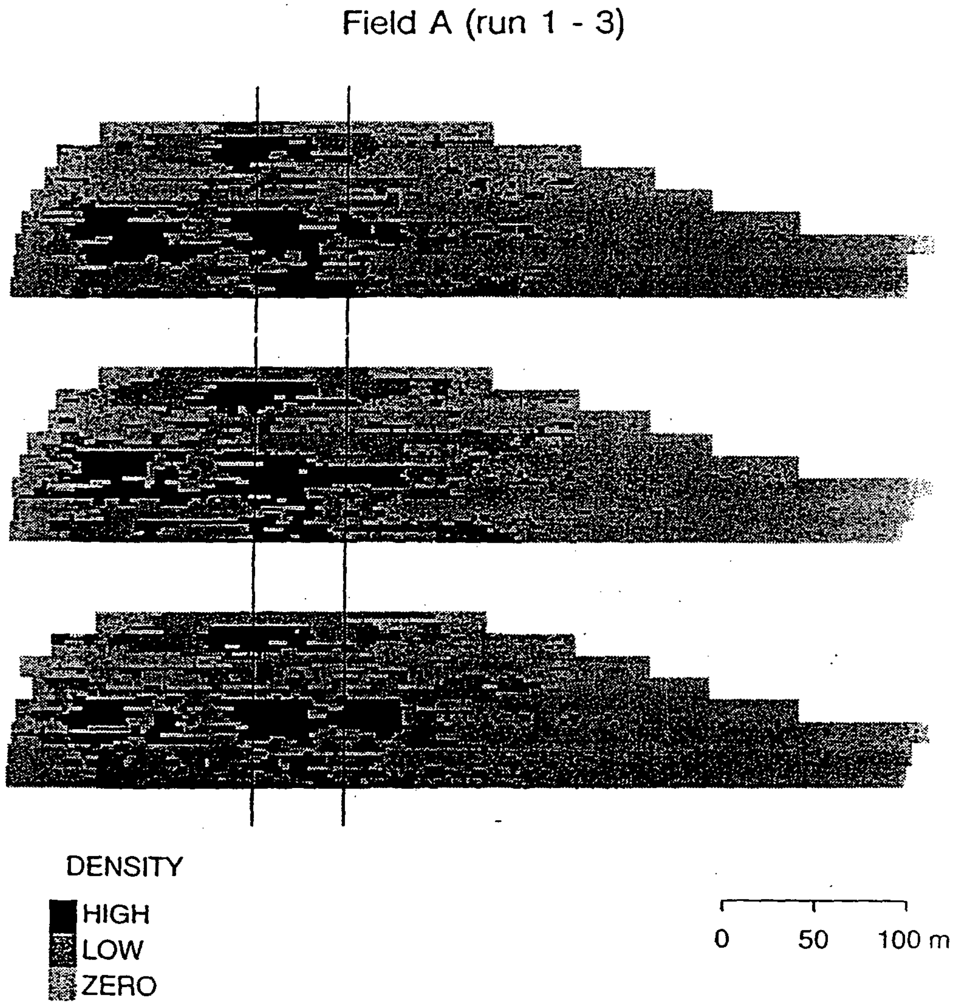


Fig. 4.3 Spatial distribution of common couch in Field A mapped consecutively to assess repeatability of detection and navigation.



4.2.2 Navigation - comparison of DGPS and realtime systems

The accuracy of four different navigation methods was assessed from data on 166 tramlines in ten different fields. The four methods used were: DGPS plus wheel sensor, DGPS plus ground-sensing radar, DGPS alone and a Marker system with the wheel sensor (see Rew *et al*, 1996a). The first two methods used DGPS data for the start position and wheel sensor or radar respectively, for the distance travelled along the tramline. The end point of the tramline was derived from DGPS data and wheel sensor, or radar data, respectively. Marker data was obtained by placing two baseline rows of marker canes transverse to the tramlines, a measured distance apart (50 m). When the survey vehicle crossed each line of canes, the driver recorded the position by pressing a dedicated computer key. These baselines served two functions; they provided a reference line for mapping purposes and checked the calibration of the wheel sensor system. The software programme "lined up" each row of Marker positions, thus delineating the shape of the field (see Rew *et al.*, 1996a). It was not possible to map weed distribution on the headlands of irregular shaped fields using the Marker system. Therefore, only data from straight field tramlines were used to evaluate the different methods. The average length of each tramline was calculated from the four different methods. The difference of each method from this average was calculated.

There was a significant difference between the four methods ($p<0.001$), with DGPS plus wheel sensor being closest to the average and DGPS plus radar the furthest (Table 4.2, Fig. 4.4). Although the mean difference was small there were several outliers, mainly from DGPS plus radar and the Marker system. Variation between the methods did not increase with tramline length and agreed with tape measurements taken on three of the fields.

The position of weed occurrences along tramlines using DGPS plus wheel sensor, DGPS plus radar, and the Marker system generally showed good agreement in both pair-wise and three-way comparisons (Table 4.3). Weeds were located in the same (2 x 1 m^2) cell approximately 80% of the time. On Fields 4 and 7 the Marker system had poor agreement with the other two methods. If these two fields were excluded from the analysis there was an overall agreement of 84%. These results again suggests that DGPS plus wheel sensor, was the most reliable method.

Table 4.2. Mean differences in tramline length measurements (m) of the four methods from a) the average, b) DGPS plus wheel sensor. ws = wheel sensor.

a) Average -

DGPS+ws	DGPS+radar	DGPS	Marker+ws	S.E.D.
-1.23	-2.34	1.44	1.30	0.252

b) DGPS plus wheel sensor -

DGPS+radar	DGPS	Marker+ws	
-2.17	2.66	2.71	0.389

Table 4.3. Agreement (%) in positioning of weed occurrences between DGPS + wheel sensor, DGPS alone and Marker + wheel sensor (ws = wheel sensor)

Field	Two-way			Three-way
	DGPS+ws cf.DGPS	DGPS+ws cf. Marker+ws	DGPS cf. Marker	3 methods cf.
1	94.6	97.3	94.5	93.3
2	87.1	97.7	87.5	86.3
3	92.3	94.2	93.8	90.4
4	89.3	64.5	64.6	59.1
5	76.1	77.4	86.0	70.0
6	73.7	95.8	73.6	71.8
7	92.7	64.2	64.4	61.8
8	95.5	99.3	95.4	95.1
9	96.5	82.7	82.8	81.0

Although, in general, DGPS plus radar provided reasonable results, the radar component failed to function correctly in cereal fields in June, which is a suitable time to monitor grass weeds. Additionally, the radar did not record usable data on one set-aside field, because it took readings from the ground and therefore incurred errors when vegetation differed in height and/or brushed against the sensor. As a result the radar is seen to have limited use. The Marker system provided variable results and due to the extra setting up time (positioning baselines) is less practical than using DGPS alone or with a wheel sensor. These experiments showed that DGPS alone or with a wheel sensor would give the best accuracy for the creation of weed maps.

4.3 Mapping 1996

The experiences in 1996 highlighted some practical problems associated with the DGPS location system used (Navstar). The system frequently failed to function correctly and it was not possible to establish the accurate locations required for mapping. Despite intensive efforts to resolve the problems, including visits from the GPS manufacturer, the system failed to work reliably. The causes of the unreliability are still not fully understood. Satellite location systems involve new technology and so practical problems are to be expected. Other users of GPS in 1996 also experienced problems. These problems are being addressed by the companies concerned and each year the technology improves.

4.4 Weed mapping from a combine harvester

The cab of a modern combine harvester provides a good platform from which to observe the condition of the crop at the time of harvest. Weed patches that are visible at the time of harvest can therefore be mapped from the combine harvester. It is recognised that some weeds may be difficult to see with the human eye at harvest, for example black-grass particularly in a dry year, and that the technique of weed mapping from a combine harvester may not be applicable in such situations.

Combine harvesters fitted with a field mapping capability are particularly suited to the mapping of weed patch positions at harvest since the machine is already using GPS, and has facilities to record information tagged with position for subsequent plotting on to a map. As part of the work of this project, a commercial combine harvester fitted with a yield mapping system (Massey Ferguson) was modified to provide an additional key pad in the cab which was fitted with six two-position switches. The yield mapping software was extended such that the positions where the switches were "on" was logged at the same frequency as grain yield - approximately 1.0 hz. This system was then used to monitor weed patch positions in the harvests of 1995 and 1996 in Field U (see also section 6.3.3.2), and a typical result is plotted in Figure 4.2. This can be compared with Figure 4.3 which is a map of the same field with weed patch positions determined using the backpack mapping system (section 4.5).

For the initial experiments the monitoring of weed patch positions was undertaken by having a second person in the combine cab whose sole task was to map weed patch positions. In some subsequent work, the weed patch mapping was successfully achieved by the combine driver although there was some increase in detection errors due mainly to switches being left in the "on" position after the weed patch had been passed. Supporting experiments were also conducted on a number of fields at Silsoe Research Institute, and gave results that were directly comparable with those reported above.

The ability to map weeds from the combine harvester can make an important contribution to weed patch detection but that there are limitations relating to:

i) the visibility of some weed species at harvest: a factor that is crop and season dependent;

ii) mapping weeds at harvest is post any weed control treatment and therefore further analysis is required to interpret the implications for treating the subsequent crop.

4.5 Weed mapping using the backpack DGPS system

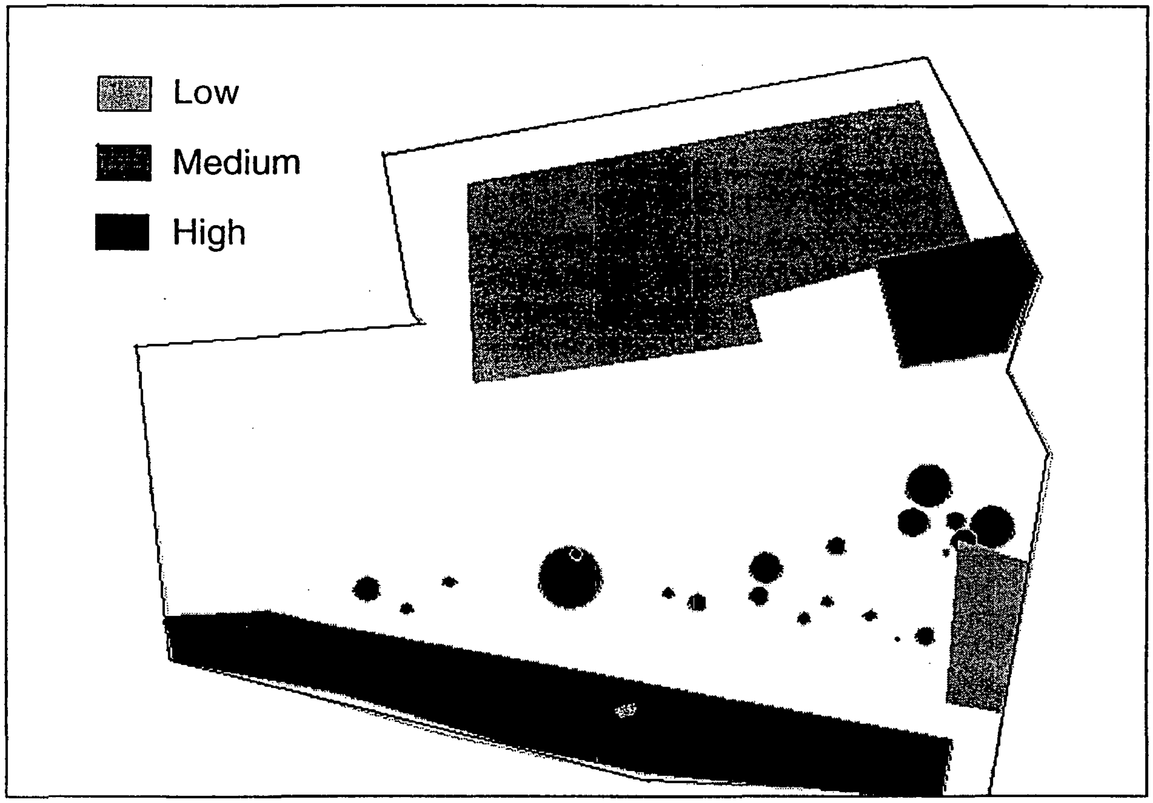
A backpack mapping system was designed and built (Stafford & Le Bars, 1996) to provide the farmer with a simple means of logging crop and soil information whenever walking the fields. A small hand-held data logger in the form of a 'palm top' computer provides a means of entering information in response to menu-driven on-screen commands. A map of the field, showing the field boundary, features logged so far and the operator's current position in the field, is also displayed on the screen. When a weed patch is encountered, the operator is given the options of walking round the patch to log its boundary, or of approximating the patch as circular or rectangular and estimating its size. When the patch boundary has been logged, the operator is requested to input information on weed species and density of infestation. To aid with species identification, a database of species is presented on the screen with the option of defining a new species which is added to the database or not specifying species for the current patch. Weed density information to aid in the later generation of treatment maps, is defined as low, medium or high.

At the end of field walking, the map information is downloaded by serial link or RAM card to the farm office computer to update a master field map. Compatibility of file format was required at all stages from field map production through map editing to generation of treatment maps used to drive a precision application system. A geographic information system (IDRISI from Clarke University, Massachusetts, USA) was used to store, manipulate and output spatial data in the complete system. The rationalised data file formatting system defined in IDRISI was therefore used in the backpack mapper. In this system, vector map information is defined in files by attribute data, vector type (point, line or polygon) and a series of coordinate pairs. Both field boundaries and weed patches were stored as closed polygons. Weed species and density information were held in value files associated with the relevant vector files. Tramlines were held as line objects and grid data as point objects.

The system was used to map a number of fields and example maps are shown in Figure 4.3 and in Stafford & Le Bars (1996). The backpack mapper was designed as an aid to field walking rather than as a tool to be used for the detail mapping of weed patch positions. Results from using the system and comparing the results with surveyed weed patches and those mapped from the combine harvester showed reasonable agreement within the limitations of a surveying system based on field walking. This system is probably most suited to monitoring known patches of weeds, rather than for creating new patches.

Figure 4.2 Patches of couch grass in Field U mapped from a combine harvester.

Figure 4.3 Patches of couch grass in Field U mapped with the backpack weed mapper.



5. CONVERSION OF WEED MAPS TO TREATMENT MAPS

5.1 Buffers

The weed maps created during this project are not 100% accurate, as discussed earlier in this report. A number of factors such as observer and navigation errors will mean that some weeds may be present outside the identified patches. Therefore, in order to minimise the risk of not treating some of these weeds on the edges of the patches it was considered prudent to expand the patches with a small 'buffer' area on either side. The evidence from our data was that a 2m buffer was adequate for the avoidance of navigation error. Further, if the map is to remain effective for several seasons, it should be robust enough to accommodate movement of weeds as a result of natural seed dispersal and agricultural practices. Evidence presented earlier would suggest that 2-4 m was adequate. Finally, the sprayer does not respond instantly to instructions to switch between dose levels and a forward distance of 0.5m is needed to cover this response time. Thus a buffer of 2-4m on either side of the weed patch is needed to ensure that the herbicide is applied to the infested area.

In the five fields surveyed for common couch in 1994, the proportion of the surface area infested was calculated on the "raw" data in modules of 2 x 1 m or with the addition of buffer areas of different sizes. Using the computer in this way, it was also possible to estimate the effects of mapping on a coarser scale - dividing the tramline widths into units of four metres instead of two. The area recorded as infested ranged from 3% to 79%. The addition of buffer areas increased the notional sprayed areas most in fields with numerous small patches (eg the first field in Table 5.1) and least in fields with highly clustered distribution (eg the last field in Table 5.1). Reviewing the maps of all 13 fields of black-grass, the average infestation level without buffers was 51% and the addition of a 4m buffer increased the potentially treated area by 12%.

5.2 Changing resolution

The mapping that was done in this programme was all based on six 2m units in each 12m boom width. This provides a very fine measurement system for identifying weeds of 2 x 1m. The current resolution is too small if one observer was to map the whole of a 12m boom or if the boom widths were 18 or 24m, as are now commonly found on UK farms. Therefore, an important aim of the work was to quantify the increase in target area to be sprayed resulting from a lowering of the spatial resolution. The data collected from the map fields on the basis of 6 x 2m units was re-analysed with 3 sections of 4m and 2 sections of 6 m. The effects of changing resolution from 2x1m to 4x1m or 6x1m was to increase the % of the field that was treated. The effects again were most marked in the fields with a large number of small patches (Table 5.2). This is particularly clearly seen in the first black-grass field. Overall (mean of all fields mapped) the effect of decreasing resolution from 2 to 4m was to add 5.5% to the area to be treated. A further decrease in resolution from 4 to 6m had less of an effect, only adding a further 2.2% to the area to be treated.

Table 5.1 Percentage infestations of five fields infested with common couch and the % area requiring treatment with herbicide with different size buffers:

Buffer	Fields (% infestations)				
None	27	79	3	10	48
Small	33	84	5	13	49
Medium	38	88	6	17	50
Large	44	92	9	23	53
Wide	49	96	12	31	57

Small buffer = ± 2m parallel to tramlines: Medium buffer = ± 4m; Large buffer = ± 8m
Wide buffer = 4m parallel & ± 2 m transverse to tramlines

Table 5.2 Percentage infestation of grass weeds as mapped from the high clearance vehicle, and % area to be sprayed with the addition of a 4 m buffer, using a high (H) resolution (2 x 1)m^2 and medium (M) resolution (4 x 1)m^2 and low (L) resolution (6 x 1)m^2.

Buffer/Resolution	Black-grass									
None	20	26	40	45	54	56	59	69	72	85
4 m buffer H	55	31	57	53	66	67	765	80	80	93
4 m buffer M	76		69	60	75	76	84	88	89	97
4 m buffer L	89		76	64	82	78	87	90	88	97

Buffer/Resolution	Common couch	Wild-oats	
No buffer	57	2	14
4 m buffer H	68	4	24
4 m buffer M	75	7	31
4 m buffer L	77	10	36

6. PATCH SPRAYING

6.1 System Design Considerations

The field evaluation study reported here used an experimental patch spraying rig which was designed and constructed at Silsoe Research Institute as part of project work funded by the Ministry of Agriculture, Fisheries and Food. The system had been designed to use a novel injection metering system developed by the Institute (Frost, 1990) in which the liquid chemical formulation was drawn into metering cylinders mounted on the 12m sprayer. The experimental patch sprayer was based on an existing 12.0 m mounted design which was modified to accommodate the injection metering system and to incorporate changes to the pipe arrangements supplying nozzles on the boom. The system was designed to operate with clean water in the spray tank. Concentrated chemical formulation was metered into the spray delivery lines by pumping water into the base of the metering cylinders to displace the active formulation at a rate depending on the speed of the spraying vehicle and the dose requirements specified on a treatment map (Paice *et al.*, 1995). An important advantage of this arrangement is that, because the gear pump delivering water into the bottom of the metering cylinder is always operating with the same liquid (water), the pump can operate as a flow meter in a closed loop control system. The pump characteristics are incorporated into the control system such that, by measuring the pressure drop across the pump and its rotational speed, the pump output can be predicted and controlled.

The patch sprayer was controlled by a treatment map generated from field survey data adjusted by an appropriate transform to accommodate a range of factors relevant to the applied treatment - see sections 4 and 5 above. For the purposes of the work reported here, the treatment map was stored on a personal computer mounted in the tractor cab which was initially interfaced directly with the control system of the sprayer. In-field location was initially determined from the distance travelled down tram-lines but later developments undertaken during the course of this project work enabled a GPS system to be used.

The experimental patch spraying system had been designed to achieve the highest practical spatial resolution with a rapid and uniform response time characteristic along the whole boom. The boom was arranged in 2.0 m sections with each section supplied by equal lengths of small bore pipes from a central mixing chamber. The pipe sizes were designed to give a response time of less that 4.0 s when the sprayer was fitted with nozzles to apply 120 l/ha at a speed of 8.0 km/h. It was recognised that this did give a substantial pressure drop of up to 2.0 bar between the nozzle position and the mixing chamber, but this was accounted for in the setting up and calibration of the system. The supply to each section was controlled by 12 volt solenoid valves.

The rig was fitted with a twin spray line, each line being fed by a separate injection metering system. This gave an arrangement in which the applied dose could be controlled via the injection metering system or by switching the two lines independently. The ability to independently control the effective "tank mix" was an important feature of the experimental patch sprayer.

The objectives of this LINK project in respect of the sprayer development were:

(i) to demonstrate operation of the system with a range of active herbicide formulations;

(ii) to examine the performance of the system in large scale field trials in terms 6
  (a) the accuracy and control of delivered dose;
  (b) dynamic response characteristics and spatial resolution;
  (c) the self monitoring system for performance analysis;

(iii) to further develop the system in response to the results obtained from the experimental programme.

The control requirements for the spatially selective (patch) spraying of herbicides have been reviewed by Paice *et al.*, (1996) who concluded that the optimum system would probably be based on an injection metering system. This would enable variable mixtures of herbicides to be used at different dose levels and also have important implications for the safe disposal of any unused dilute herbicide. Alternative possible control strategies based on using twin fluid nozzles, high frequency solenoid valves and on/off control with multiple nozzle lines have also been identified as possible control methods, some of which are likely to be developed commercially.

6.2 Techniques for Studying System Performance

6.2.1 Delivered dose and dynamic response characteristics

The steady-state accuracy of the dose delivered by the injection metering system was assessed by using a 2% solution of a water soluble tracer dye (Orange G: Merck Ltd) to simulate the active pesticide formulation. This was loaded into the injection metering cylinders and the sprayer operated statically with a signal generator used to provide simulated signals from the wheel mounted speed sensors. The system was operated at a range of simulated forward speeds, dose rates and boom section widths and samples of the nozzle outputs were collected once a steady state had been reached for each setting. This was generally after a period of at least 30 s. The concentration of the original dye solution, simulating the pesticide formulation, in the nozzle output was then determined by spectrophotometry techniques calibrated with the original dye solution. The performance of the system was then assessed by comparing measured concentrations with those expected based on an ideal operating characteristics.

The dynamic response of the system was assessed by using a concentrated salt solution as a simulated pesticide and accurately monitoring the flow of liquid out of the metering system and the electrical conductivity of the spray solution on the boom (Paice *et al.*, 1997). An orifice plat flow sensor was designed and used to monitor rapid changes in the flow of liquid from the injection metering system by monitoring the pressure drop across a calibrated orifice. An electrical conductivity cell was constructed for incorporation into the pipe arrangement supplying the boom. This consisted of two brass ferrules separated by a polyethylene pipe 300 mm long and with an internal diameter of 8.5 mm. The cell was connected in series with a standard resistor (15 kR; R_{sense}) and a balance square wave voltage source (500 Hz; v_{sense}). A capacitor was placed across the standard resistor, R_{sense}, to compensate for the capacitance effects in the cable between the resistor and the cell and the conductivity monitored using a data logger to monitor the voltage across R_{sense} at a sampling rate of 250 Hz. The experimental arrangement for monitoring the output of the injection metering system is shown in Figure 6.1.

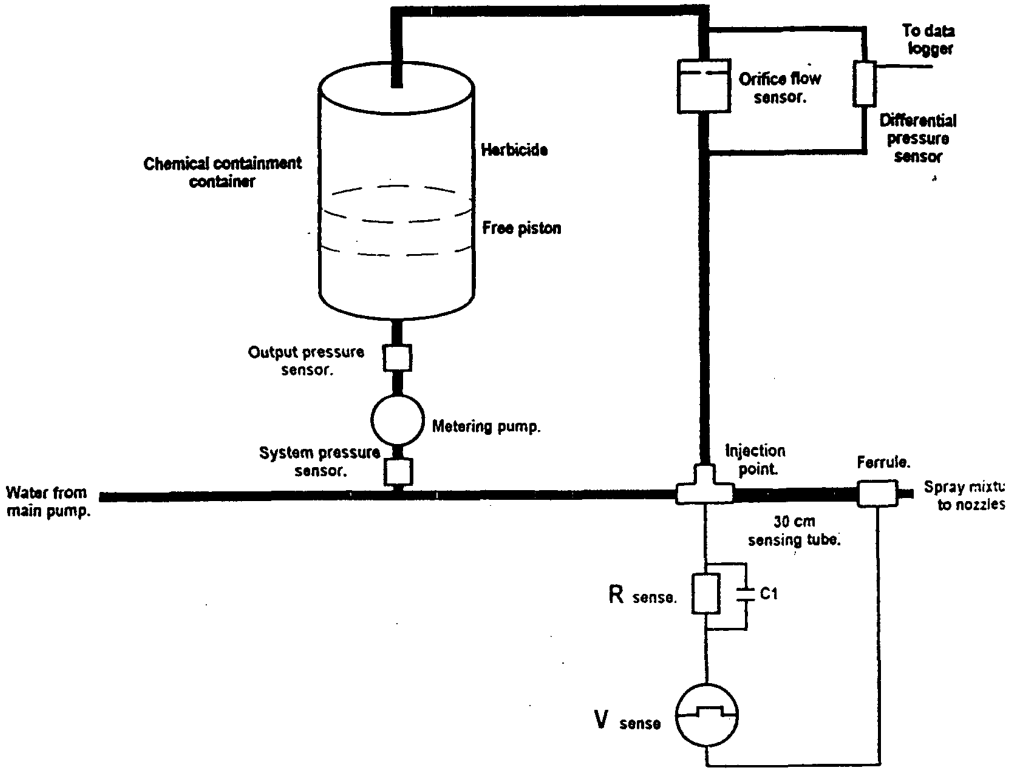


Figure 6.1 Experimental arrangement for monitoring the output of the injection metering system

The complete system was calibrated with clean tap water and with defined concentrations of salt solution. A series of experiments were then conducted with the sprayer operating statically and using signals from a pulse generator to simulate the output of the wheel speed sensor. With the system set to deliver a dose rate of 2.0 l ha^{-1}, the effect of varying forward speed in the range 4.0 to 12.0 km h^{-1} and of switching from half to full boom width were investigated. Signals from the conductivity sensor were analysed to determine the time for the dose to change from with 10% of an original value to 10% of a new set value.

6.2.2 Verification of system characteristics by monitoring biological responses

While laboratory experiments with the experimental patch spraying system had provided data relating to pesticide flows, concentrations and likely applied doses, it was considered necessary to relate the measured effects directly to herbicide performance under field conditions. An experiment was therefore conducted using a total herbicide (paraquat as Gramoxone 100) applied at a dose rate which set as close as possible to a response threshold so that small variations in applied dose would give differences in biological response. The experiment was conducted on a permanent grass ley and to determine the appropriate dose to be used in the experiment, an initial trial applied doses of 0.25, 0.5, 1.0, 1.4 and 1.6 l ha^{-1} in 120 l ha^{-1} of water to the field area using the patch sprayer. After seven days, an experimental crop scanner comprising six boom mounted radiometers was used to measure the reflectance from the plot areas in the wavebands 640-660 nm (red) and 790 - 810 nm (near infra-red). The radiometers were mounted at 2.0 m intervals on a 12.0 m boom and were operated at a height of 1.5 m such that each sensor had a circular sensitivity footprint of approximately 0.6 m diameter. An upwards pointing sensor was used to compensate for changes in incident radiation. The scanner system was configured to record radiometer outputs at 1.0 m intervals calculated as a vegetative index (Paice et al., 1997). For each of the plots, a vegetative deficit was calculated by subtracting the mean vegetative index measured from an equivalent value obtained for an area to which no herbicide had been applied. This was scaled to a percentage response value by comparing the results with those from a totally desiccated area.

Results from this initial experiment are plotted in Figure 6.2 and fitted to a sigmoid dose response characteristic. From this calibration, it was decided to conduct the system response characteristic experiments using a dose rate of 2.0 l ha^{-1}. Four replicate plots, 12 m wide and 20 m long were treated with the experimental sprayer travelling at a speed of 8.0 km h^{-1}. Reflective measurements were made 6, 7 and 8 days after spraying and, because we were interested in effects due to the sprayer response characteristics only, data from each sensor and each scan were averaged. Results from the herbicide application are presented in Section 6.3.2.

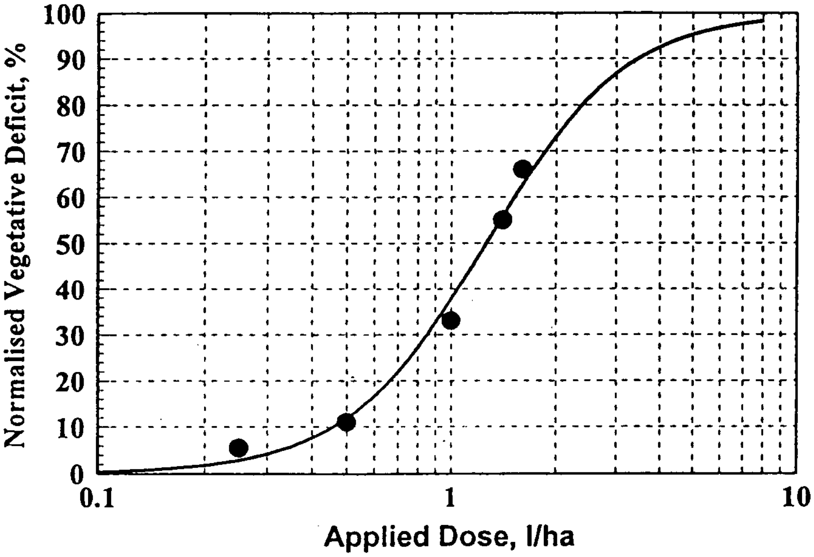


Figure 6.2 Calibration response curve of vegetative deficit with different herbicide doses

6.2.3 Field experiments and system performance monitoring

An important component of the work described in this report was to apply herbicides in a spatially variable manner defined by treatment maps generated from the mapping weed patch positions. This work was to use real herbicide formulations and the overall level of weed control achieved was to be monitored where this was possible. So as to monitor all of the functions on the sprayer at all positions in a field, the control system recorded all sensor outputs and control signals in a computer file written to the personal computer in the tractor cab. This enabled detailed records of any application to be interrogated on completion of a spraying treatment.

6.3 Experimental results

6.3.1 Delivered dose and dynamic response characteristics

The results from the experiments with the tracer dye to determine the accuracy of delivered dose at steady-state showed that the system could achieve better than a ± 5% error in the intended dose rate for forward speeds in the range 3.5 to 12.5 km h^{-1} and for dose rates from 0.75 to 5.0 l ha^{-1} - see Figure 6.3.

This performance at steady-state represents a turn-down ratio of some 25:1 (Miller *et al.*, 1995; Paice *et al.*, 1996). Although it may be possible to extend this range by changes to the instrumentation associated with the pump control, values of greater than 50:1 are unlikely to be achieved with a single pump operating at this level of accuracy. This has important implications as active herbicide formulations are developed with label recommended dose rates of less than 0.5 l ha^{-1}, while formulations with recommended dose rates in the order of 5.0 l ha^{-1} may still need to be used.

The results from the study of the dynamic response of the system using the concentrated salt solution showed that, when set to deliver a given dose rate at a constant forward speed switching from zero output to full output across the whole boom resulted in a reduction in delivered concentration of almost 50% over a period of approximately 0.35 as the metering system responded to step change in demand, Figure 6.3 (b). Figure 6.4 shows the measured system response when given a step change in demand from 4 - 16 ml s^{-1} together with an idealised controller response for the system as originally designed (Paice *et al.*, 1995) and before control modifications were made during the period of this project - see section 6.4. The 10 to 90% rise time is approximately 200 ms and the 10% settling time is between 300 and 400 ms. A small amount of overshoot has been allowed because it has been assumed that mixing within the delivery lines will mean that the concentration at the sprayer nozzles is likely to be more uniform because of the mixing process.

The response times for changing speeds and boom section widths are summarised in Table 6.1.

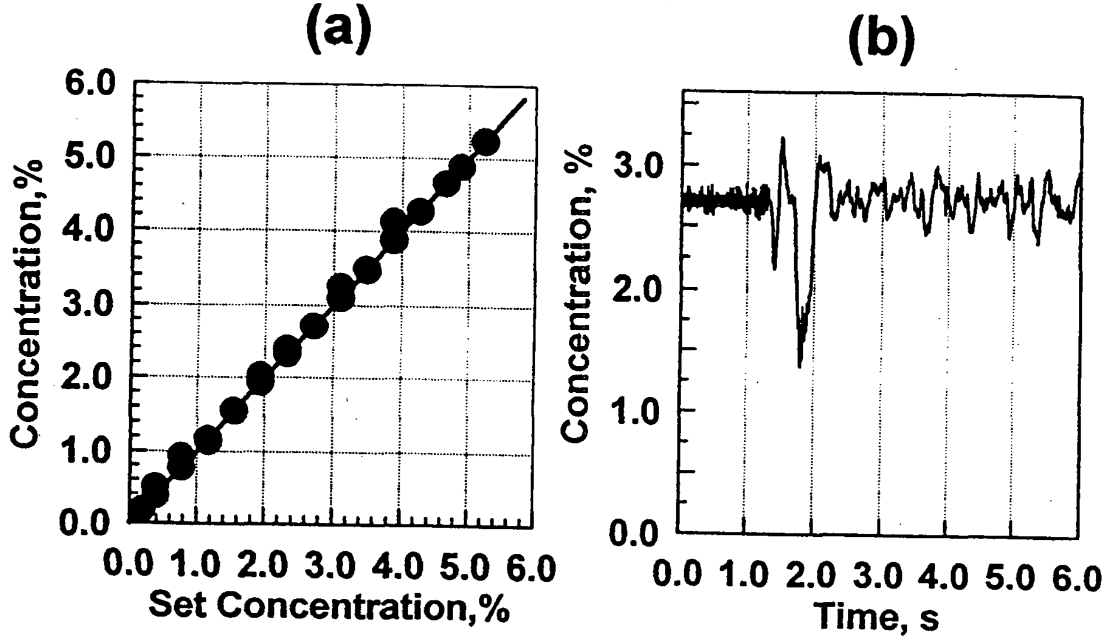


Figure 6.3 Measured spray liquid concentrations delivered by the injection metering system: (a) at steady-state; (b) dynamically

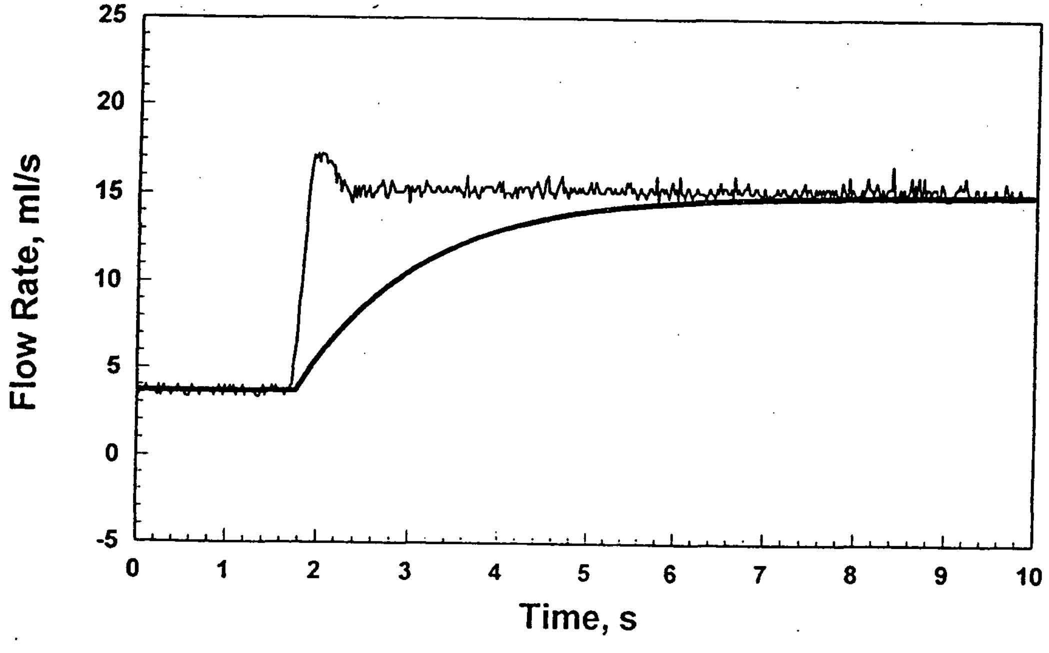


Figure 6.4 The response of the injection metering system to a step change in demand

Table 6.1. The rise and fall times for concentration changes caused by steps in sprayer speed and the amplitude and period of transients caused by step changes to the active boom width

Sprayer Speed Step (m sec^{-1})	Rise Time, Fall Time (ms)	Transient Peak (%)	Transient Period (ms)
1.1 to 3.27	150	-	-
3.27 to 1.1	250	-	-

Active Boom Width Step (m)	Rise Time, Fall Time (ms)	Transient Peak * (%)	Transient Period (ms)
0 - 6	-	+ 12	200
12 - 0 - 12	-	- 52	350
6 - 12	-	+ 40	300
12 - 6	-	- 76	450

*+ indicates a positive transient

It is estimated that the response time characteristics are approximately an order of magnitude faster than commercially available injection metering systems although there is relatively little independent published information relating to such systems. There is some scope for improving the system used for this project work by, for example, modifying the characteristics of the water flow to the boom such that there is a better match between this flow and the characteristics of the injection metering system. Such a modification would increase the total cost of the system and results to date indicate that such a further development is unlikely to be justified.

6.3.2 Biological response trials with a total herbicide

The measured vegetative indices on each of the four paraquat treated plots are shown in Figure 6.5. In all plots, the vegetative index fell rapidly at the beginning of the plot and there was no systematic pattern within the plot that could be directly related to the dynamic response characteristics of the injection metering control system. There was some reduced biological effect in the back half of the first replicated plot and this was probably due to air drawn into the metering system at the time of loading and this emphasises the need to have an effective air bleed mechanism.

Results from this experiment indicated that the performance of the injection metering dose control system and the associated sprayer controls had been well designed for patch application of herbicides.

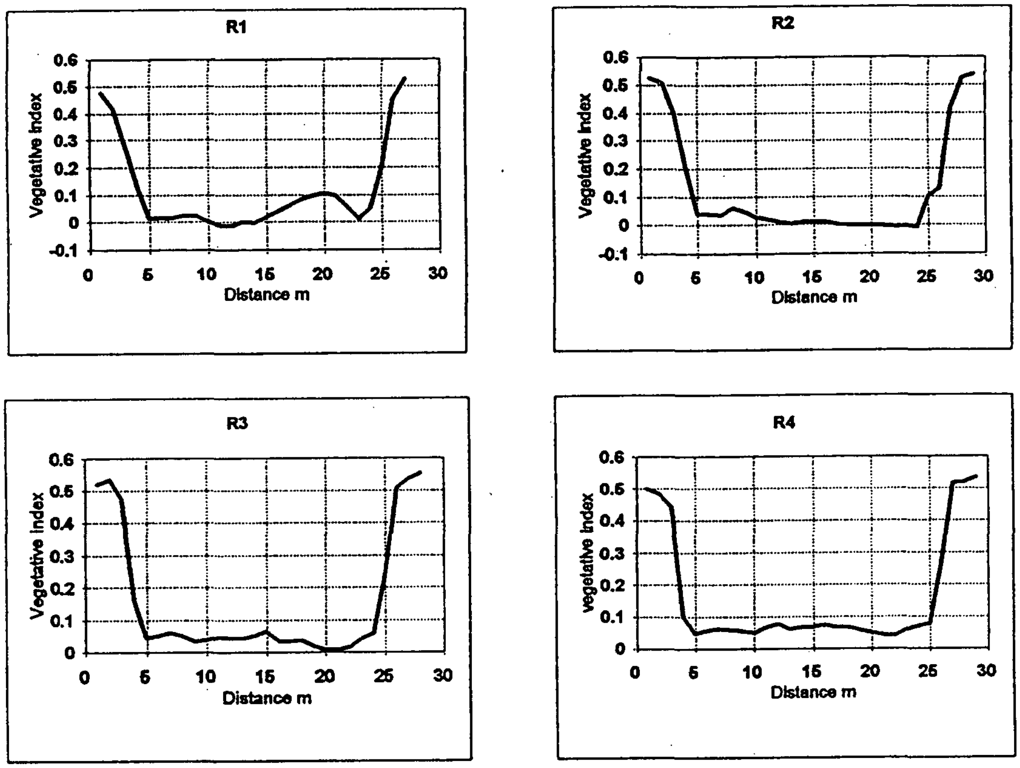


Figure 6.5 Measured vegetative indices for the replicated plot experiment, where R1 - R4 are four replicate plots

6.3.3 Results from Patch Spraying

6.3.3.1 Patch spraying in 1993

Field Z The three the tramlines surveyed for black-grass in a field of winter wheat (Fig. 4.1) were sprayed on the 25 March 1993 using 3.l/ha of Cheetah® (fenoxaprop-ethyl) on the full dose (high density patches) and 1.5 l/ha on the half dose (low density) areas. The Cheetah formulation was loaded into one of the cylinders on the patch sprayer and metered into a spray line applying 20 l/ha of water. The full and half dose areas were then sprayed in separate parts of the field. A 2% solution of a water soluble dye was loaded into the second metering cylinder on the sprayer and set to deliver 1.5l/ha of this dye solution on to the sprayed areas.

To assess the accuracy of the spray delivery, 50 mm wide strips of filter paper were placed within defined areas to be sprayed and at the edges of the main weed patch. The quantity of spray liquid delivered to the treated areas was determined by recovering the dye from the sprayed filter paper in the water and quantifying the amount of dye using spectrophotometry techniques. The positions where the spray had switched on/off were determined by manual inspection of the sprayed strips and the "error" to the marked position on the field measured with a tape.

Results from the Cheetah application to black-grass showed that the positional error assessed in five different places in the field was less than 3.0 m. The dose rate of traced dye recovered from the paper strips (mean of five samples) gave a value of 91% of the intended dose. However, it was noted that the quantity of Cheetah formulation used did not match expectation and therefore a laboratory experiment was conducted to measure the metered flow rates when operating with this formulation (Figure 6.6). The results showed that the delivery of the formulation was substantially less than the intended rate and it was estimated that actual rates of 0.8 and 1.6 l/ha had been applied to the low and high dose areas respectively. The reason for this discrepancy was traced to the pressure drop in the 4.0 mm tube from the top of the metering cylinder to the injection manifold when operating with the viscous formulation. This problem was solved by increasing the internal diameter of the pipe to 5.5 mm. The field was then re-sprayed at a rate of 0.7 and 2.4 l/ha, so that the intended rates of 1.5 and 4.0 l/ha were achieved.

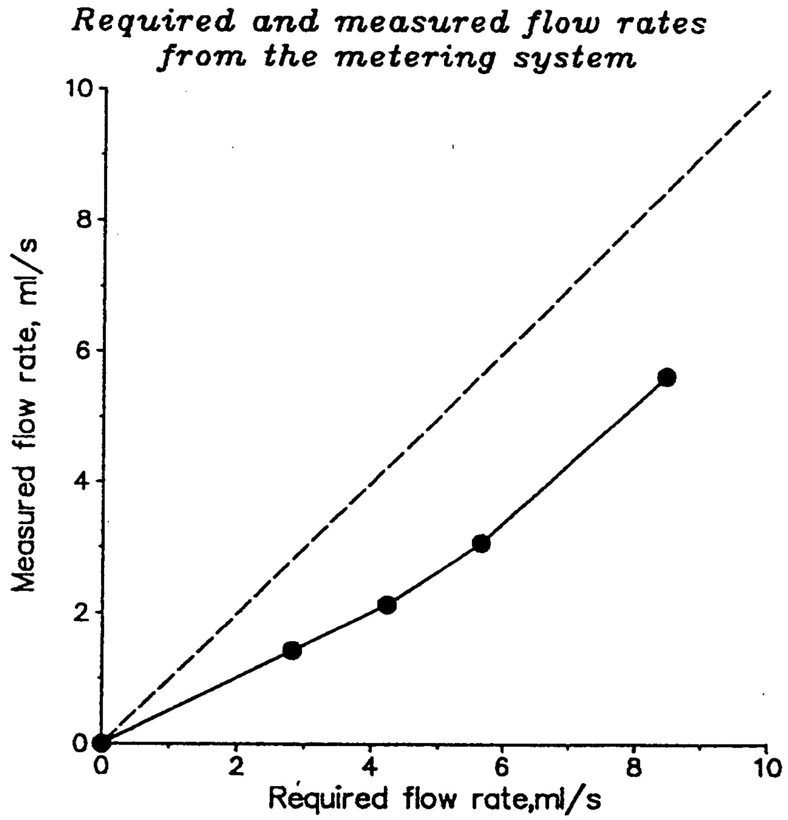


Figure 6.6 Required and measured flow rates of Cheetah from the injection metering system fitted with 4.0 mm tube (4.24 ml/s is equivalent to 1.5 l/ha)

Field Y An area of common couch in winter wheat was sprayed on 13 August 1993. Five tramlines were mapped with the survey vehicle as both a test of the mapping software and the handling of mapped data in OS grid reference format, Figure 6.7. Round-up (glyphosate) was sprayed at 4.0 l/ha on the full dose areas and at 2.0 l/ha on the half dose areas, each being metered into 120 l/ha. The performance of the application system was assessed by:

(a) comparing the recorded actions of the sprayer with those expected from the weed map;

(b) monitoring the total herbicide use and comparing this with a calculated figure from the treatment map;

(c) visually assessing the operation of the sprayer against the position of canes placed at recorded positions in the field.

The results from this work showed that the system was operating as expected with both herbicide use and the position of sprayed areas being in agreement within the error bounds of this relatively coarse assessment. Modifications made to both the injection metering systems and the mapping software were found to operate satisfactorily although a need for further modifications to the mapping software to account for the effects of tramlines being at an angle to the grid system was identified.

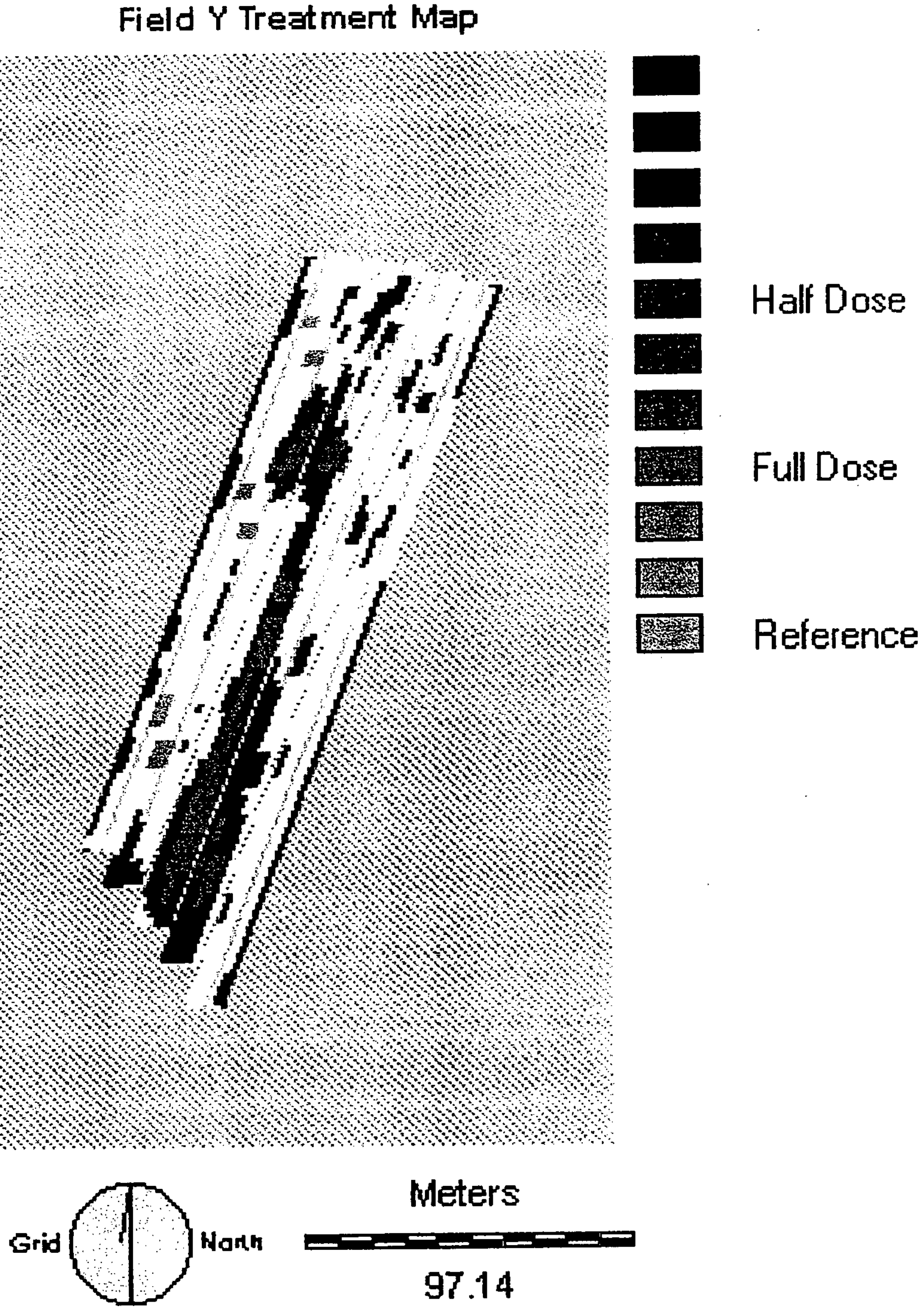


Figure 6.7 The treatment map used to spray Field Y

6.3.3.2 Patch spraying in 1994 - 96

The Patch Sprayer has been used to treat five fields, all cropped with winter cereals:-

i) *Field U* (5.3 ha) has been mapped 3 times and sprayed 4 times. It was mapped in winter 1994/5 for black-grass presence and absence with the survey vehicle, and for cleavers with a backpack mounted field scouting aid, which used the DGPS satellite navigation system. It was re-mapped for black-grass using the Massey Ferguson combine harvester based system at the time of the 1995 harvest. Grass weeds were sprayed in spring 1995, applying IPU® (isoproturon) at 3.0 l/ha (1.5 kg/ha) as a blanket application and Cheetah Super® (fenoxaprop-P-ethyl) at 1.5 l/ha to areas of black-grass presence using on/off solenoid valve control. Broad-leaved weeds were treated with a blanket application of Ally® (metsulfuron) (pre-diluted with water) at 30 g/ha, and Starane® (fluroxypyr) was applied at 1, 0.75 or 0.5 l/ha according to the density of cleavers using the injection metering system. The field was treated again for the 95/96 crop in autumn 1995 with Panther® (diflufenican + isoproturon) as a blanket application for residual control of broad-leaved and grass weeds, and Cheetah Super® on a tramline basis according to combined information on black-grass presence from the winter 1994/5 and autumn 1995 maps. Finally, Topik® (clopdinafop-propargyl) was applied in the spring of 1996 at 125 ml/ha for black-grass presence and 60 ml/ha for absence according to a "buffered" version of the 1994/5 map.

ii) In *Field A* a pre-harvest spatially selective application of Roundup Biactive® was applied for control of common couch. A weed map was produced with the surveying vehicle which showed areas of high density infestation (>25 shoots /m^2), low density infestation ($\leq$ 25 shoots/m^2) and no weeds observed. Roundup Biactive® was applied at 4 l/ha to high density areas and 2 l/ha to low density areas.

iii) *Field I* (6.36 ha) was used to test the injection metering systems under steady state conditions (not switching on and off boom sections). A blanket application of Javelin Gold® (diflufenican + isoproturon) at 4.0 l/ha and Hoegrass (diclofop-methyl) at 1.5 l/ha was applied to the field

iv) *Field A* The black-grass population in this field (9.7 ha) was mapped in the summer of 1994. A 4 x 2 m buffer was added to the map (4 m in the direction of the tramlines and 2 m perpendicular to them) was used to treat the field in the Autumn of 1995. Panther® (diflufenican + isoproturon) was applied as a blanket application at a rate of 2.0 l/ha with Cheetah Super® applied at 1.5 l/ha where black-grass was present.

v) *Field S* was mapped on set-aside in spring 1995 and this map (buffer as above) was used to apply Topik® in the spring of 1996. Topik® was applied at 125 l/ha (with adjuvant: Agral 90®) to areas where black-grass was present and 60 l/ha to areas in which no black-grass was observed.

For all the field experiments the Patch Sprayer's in-built monitoring system was used to record the herbicide dose applied at each point in the field.

Fig 6.8 shows the map used to treat Field "S" and Fig 6.9 shows the output from the sprayer monitoring system when travelling along one of the tramlines. The upper two traces in Fig. 6.9 show that the state of the solenoid valves the rate of output from the injection metering system A were constant, consistent with application of a uniform dose of Panther®. The lower two traces show variations in the number of boom sections switched on and in the delivery from injection metering system B as the system moved across the mapped patch areas and applied Cheetah Super® to the areas of black-grass. Positions when no solenoids controlling boom sections are open correspond to those where the output from the metering system is zero, as expected.

The patch spraying of common couch in Field "A" provided an opportunity to re-map the field in seasons after the patch application. The treatment was applied pre-harvest in 1994 and in 1995 the same field was cropped with oilseed rape which did not enable appropriate weed patch mapping in the spring/summer. The following season (1996) the field was again cropped with wheat and a weed survey was conducted of a section of the field using the back-pack mapping system once the cropped had started to ripen. The results of this survey are shown in Fig 6.10. Only the central tramlines in the field were monitored using the backpack GPS weed mapping equipment. the level of weed carry over from the patch application was low and was completely acceptable to the farmer. However, there were areas where weed patches had persisted and the positions of these correlated reasonably well with the original survey.

Figure 6.8 Weed map of black-grass in Field A, before dilation was used to generate a buffer area around the patches. (high density = light grey, low density = dark grey, no weeds = white)

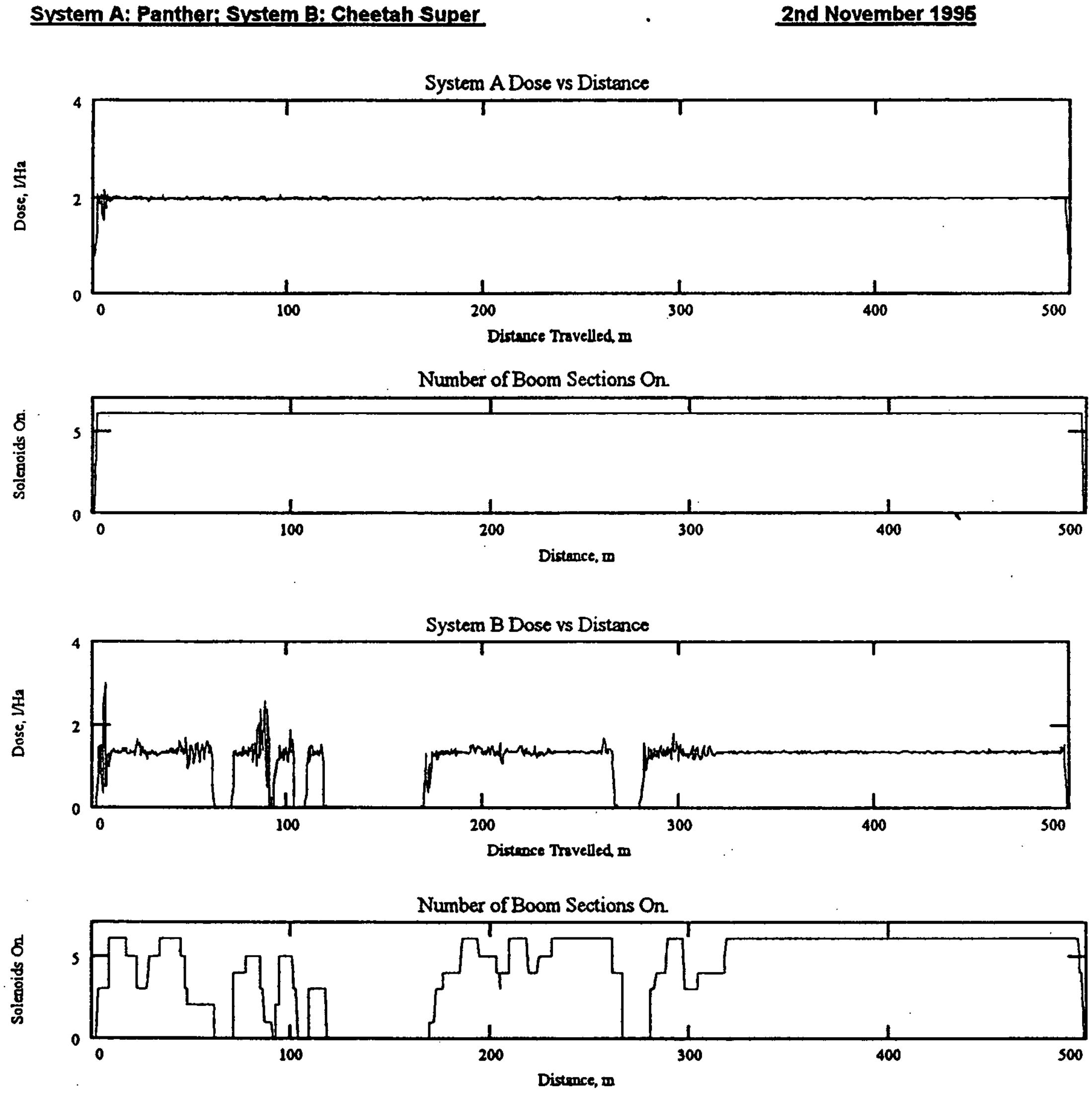


Figure 6.9 Output from the sprayer monitoring system when traversing tramline 8 of Field A. Top two traces relate to uniform application of Panther and the lower two to spatially selective applications of Cheetah Super to patches of black-grass

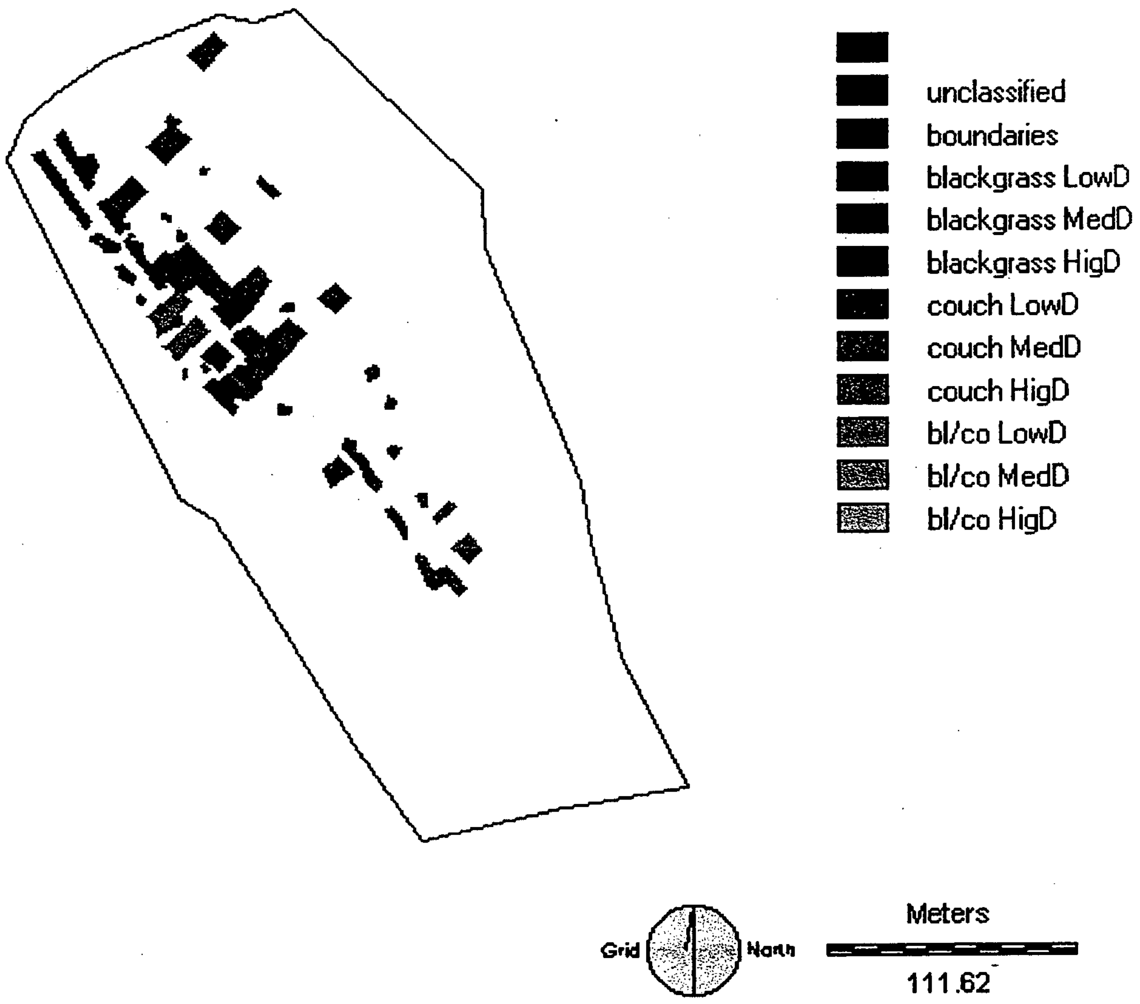


Figure 6.10 Back-pack survey of Field A in summer 1996, following treatment for the control of common couch in autumn 1994

6.4 System developments during the project

6.4.1 The development of the experimental rig

The combination of solenoid valve boom section switching and injection metering posed particular control problems in the early parts of the project. Switching boom sections in and out introduces step changes in the water flow to the boom and if the injection metering system is to keep the concentration of herbicide in the spray liquid constant, it must respond very quickly to a step change in demand. Changes to the sprayer hydraulic circuit, electronic control system and associated sensors were made to reduce the system settling time from approximately 2.0 s to 200 ms. This is almost an order of magnitude faster than most commercially available injection metering systems.

In association with the improvements described above, the electronic control system for the rig was rebuilt in 1994/95 around a Controlled Area Network (CAN). The system was split into a number of autonomous functional units each with its own microprocessor based intelligence. The CAN system is becoming a de-facto standard in relation to tractor/implement control systems and is likely to provide a simple interface with such systems. On the experimental rig it provided improved system error recognition and handling which is an important safety feature when dealing with the electronic control of pesticide dose. It also made it easier to provide for the logging of system performance to provide data for pesticide use accountancy and crop management systems.

In a performance assessment of the modified control system, pressure pulsations caused by the main sprayer pump was found to have a de-stabilising effect on the injection metering dose control system. The effect was minimised in two ways, namely:

(i) mechanically by introducing a hydraulic damper into the pressure supply line from the main sprayer pump; and

(ii) electronically with low pass filtering of the control feedback signals.

The final version gave a performance as described in section 6.3 of this report.

6.4.2 The design of a commercial prototype system

A commercial prototype patch spraying system is being developed based on a treatment map which has been generated and stored within a commercial control system designed to provide in-field location, yield mapping and treatment map control capabilities (Massey Ferguson "Field Star"). Treatment maps are generated on the farm office computer and then down-loaded to a unit in the tractor cab which is also connected to a GPS receiver to give field location. A key part of this part of the development of the commercial prototype was the development of an application systems to give a wide range of dose rates applied with conventional nozzles but retaining the required spray quality and volume distribution pattern (patternation).

Discussions during the initial stages of the development work reported here concluded that the approach of using a relatively high specification patch spraying system with both injection metering and map based control strategies could limit the commercial up-take of the technology. Work was therefore commenced to design, construct and evaluate a patch spraying system that would be directly compatible with existing spraying equipment and, if appropriate, could be retro-fitted to existing machinery

For a fixed size of conventional nozzle, output can only be altered by changing pressure. However, pressure also influences the droplet size and spray volume distribution patterns and therefore, for a given application, the range over which the output from the sprayer can be varied is limited typically to less than ± 20% of a nominal value. For patch spraying applications, work as part of this project has shown that it would be desirable to change the output from the sprayer by at least a factor of 3 such that low doses can be applied in places with low pesticide requirement and full dose used where problems have been identified.

An approach in which nozzle sizes are switched and the pressure at the nozzle varied at the same time was used so that sprayer output can be varied almost continuously. At each position in the field, the control system delivered a message to the sprayer containing the required dose rate and sprayer speed. The control system on the sprayer then selected the nozzle(s) to be used and the spraying pressure to give the appropriate flow rate, see Figure 6.11. In the prototype system, the switching of the nozzles and the control of spray pressure was done using a compressed air control system. Each nozzle on the boom was fitted with a pneumatic on/off valve activated by small air lines mounted along the boom. The original design used three nozzles at each position giving a continuously variable output over a wide range. In practice, it was found that good performance could also be obtained using two nozzles at each nozzle position on the boom.

The patch spraying unit that has been developed is directly compatible with existing spraying systems and it has been used successfully to apply herbicides, fungicides and liquid fertilisers at different rates in different parts of a field in a series of evaluation trials. The prototype unit will be used to help determine future directions for the commercial development of patch spraying systems. This will include identifying how all the factors required for effective patch spraying can be brought together in a way that provides a practical, cost saving system for the farmer.

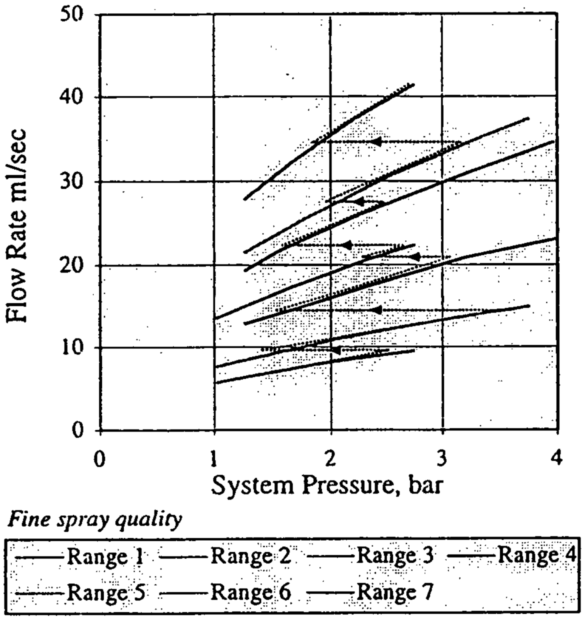


Figure 6.11 A typical response for a system using three nozzles at each location showing a possible path through increasing flow rates

7. ECONOMIC CONSIDERATIONS FOR PATCH SPRAYING

The uptake of patch spraying practice is likely to depend on our ability to show real long term economic benefits. Will the savings accruing from the reduction in herbicide use exceed the extra cost of the specially designed sprayer, the computer and navigation system and the creation of the maps? At the same time it should be recognised that there are likely to be environmental benefits from the overall reduction of herbicide usage. To some extent these go hand in hand with the analysis of costs, although environmental considerations will tend to bias the recommended approach towards greater optimisation of herbicide use. The following sections review the economic consequences of the patch treatment of weeds.

7.1 Classification of cost factors.

Cost factors associated with patch spraying fall into three categories:-

Agronomic Costs have been defined as the balance between the overall herbicide cost and the financial costs arising from weed induced loss of yield. These are annual costs and for the purposes of economic analysis an annual interest factor has been applied to calculate the present value of patch spraying. The discounted cost of maintaining the weed seed-bank existing at the end of the period of analysis has been modelled by Audsley (1993). In this modelling work it has been assumed that the weed infestation has no economic effect other than to reduce crop yield.

Equipment Costs are dominated by fixed capital expenditure on equipment which will allow the farmer to apply herbicide according to a spatially variable regime. This might include: specialised application equipment, equipment controller and user interface, a navigation system, management software and possibly weed mapping systems. In practice it is unlikely that the full cost of these would need to be offset against herbicide savings alone, particularly if the farmer was working within the wider sphere of precision agriculture, including yield mapping and spatially variable fertiliser application. For instance, a combined equipment controller, user interface and satellite navigation system is now available commercially in the form of the Massey Fergusson Fieldstar™. This can be configured for a variety of map based precision agriculture operations. Similarly, application equipment might also be used for other crop protection products (e.g. fungicides, insecticides and nematicides). Paice *et al.* (1996) have reviewed application system technologies which might be adapted for patch spraying.

Management Costs in patch spraying are dominated by the labour cost required to survey fields for weed infestation and develop a spatially variable treatment strategy. Surveying costs will be incurred periodically and will increase with spatial resolution, weed density resolution, frequency of surveying and, with the number of weed species treated. Much of the thrust of our simulation modelling work (section 3), and work we have undertaken on decision support (Audsley & Beaulah, 1996) is targeted at developing our understanding of weed patch dynamics with the practical goal of developing management systems to minimise surveying effort. The most critical aspect relating to the cost of mapping is the longevity of the map. If weed patches remain relatively stable, the map will remain accurate for a number of years and the original costs of creation can be discounted over all these years. If, however, the patches are less stable the map will have to be redone more often and so the costs/year will be greater.

It is not within the scope of this project to undertake a full cost-benefit analysis of all the factors pertaining to patch spraying. In practice the results of such an analysis are likely to be inaccurate whilst the technology is in a phase of rapid development. One innovation (in machine design or weed surveying technology for instance) might have a dramatic impact on the economic viability of patch spraying. We can however make general statements about the sensitivity of agronomic, equipment and management costs to common factors.

7.2 Comparison of patch spraying methodologies and cost sensitivities.

The spatial dynamics model described in Section 3.3 simulates the main processes which affect weed patchiness and scale of aggregation. It can be used to investigate the likely long term effects of patch spraying. We have compared alternative strategies for patch spraying with conventional whole field weed control practice and have examined cost sensitivities in relation to agronomic parameters.

Table 7.1 Simulation of potential savings (£) from on/off patch spraying fields with three contrasting initial distributions of black-grass (Field I: 35%, II: 54% and III: 72%) over a ten year period, including the effect of adding a 4 or 8m buffer zone to the treatment area

	Field		
	I	II	III
No buffer	187	83	5
4 m buffer	207	111	27
8 m buffer	202	93	19

Table 7.1. shows the combined herbicide and yield loss savings associated with on/off patch spraying, at 4m spatial resolution, for 3 initial seed-bank distributions. These are deduced from real field weed distributions observed with the mapping system discussed in section 4. The effects of mapping resolution and buffers on the area of the field requiring treatment is discussed in section 5. It will be noted that costs are very sensitive to the initial proportion of the field infested. Long term costs can be reduced by applying a buffer region around areas in which weed plants are observed (as in Field 1 Table 7.1). This is because in general the weed seed-bank does not terminate abruptly and a 'tail' or density gradient will form at the boundaries of high density "patches". Failure to apply herbicide in this region will result in rapid encroachment of the weed patch into uncolonised or lightly infested parts of the field. Costs start to increase again if the buffer region is too large because herbicide is being applied to a larger proportion of the field throughout the period of simulation, as can be seen with the 8m buffer in Field 1.

This discussion of the effects of buffer zones raises another issue of considerable relevance to the development of patch spraying. Reductions in herbicide use are maximised by maximising the resolution, as this reduces the areas of the field that are treated unnecessarily. However, high resolution requires much more complex engineering and computer control systems. Lower resolution simplifies the construction of the patch sprayer and thus lowers the initial cost. It is not possible yet to say where the economic balance between resolution and engineering costs actually lies.

Table 7.2 compares the cost of on/off patch spraying with dual dose application of isoproturon (IPU). It can be seen that the latter is generally less sensitive to sprayer spatial resolution. This is mainly because the application of a lower 'assurance' dose tends to inhibit the spread of patches with less reliance on buffer regions. Dual dose control is more effective than on/off control where the weed distribution is characterised by areas of higher and lower density rather than being entirely confined to a few discrete patches. Our analysis of weed presence/absence maps (c.f. section 4) observed on set-aside (before control measures) would suggest that for black-grass the former is more typical. As a generalisation we can say that dual or multi-dose patch spraying is likely to be a more robust approach than on/off control in that it is less sensitive to the effects of seed dispersal. On/off control will be useful only at high spatial resolution (better than 6x6m) or where net propagule dispersal range is limited e.g. for perennial weeds (common couch or creeping thistle) in a minimal tillage environment.

Table 7.2. Cost (£/ha) of controlling black-grass over 10 years in two contrasting fields: A. all weed seeds confined to a discrete patch and B. most of the weed seeds in a high density patch but some distributed at much lower density over the rest of the field.

	A. Discrete Patch		B. Bimodal Distribution	
Sprayer Resolution, m	On/off	Dual Dose	On/off	Dual Dose
4 x 4	150	94	202	110
6 x 6	218	113	265	121

7.3 Common factors controlling patch spraying costs.

The key controlling factor relating to the cost of patch spraying is the infestation level of the weed. This has been clearly shown in the modelling work described in section 3.3 and in single year calculations based on the weed maps generated in this project. Low infestation levels generate more benefit for patch spraying than high infestations (eg see Table 3).

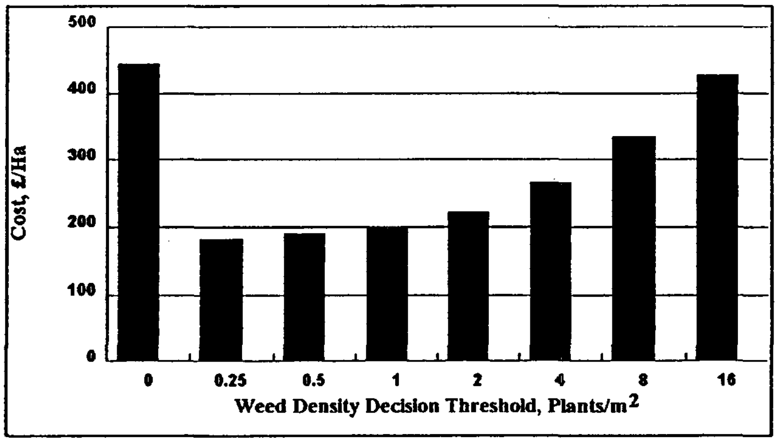
Spatial Resolution vs Dose Resolution: As discussed in section 7.2 the sensitivity of agronomic costs to the spatial resolution of the sprayer is greater for on/off than for dual/dose patch spraying (Table 7.2). If the spatial resolution of the system is high, on/off patch spraying can become more profitable but at lower spatial resolution dual, multidose or continuous dose systems are likely to be required. Simulations suggest that if the resolvable area is above 6x6m, sustainable savings from on/off patch spraying will be minimal, whereas for dual/dose patch spraying it is likely that appreciable savings will continue to be achieved at much lower resolution. It follows that there is likely to be a trade-off between dose resolution and spatial resolution so that even greater savings are possible with multi-dose and continuous dose systems operating at a given spatial resolution. In practice the optimum levels of spatial and dose resolution are likely to be limited by both machinery and management costs.

Sprayer Paice *et. al* (1995) (cf section 6) have described a patch sprayer that has the operating characteristic of continuous dose resolution and high (2x2m) spatial resolution. Whilst from the agronomic point of view this specification has the potential to generate very substantial savings, the combination of injection metering and real time boom section control demand high capital outlay and maintenance costs. Paice *et al.* (1997) have discussed how some of the technical difficulties in meeting this specification have been solved.

Surveying Weed surveying costs are likely to be an even more important factor in limiting practical dose and spatial resolution. The surveying system described in section 4.2 is capable of mapping a single weed species at a spatial resolution of 2x1m at three weed density levels (defining required dose resolution) or two weed species for presence/absence. However, initial outlay for such a machine (if it were commercialised) would be in the region of £15k and the required labour is around 0.3 - 0.6 man-hours/ha. Surveying costs fall off rapidly as spatial and weed density resolution is reduced and it may be possible to gather some useful data during normal field operations. However, this aspect has not received detailed study in this project and further work is needed to clarify the potential of mapping from other farm vehicles (eg tractors, self-propelled sprayers, combine harvesters) and the costs of map production. The other issue relating to mapping costs, is the longevity of the maps. The more stable the patches, the longer the map remains accurate and the lower the mapping cost/yr.

Weed density decision threshold: Figure 7.1 shows the effect of the decision threshold on the agronomic costs of on/off patch spraying with spring applied contact herbicide. Costs can be compared with that for zero threshold, which is equivalent to conventional whole field application. The decision threshold is the level below which no herbicide is applied. It will be noted that costs rise with threshold and there is no threshold level (for black-grass in particular) at which cost are at a minimum. In practice the lowest practicable threshold should be adopted and this will depend on the weed surveying method, the care with which it is undertaken and will thus be related to its cost.

Figure 7.1 The effect of decision threshold on the cost of black-grass control with on/off patch spraying, simulated over ten years.



Uncertainty of weed density and position. Any observation of weed density or presence/absence will carry with it a some uncertainty. Inaccuracies in the navigation system will affect both the information gathered by weed surveying and the spatial accuracy of herbicide application. Incorrect assessment of weed density is likely to be most damaging in regions of rapidly changing seed-bank density i.e. in the density gradient region around the periphery of high density patches. The application of buffer regions as described in section 5.3 is a simple management technique for overcoming both these problems but carries with it the penalty of reduced short term agronomic savings. Audsley & Beulah (1996) have discussed how multiple it the penalty of reduced short term agronomic savings. Audsley & Beulah (1996) have discussed how multiple sources of uncertain data can be combined to generate a treatment map with increased confidence. We have shown through simulation how dual-dose patch spraying reduces the need for buffer regions.

Seed Dispersal Range: It is clear from simulation that a large seed dispersal range will reduce the agronomic savings achievable with patch spraying. Seed dispersal will: reduce patchiness, encourage patch growth and increase the uncertainty of seed-bank density. Seed dispersal range will not be affected by the patch spraying process itself but the need to minimise it where patch spraying is employed may influence decisions on other crop husbandry practices and on cropping decisions. Movement of seed by cultural operations does not seem large, as has been discussed in section 3.1, but the extent of natural dispersal is still largely unquantified. It is clear that movement of propagules of perennial weeds such as common couch and creeping thistle will be less than that of annual species, which rely on seeds for their propagation.

7.4 Economic benefits of patch spraying

Preliminary financial benefits attributable to patch treatment of weeds can be calculated for the two weed species, studied most intensively in this work, black-grass and common couch. With black-grass the mean infestation level for this weed over the 13 surveyed fields was 53%. If a 4m buffer is added to this infestation level the treated area increases to 63%. Using the standard herbicides available for the control of this weed, the single year economic savings are in the region of £5-10/ha/yr, depending on the spray strategy adopted, and the number, distribution and size of patches. These figures concur with the modelled values calculated for a ten year period (see section 7.2). Calculations for couch (Rew *et al.*, (1996a) suggest a similar level of saving of £5-12/ha/yr, depending on the spray strategy adopted by the users (eg on/off, dual dose). It must be realised that these preliminary calculations are based on only two weed species. More work is required to identify the range of infestation levels and distributions that can occur and appropriate herbicide treatments.

Further estimations of the economic benefit of patch treatment can be obtained from calculations of the amount of herbicide used on the patch sprayed fields. The seven patch sprayed treatments are described in Section 6.3.3.2 and the amount of herbicide used and consequently the cost has been estimated. These data, presented in Table 7.3, indicate a greater reduction in costs than estimated from the calculations based on infestation level, presented in the previous paragraph. Savings are appreciable in all four fields, being in excess of 40% in 6 of the 7 tests, with a mean financial value over the seven experimental treatments of £15/ha. No data is given for Field "I" since this was sprayed with a uniform dose rate as part of a test of the injection metering system.

Table 7.3. Actual herbicide cost saving achieved for each field experiment treated with the patch sprayer.

Field	Appln	Herbicide	Target Weed	Herbicide Cost £/ha	Savings £/ha	% Savings
U	1	Cheetah Super	black-grass	35.00	24.00	69
U	2	Starane	cleavers	30.00	10.00	33
U	3	Cheetah Super	black-grass	35.00	22.00	63
U	4	Topik	black-grass	40.00	26.00	65
A	1	Roundup Biactive	couch grass	20.00	8.50	42
A	1	Cheetah Super	black-grass	35.00	17.00	49
S	1	Topik	black-grass	40.00	23.00	57

8. CONCLUSIONS

The work carried out over the last four years has clearly identified the potential of this technology in the treatment of weeds. Surveys of fields using a high clearance platform are possible at certain times of the year, depending on the crops present. Using computer and satellite location technologies, it is possible to map these surveyed weeds to an accuracy of 2-4 m. This information can then be used to control the application of the herbicides. The requirement for a sprayer with a definable and rapid on/off response time has been met by the work at Silsoe Research Institute, based on an injection metering control system. The simplified analysis of the economics of patch spraying conducted as part of this project work shows substantial benefits but further work is required to quantify the costs of generating treatment maps, to determine the scale of patchiness and to confirm the benefits over an extended time period. Economic factors have been discussed in more detail in section 7. However, there remain some outstanding issues that require more development before patch spraying can be fully commercialised.

8.1 Mapping

In this project, virtually all the mapping was done with a specialist vehicle, although some was done from a combine harvester. Mapping is only possible at certain times of the year and is influenced by the presence of crops. Pre-harvest mapping of weeds that remain above the crop can be done at harvest from the combine, but these maps will only identify weed survivors. Thus surveyors may miss patches where control has been too good to permit obvious survivors. The approach will however identify core infested areas. Mid-summer mapping of grass weeds and probably cleavers is possible in winter cereals, as the flower heads or the shoots can be easily seen. Again, this mapping will only identify plants surviving from earlier treatment. Mapping earlier in the year, prior to herbicide treatment may be possible but if the weeds are small, speed of travel would have to be reduced. Set-aside, prior to summer control of weeds with herbicide, provides an ideal 'window' for mapping and has the advantage that the entire population of weeds would be mapped. Mapping is most effective when the assessor can look down on the crop and weeds, rather than across the top of the vegetation. Mapping from a tractor or self-propelled sprayer should be possible but this possibility remains to be confirmed. This is a key area requiring further work.

A further aspect requiring more study relates to the width of tramlines and the extent of vision that the surveyor can achieve. To date, all maps have been based on surveys from 12 m tramlines, which were the standard width when the project started in 1993. It is not clear how to survey 18 or 24 m tramlines.

The potential for automated detection of weeds, particularly at early stages of growth, also requires further study. Experimental work in widely spaced row crops has shown that a combination of image analysis and discrimination on the basis of colour can enable crop plants in the row to be identified together with most of the weeds (Stafford & Benlloch, 1997). The potential for this approach has been demonstrated in work associated with this project and now needs to be developed such that the commercial viability of these techniques can be evaluated.

8.2 Location technology

In the last two years of the project, a Differential Global Positioning System (DGPS) was used to create maps of the surveyed weeds. The reliability of the systems is still not adequate. Topographic conditions, woods, buildings and multi-path reflections can prevent the location device from obtaining an accurate fix. In extreme cases this can mean that mapping is impossible but in other circumstances positions can 'drift' several metres. This may not be too critical for some aspects of Precision Farming but may pose problems for weed mapping where there is an need for accuracy of 2-4 m. Our experiences in 1996 demonstrated that DGPS is still not a sufficiently reliable technique, but the technology is improving all the time.

8.3 Computer hardware

The research group involved in this project work developed their own software to create the maps from the DGPS location positions and then to use this to control the sprayer. Such software is now being developed by commercial agricultural software companies and is, or will be soon readily available to potential users.

8.4 Sprayer technology

As indicated in section 6.4, discussions with commercial organisations concerning the development of patch spraying systems has suggested that for many, the adoption of both injection metering technologies and a map based control strategy may be too difficult to take in a single step. There is a need for a patch spraying system that is directly compatible with existing spraying machinery and that, if appropriate, can be retro-fitted to current designs. Results from this project work have established the basis for the design of such a system.

The results from the work on this project has shown that patch spraying systems based on injection metering control are likely to give the required performance particularly in respect of minimising the need for disposal of unused dilute herbicide and for decontaminating the machine after use. The ability to control both the applied dose rate and the mixture of herbicides to different areas of the field are very important advantages of this method of control. One possible disadvantage of injection metering control is the large turn-down requirement that arises from the wide range of volume rates that represent the full dose rate of different formulations. This means that practical systems are unlikely to be able to achieve the required performance characteristics using a single size of metering pump.

8.5 Patch-spray system

The combination of mapping, location technology, computer hardware and sprayer technology into a commercially viable patch spraying system still requires several areas of development, as outlined above, but commercial interest in the production of a patch sprayer is providing an impetus towards the resolution of existing problems.

Alternative approaches to the patch treatment of weeds involving real time detection of weeds would eliminate the need for the creation of maps and the associated location technologies. So far, although such systems are feasible in wide spaced crops, they are not possible in the majority of UK arable crops. Even if the technology for on-line weed detection were available, the approach of using weed maps from which to generate a treatment map still has important advantages relating to:

i) the ability to make management judgements concerning the dose and mixture of herbicides to be applied to different areas accounting for external factors and the overall situation on the field/farm;

ii) the fact that the sprayer can be loaded only with the appropriate herbicides and quantities needed to treat the mapped areas so minimising the human and environmental safety implications of having a machine loaded with pesticide materials that would not be used in that field.

Thus, this project has progressed the patch spraying of weeds from a theoretical concept to a reality. There are still a number of unanswered questions but the basic information to develop commercial, practical, spatially selective weed control systems is now in place. The commercial development of the system needs to be the next phase of the project and the collaborative work between Micron Sprayers and Silsoe Research Institute, is already laying the groundwork for such progress.

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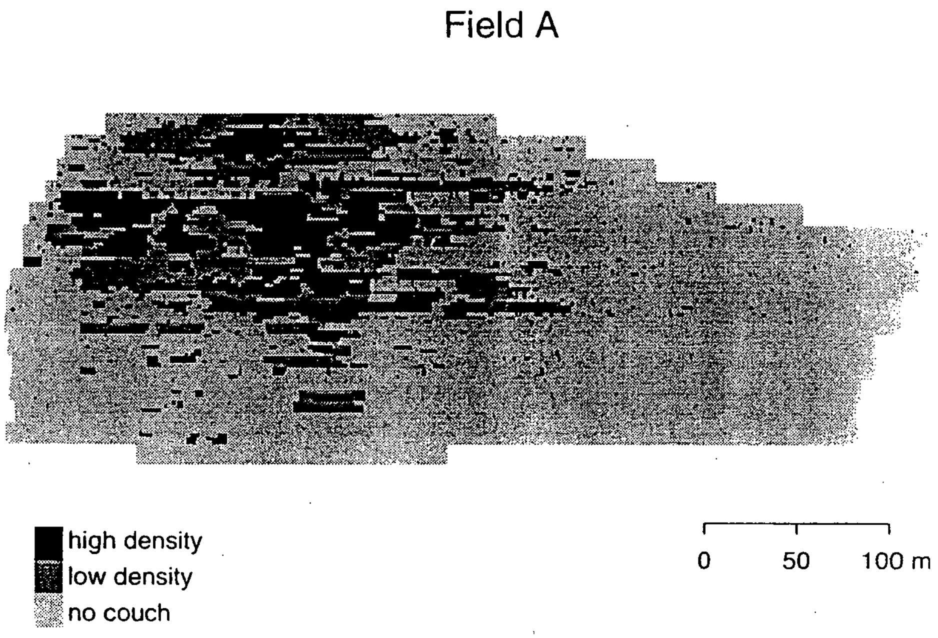
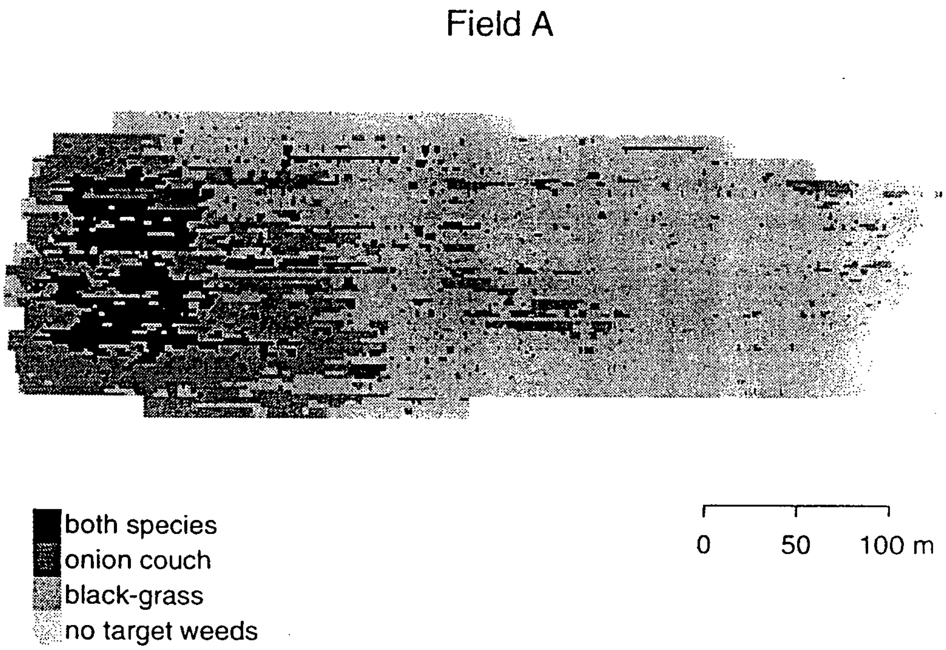
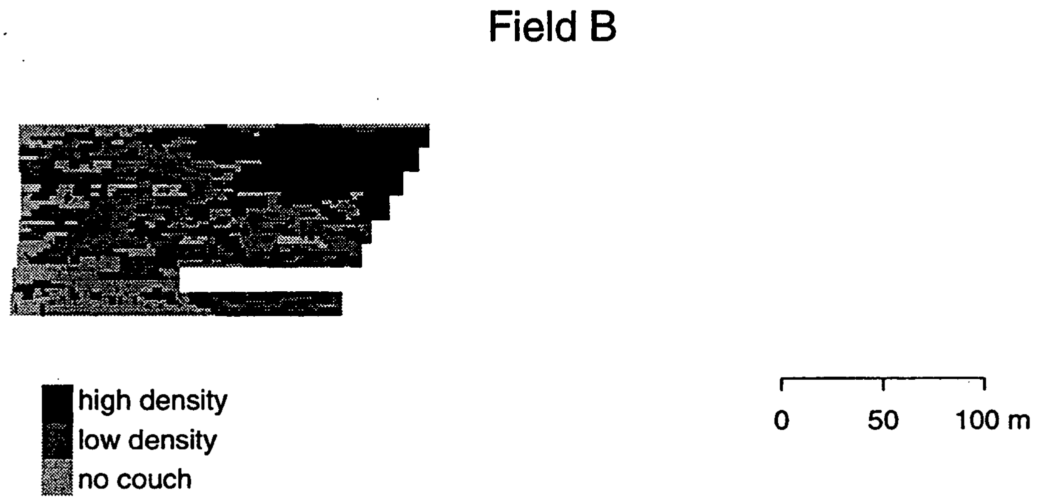
Appendix 1 Field Maps

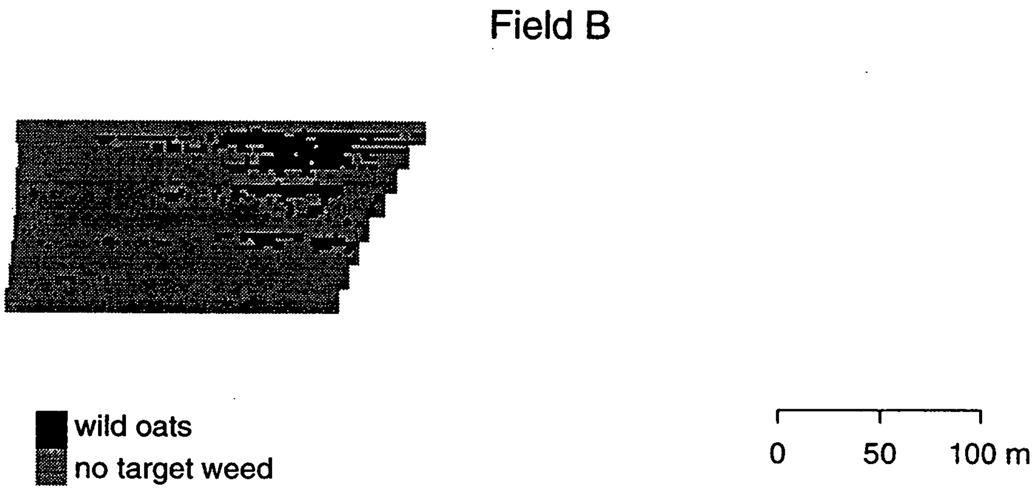
Field A (Farmers Field)



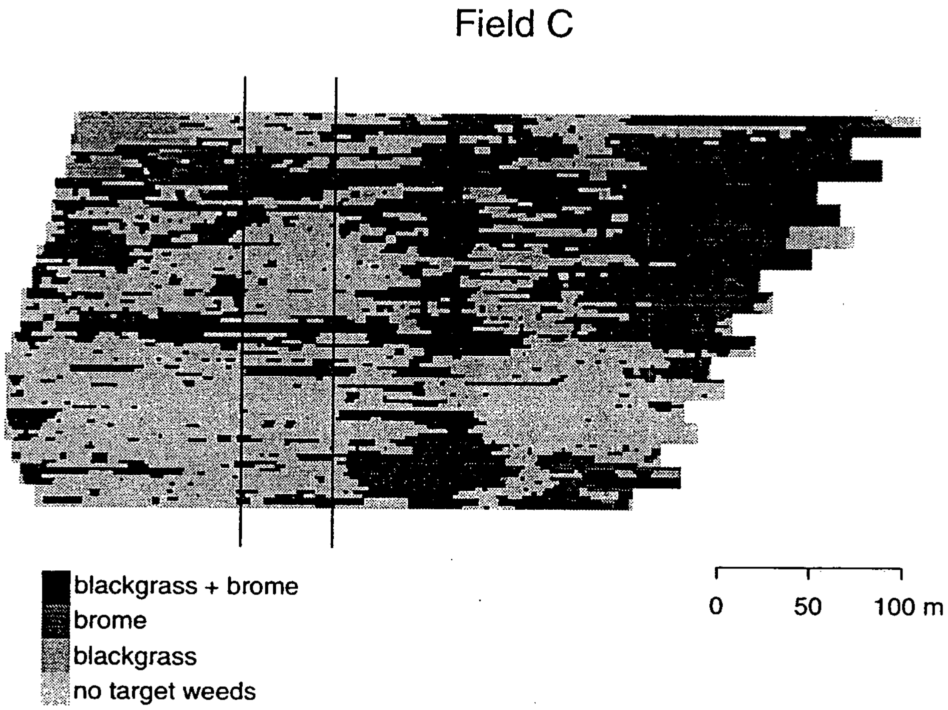


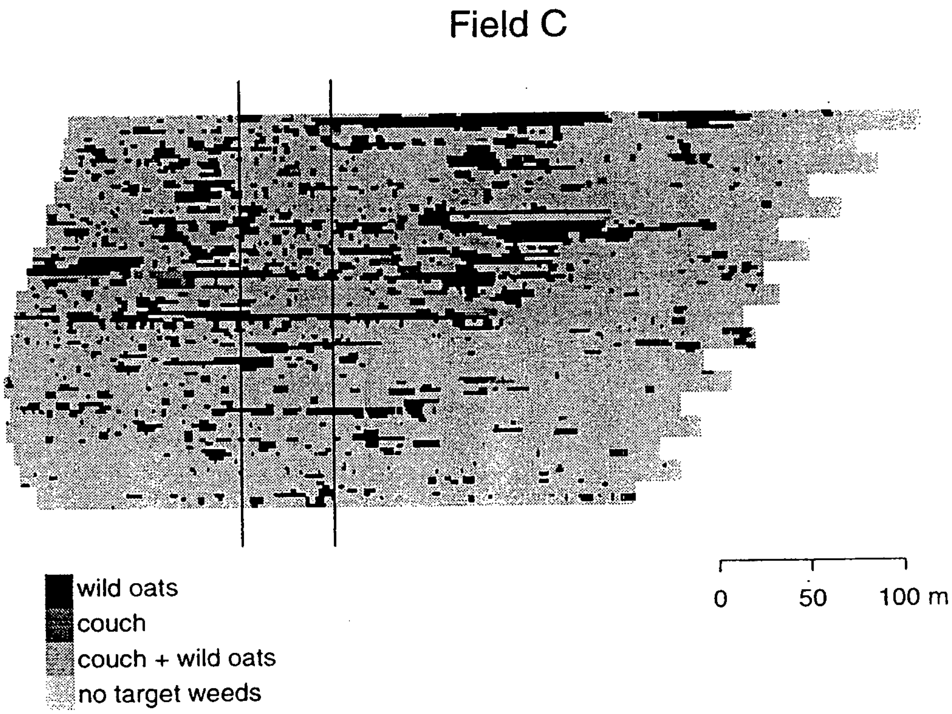
Field B **(Mrs Platts)**





Field C (CT Field 1)





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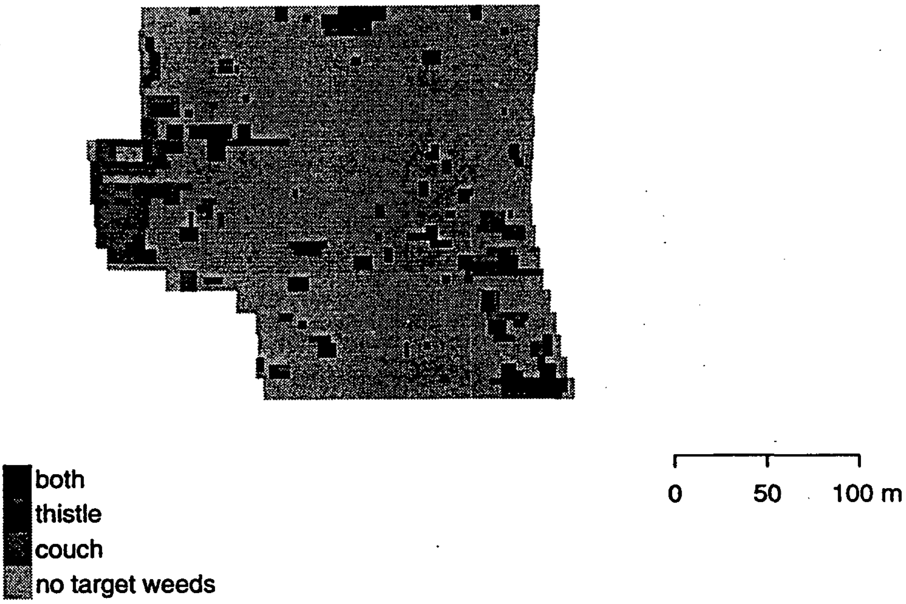
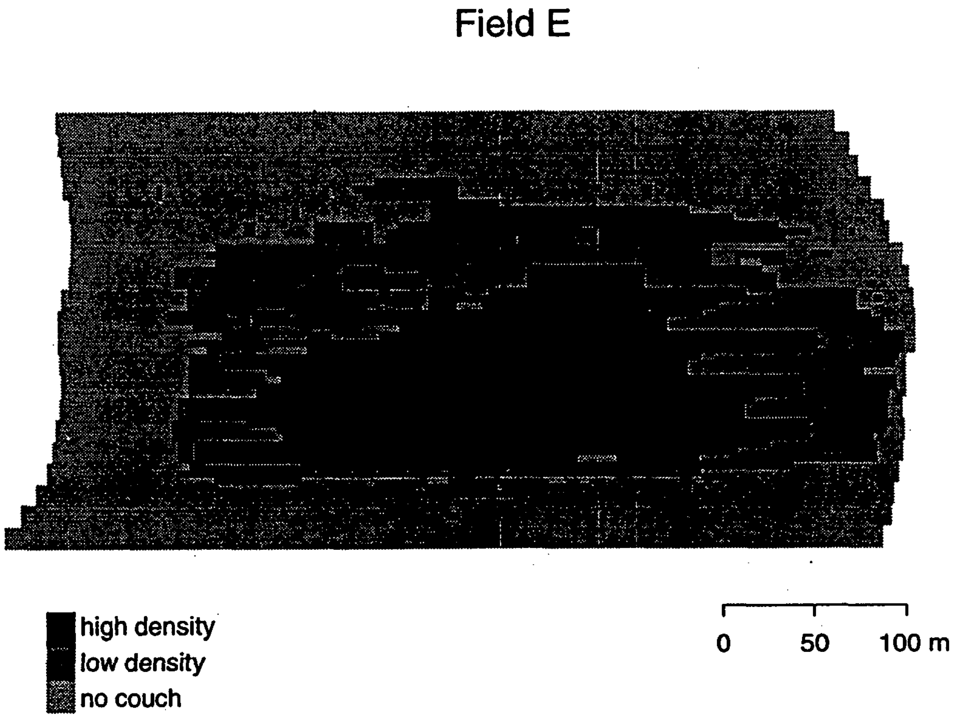
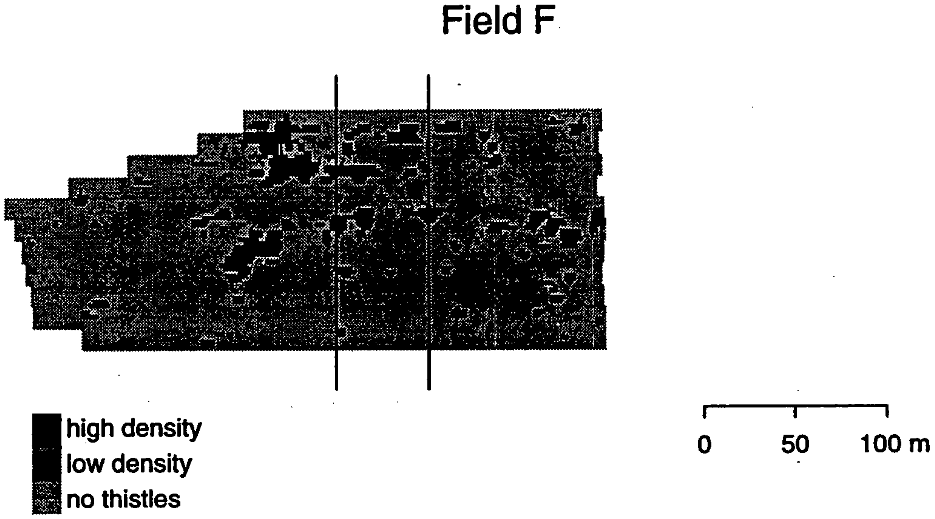

Field D

Field E (24 Acre)

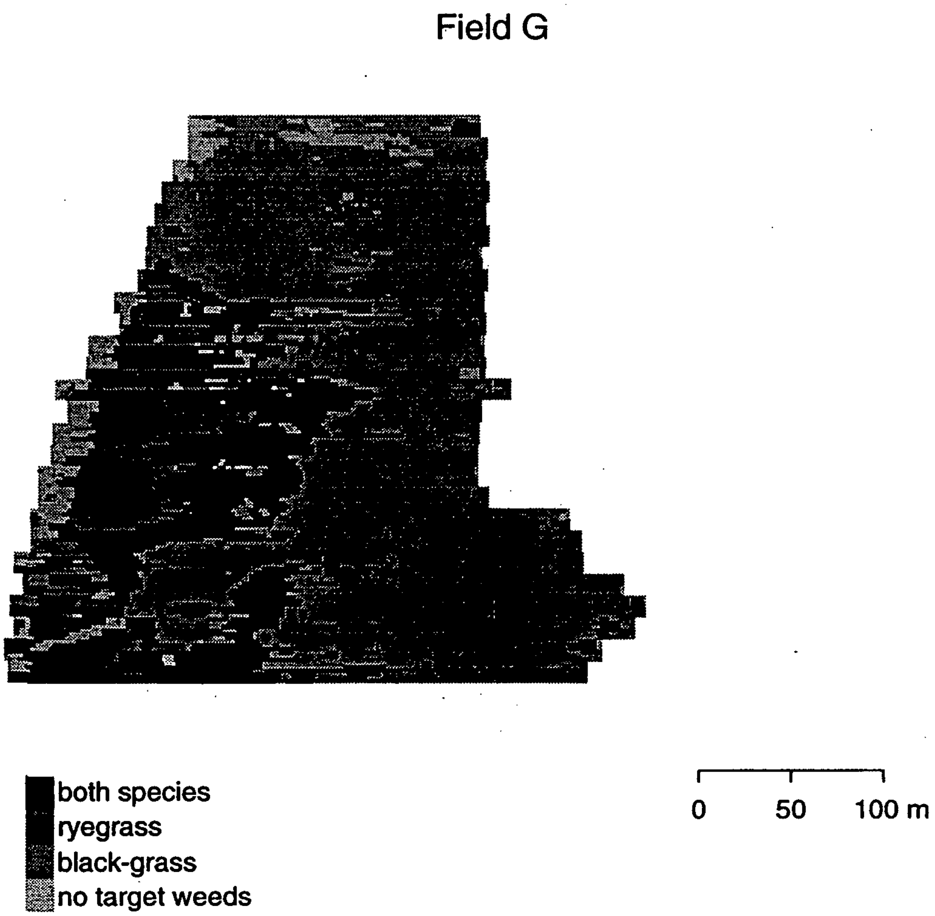
NB Surveyed with hand pushed machine



Field F (Great Knott)

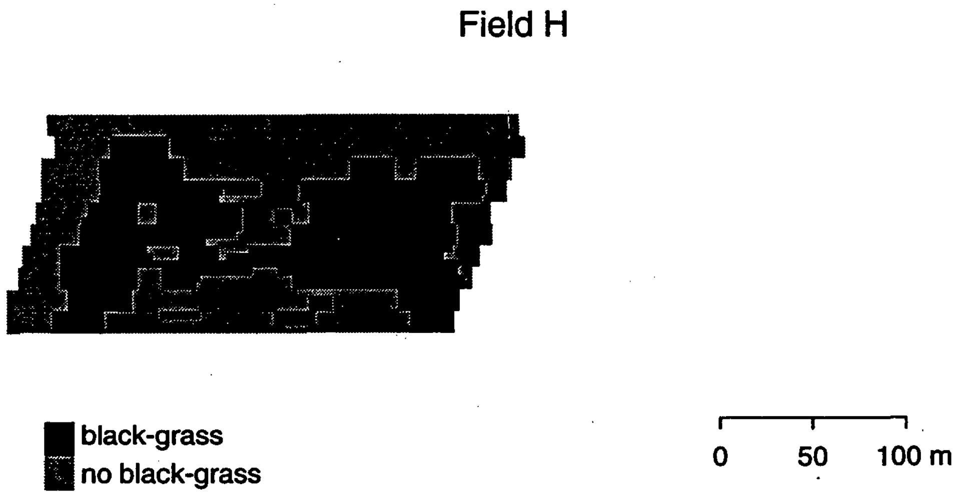


Field G (RC Field 1)

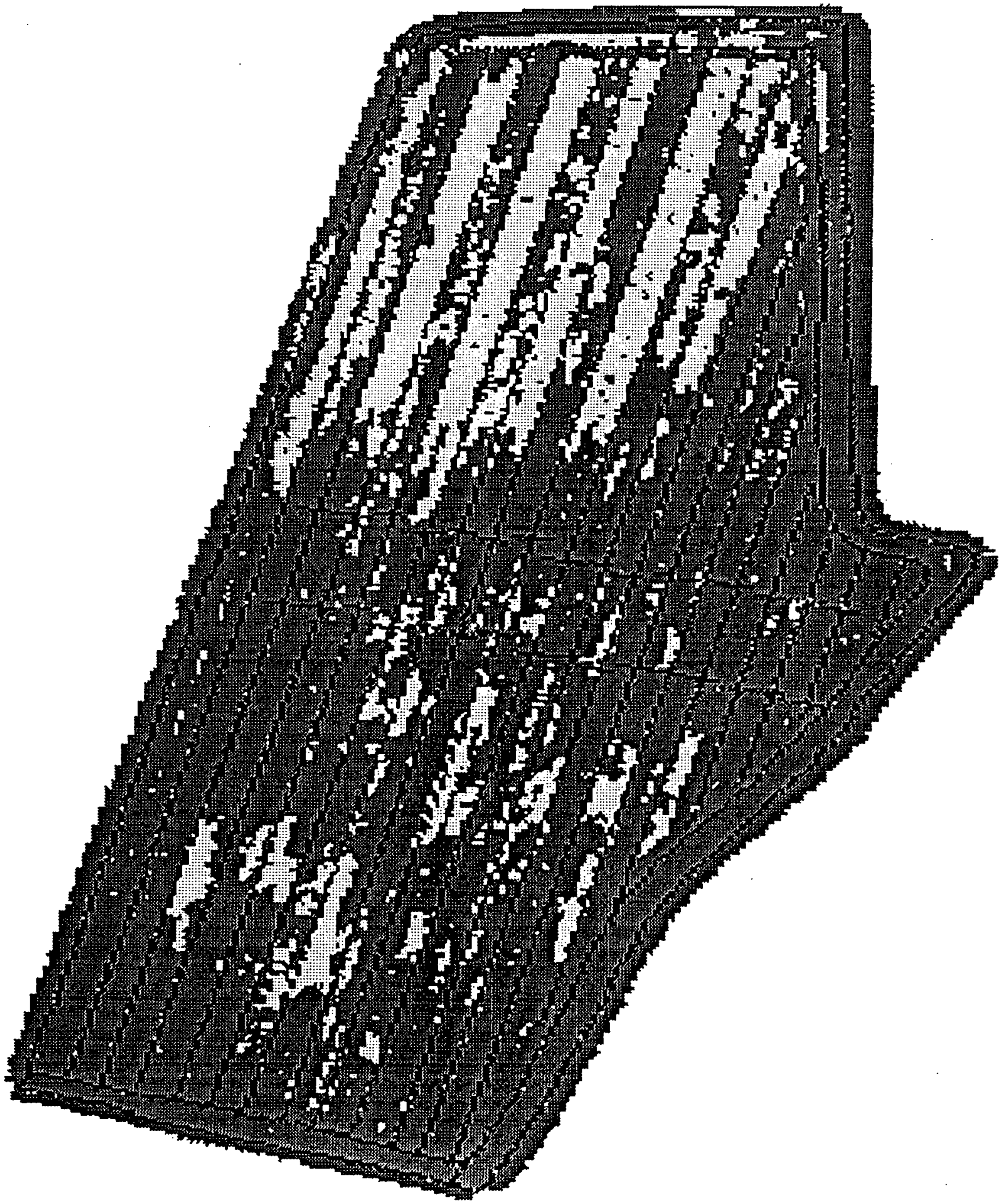


Field H (Swingbridge)

NB Surveyed with hand pushed machine



Field J **(Caledonian)**

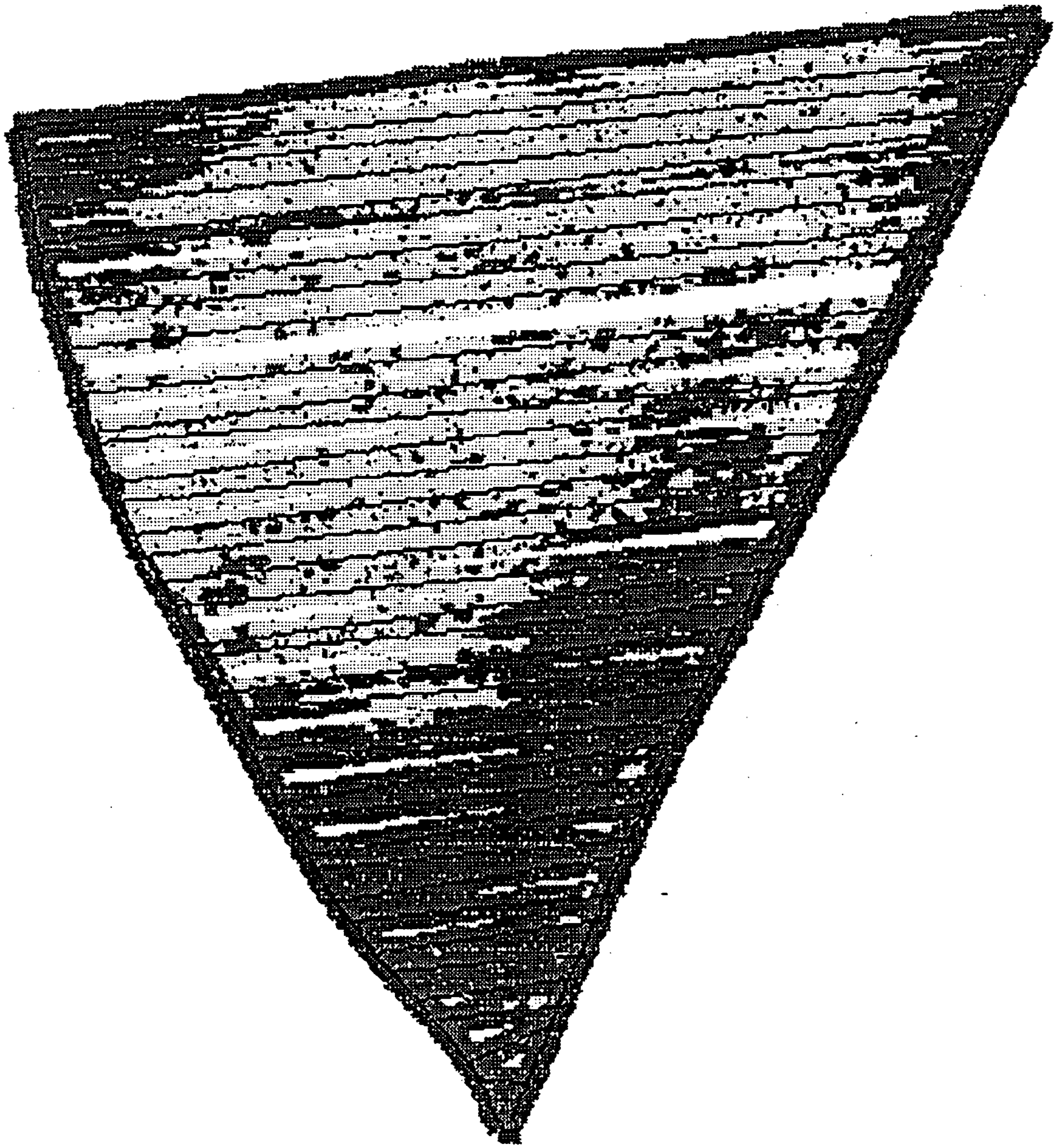


░ No black-grass

▓ Black-grass

NB Vertical lines are tramlines
Horizontal lines are positions of reference canes

Field K (Waverley)

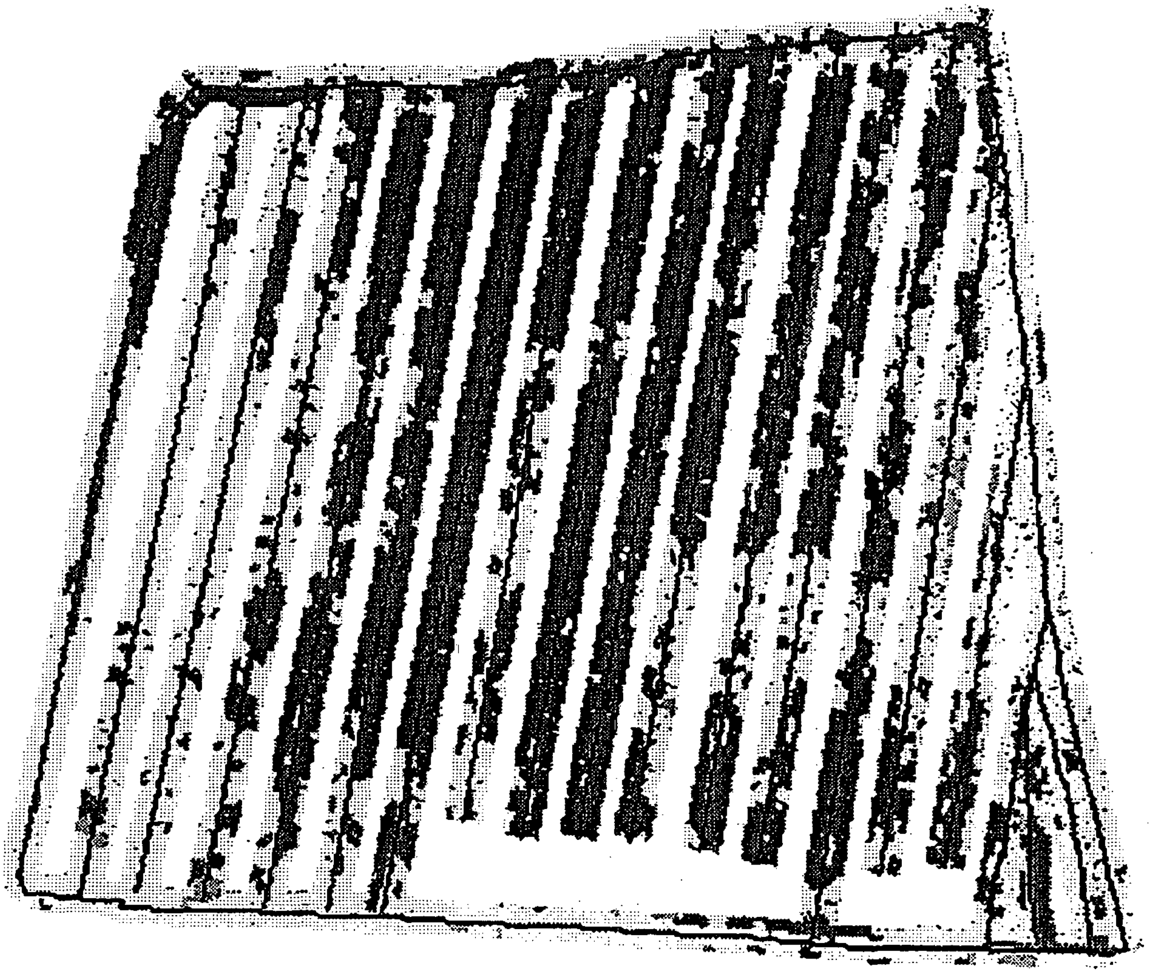


░ No black-grass

▓ Black-grass

NB Horizontal lines are tramlines

Field L (Elm)



☐ No black-grass

■ Black-grass

NB Vertical lines are tramlines

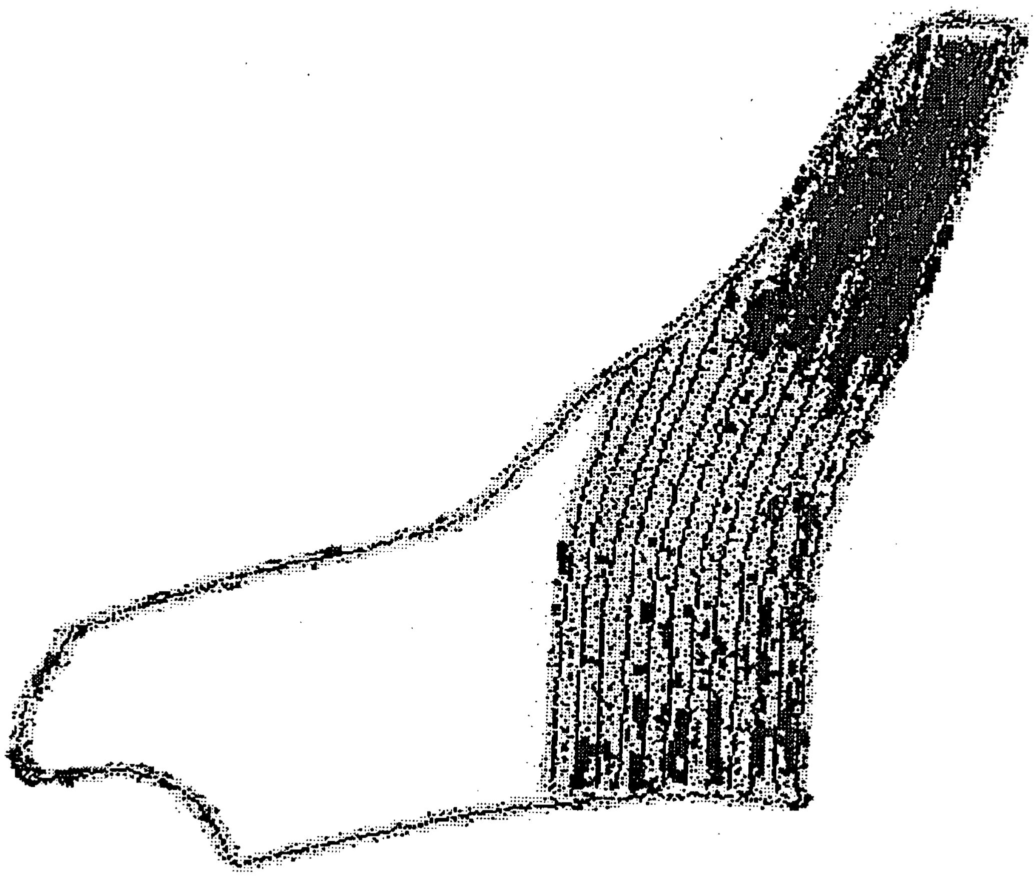
Field M (JS Field 1)

□ No black-grass

■ Black-grass

NB Vertical lines are tramlines

Field N **(Stewarts Moor)**



☐ No black-grass

■ Black-grass

NB Vertical lines are tramlines

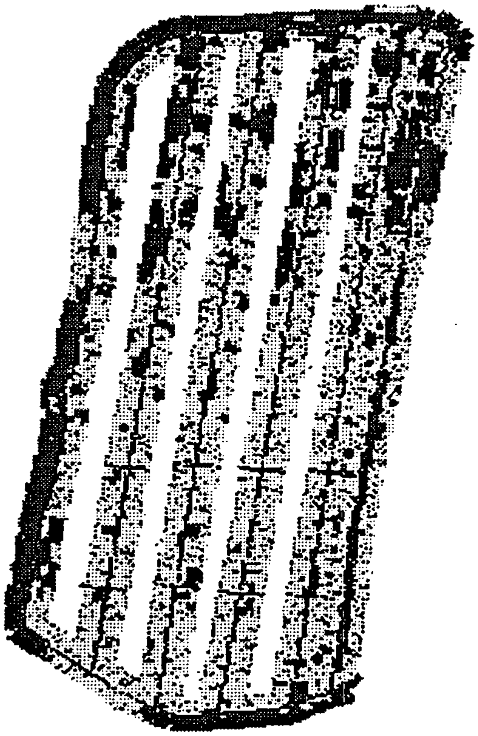
Field O (Long Meadow)

☐ No black-grass

■ Black-grass

NB Vertical lines are tramlines

Field P **(Little Meadow)**

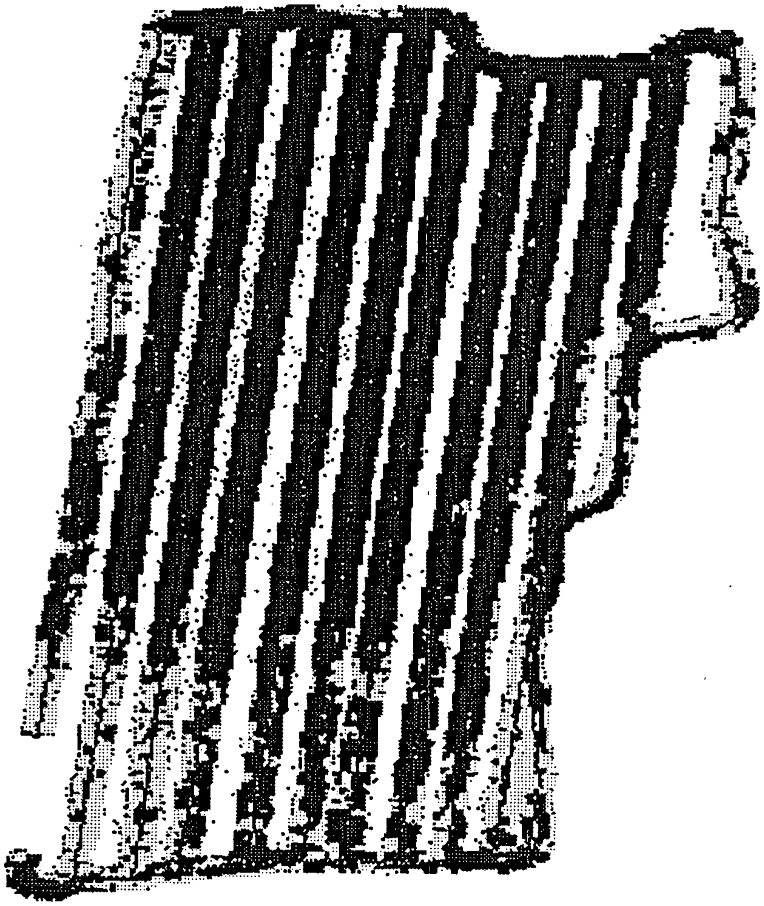


☐ No black-grass

▨ Black-grass

NB Vertical lines are tramlines
Horizontal lines mark positions of reference canes

Field Q (Lock House)

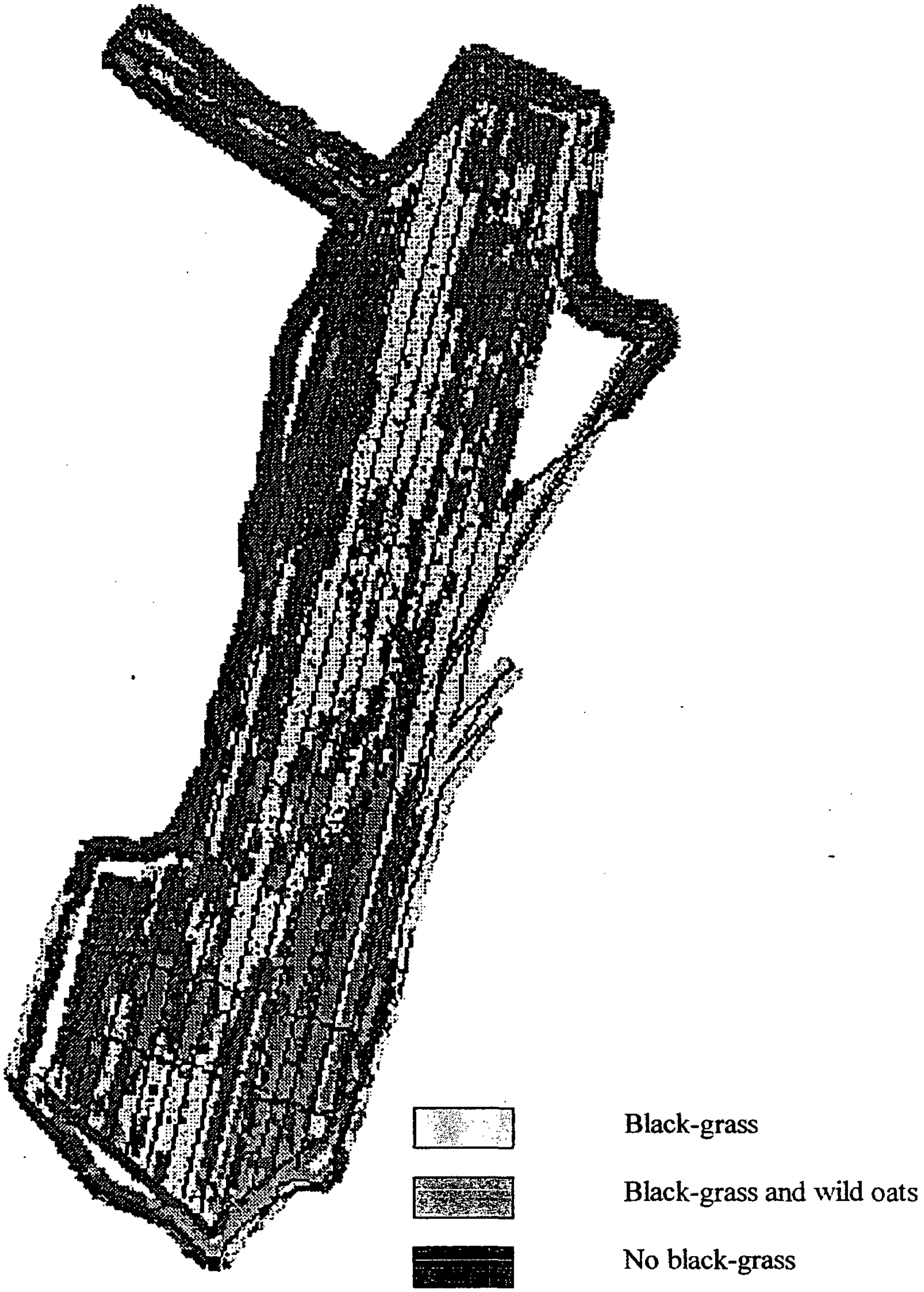


☐ No black-grass

■ Black-grass

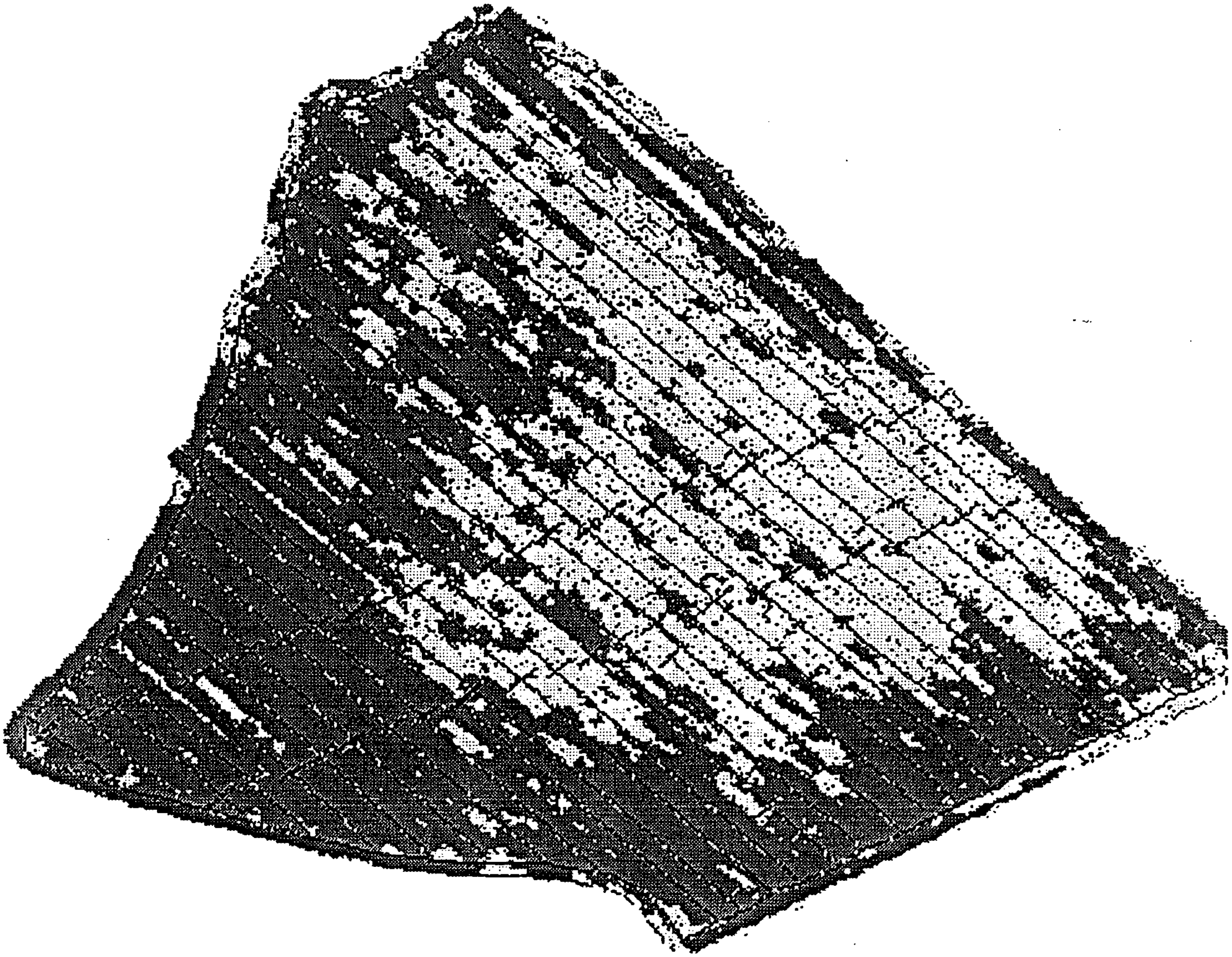
NB Vertical lines are tramlines
Horizontal lines mark positions of reference canes

Field R **(Barley Cut)**



NB Vertical lines are tramlines
Horizontal lines mark positions
of reference canes

Field S (Ditches)

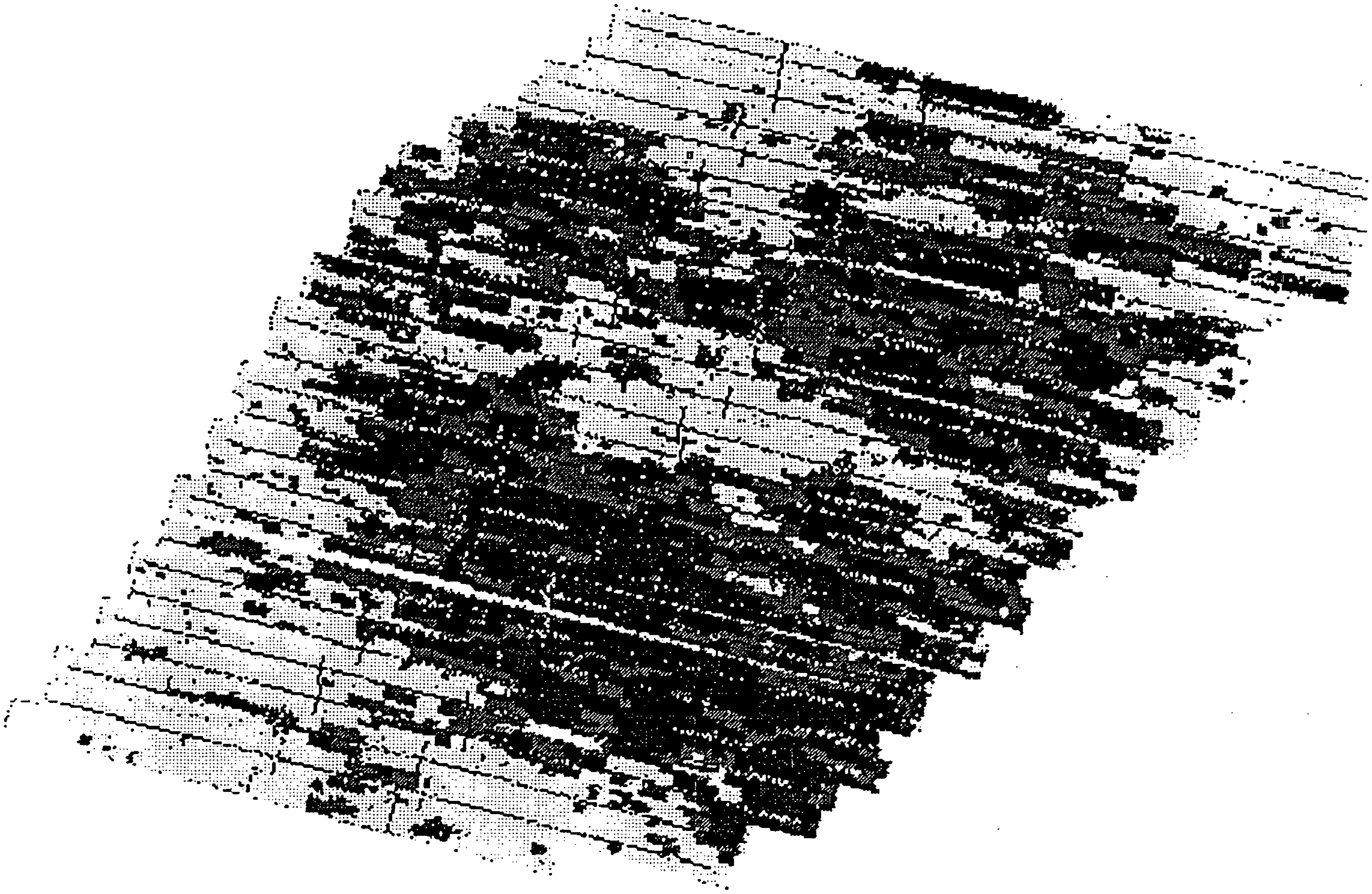


░ No black-grass

▓ Black-grass

NB Vertical lines are tramlines
Horizontal lines mark positions of reference canes

Field T (Bottom Collie)



☐ No common couch

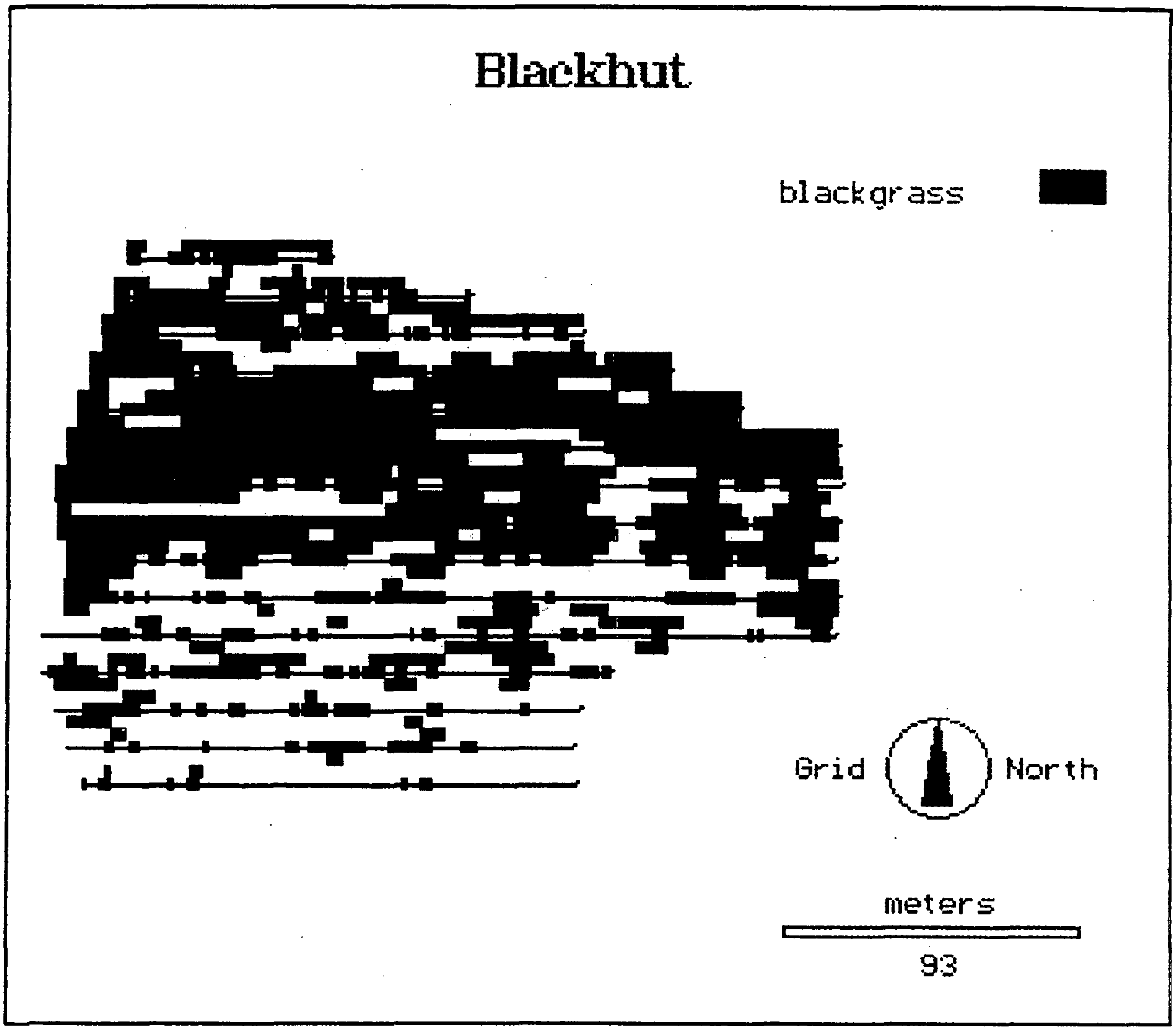
▨ Common couch up to 70 tillers/m^2

■ Common couch greater than 70 tillers/m^2

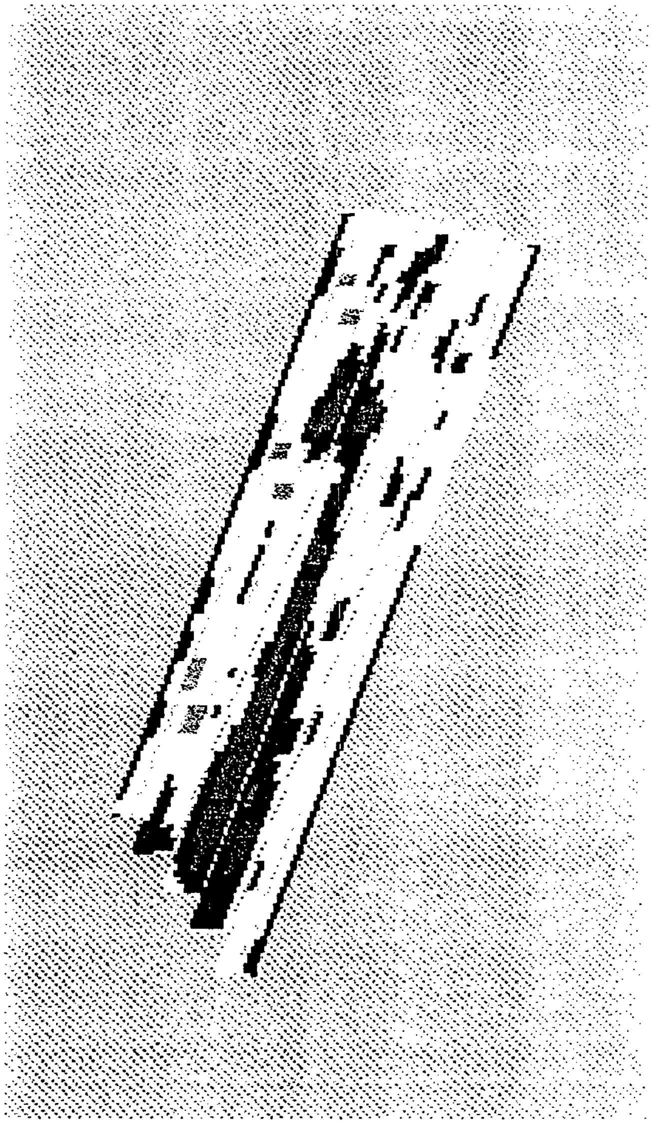
NB Horizontal lines are tramlines
Vertical lines mark positions of reference canes

Field U **(Blackhut)**

NB Field surveyed using hand pushed machine

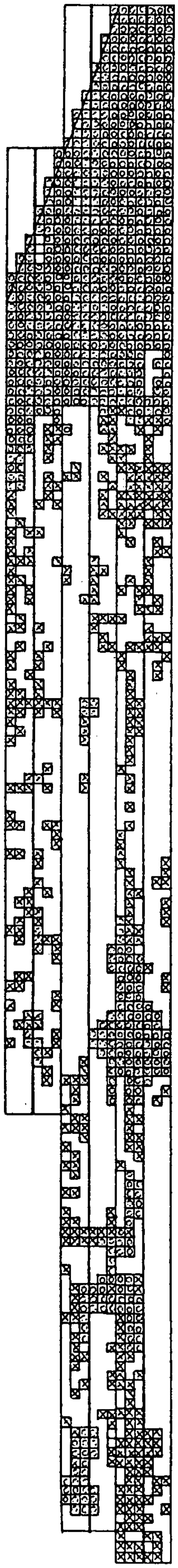


Field Y (Agdell)

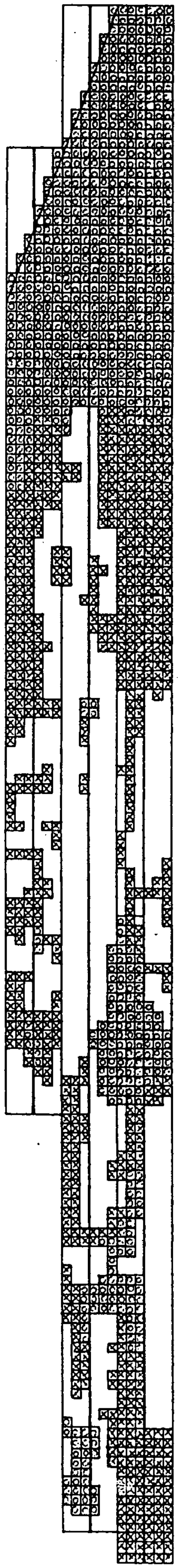


Coloured areas demonstrate parts of the field infested with common couch

Field Z (Hockcliffe)



Hockcliffe weed map



Hockcliffe treatment map

Coloured areas show
presence
of black-grass

Appendix 2 Publications from the Project

Day W., Paice M. E. R., Audsley E. (1996) Modelling weed control under spatially selective spraying. *In Procs: 1995 Math and Contr Applic in Agric, and Hortic.* Ed Day W., Young P. C. *Acta Horticulturae,* **406,** 281-288. ***(50% this project)***

Lutman, P. J. W. & Rew L. J. (1997) Spatially selective weed control in arable crops - where are we now? *Proceedings Brighton Crop Protection Conference, Weeds,* 637-640.

Lutman, P. J. W., Rew L. J., Cussans G. W., Miller P. C. H., Paice M. E. R. & Stafford J. V. (1998) Spatially selective treatments in agriculture - patch spraying weeds in winter wheat. *HGCA Project Report* (submitted).

Miller P.C.H., Paice M. E. R., Ganderton A. D. (1997) Methods of controlling sprayer output for spatially variable herbicide applications. *Proceedings Brighton Crop Protection Conference, Weeds.* 641-644

Miller P. C. H., Stafford J. V., Paice M. E. R., Rew L. J. (1995) The patch spraying of herbicides in arable crops. *Proc Brighton Crop Protection Conference, Weeds,* 1077-1086. ***(50% this project)***

Paice M. E. R., Day W. (1997) Using computer simulation to compare patch spraying strategies. *In Procs: 1997 1st European Conference on Precision Ag.* Warwick, England, **1**, 421-429.

Paice M. E. R., Miller P. C. H., Day W. (1996) Control requirements for spatially selective herbicide sprayer. *Computers and Electronics in Agriculture,* 14, 163-177 ***(50% this project)***

Paice M. E. R., Miller P. C. H., Lane A. G. 1997 The response characteristics of a patch spraying system based on injection metering. *Aspects of Applied Biology* **48** Optimising pesticide applications, 41-48.

Paice, M. E. R., Miller P. C. H., Power J. D. (1993) A practical pesticide injection metering system for agricultural sprayers. *In Procs: 1993 ANPP-BCPC 2nd International Symposium on Pesticide Application Techniques,* Strasbourg, France 22-24 September 1993, 313-320. ***(50% this project)***

Paice M. E. R., Miller P. C. H., Bodle J. D. (1995) An experimental sprayer for the spatially selective application of herbicides. *Journal of Agricultural Engineering Research* 60(2), 107-116. ***(70% this project)***

Rew L. J. & Cussans G. W. (1995) Patch ecology and dynamics - how much do we know? *Proceedings Brighton Crop Protection Conference, Weeds,* 1059-1068. ***(75% this project)***

Rew L. J. & Cussans G. W. (1997) Horizontal movement of seeds following tine and plough cultivation: implications for spatial dynamics of weed infestations. *Weed Research,* **37,** 247-56.

Rew L. J., Cussans G. W. & Miller P. C. H. (1996) Evaluation of four distance and navigation methods for mapping weed positions within arable fields. *Proceedings 2nd International Weed Control Congress, Copenhagen,* 1103-1108.

Rew L. J., Cussans G. W., Mugglestone M. A., Miller P. C. H. (1996) A technique for surveying spatial distribution of *Elymus repens L* and *Cirsium arvense L* in cereal fields and estimates of the potential reduction in herbicide use from patch spraying. *Weed Research* **36** 283-292.

Rew L. J., Miller P. C. H. & Paice M. E. R. (1997) The importance of patch mapping resolution for sprayer control. *Aspects of Applied Biology, 48, Optimising pesticide applications,* 49-55.

Stafford J. V. (1993) Precision arable agriculture: sensing and control requirements. *Measurement and Control* **26** No. 7 Sept. 202-205. ***(20% this project)***

Stafford J. V., Ambler B. (1994) In-field location using GPS for spatially variable field operations. *Computers and Electronics in Agriculture* **11** 23-36. ***(20% this project)***

Stafford J. V., Le Bars J. M. (1996) A GPS backpack system for mapping soil and crop parameters in agricultural fields. *Journal of Navigation,* **49,** (1) 9-21. ***(25% this project)***

Stafford J., Le Bars J. M., Ambler B. (1996) A hand-held data logger with integral GPS for producing weed maps by field walking. *Computers and Electronics in Agriculture,* **14** (2/3), 101-120. ***(25% this project)***

Stafford, J. V., Miller P. C. H. (1993) Spatially selective application of herbicide to cereal crops. *Computers and Electronics in Agriculture* **9** No 3 217-229. ***(75% this project)***

Appendix 3 Acknowledgements

We would like to acknowledge the support given to this project by many of the staff of IACR Rothamsted and Silsoe Research Institute. Without their support progress would have been much less. We are particularly grateful to Barry Ambler, for his work on the mapping systems and to Tracey Potter for her work contributing to the biological studies. We also wish to acknowledge the financial support from MAFF and from the Home-Grown Cereals Authority that enabled this project to reach a successful conclusion. IACR Rothamsted and Silsoe Research Institute receive grant aided support from the Biotechnology and Biological Sciences Research Council.