SESSION 7B AND 8B

AGGREGATED WEED DISTRIBUTION – BIOLOGICAL AND TECHNOLOGICAL CHALLENGES

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Workshop Papers	7B-1 to 7B-10

SPATIAL DYNAMICS OF WEEDS: AN OVERVIEW

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ABSTRACT

This paper reviews the current extent of knowledge of the spatial dynamics of weeds and the modelling approaches used in predictions of spread. It is concluded that there are few empirical data and that models concentrate on new invasions. Future modelling needs to be closer to field equilibrium and with a spatial scale sufficient to describe dispersal curves accurately. Empirical research needs to concentrate on dispersal. Mapping should be at a scale appropriate to spray decisions.

INTRODUCTION

The spatial dynamics of weeds is only of interest because weeds are spatially heterogeneous in their distribution. Within a field we recognise patches of higher population density surrounded by lower density, and especially areas in which a species is present and around which it is absent. Despite the obvious existence of patchiness, it is only very recently that any concerted effort has been made to study spatial distributions of weeds. Papers have been published on methodologies of weed mapping, and there have been several case studies of weed distributions within fields, but few generalisations have emerged regarding spatial pattern. Questions are now being asked concerning the implications of patchiness for weed management: in particular, how much money could be saved by only spraying patches, and how can this best be achieved? It may be argued that we need to understand the processes involved in generating patchiness and the factors that cause spatial distribution to change over time; we will then be able to predict and assess the implications of particular spatial management regimes and to optimise their effectiveness.

Why are weeds patchy? A number of reasons appear likely: field habitats may be patchy, for example in soil type, drainage or crop density, so that a species is more abundant in patches of its preferred habitat; weed mortality (or sub-lethal reduction in reproduction) may be patchy, perhaps because of uneven spraying or localised outbreaks of predators; dispersal may be highly aggregated, such as where reproduction is vegetative, where a harvester deposits seeds in swaths or where ants drop seeds around their nests; the species may still be invading and may not yet have spread to all parts of the field; species may simply be rare (perhaps the habitat is marginal for them) and occurrences of the weed may be sporadic. However, there has been almost no research to explain the reasons for the patchiness of particular species. For now we must rely on supposition

In this paper, we will review the extent of our current knowledge and understanding of the spatial dynamics of weeds. We will discuss empirical evidence and the predictions of models, before returning to a discussion of the critical needs for research.

THE EMPIRICAL EVIDENCE

Our knowledge of the spatial dynamics of real weed populations is extremely rudimentary. The limited evidence comes from four main sources: anecdotes; monitoring of deliberate releases of annuals; marking the extremities of clonal perennials; repeated mapping of established populations.

Anecdotes

On occasion, farmers or other land managers are unlucky enough to observe an invasion in action. Despite attempts at control, an invading species spreads from an initial focus to become common throughout much of the property. Anecdotes of such invasions generally concern the year first observed and the length of time taken to spread throughout a field. There has been little attempt to collate such data for research purposes. In contrast to such cases of rapid spread, many researchers have anecdotes concerning lack of spread. These are commonly observations of where rectangular plot margins move little over a number of years; by locating the exact location of the original plots it would, in theory, be possible to establish rates of spread (though this is rarely done). However, it has served to establish the fact that even very abundant, fecund weeds may not necessarily spread rapidly.

Monitoring of deliberate releases of annuals

A few studies have initiated new invasion foci of annuals (or occasionally biennials) within fields from which the species were previously absent (Harradine, 1985, Auld 1988, Bergelson *et al.* 1993). Locations of plants in following years can be mapped. It can be difficult to define the edge of a population, since few annuals spread as a clearly demarcated advancing front. This problem can be partially overcome by recording densities in quadrats along transects away from the source. However, high variation between years (Auld, 1988) can still make it difficult to convert these data into rates of spread. Seldom is monitoring for longer than two or three years, and hence is insufficient to smooth out annual variation. Moreover, few managers (even of research stations) are happy to allow the deliberate introduction of new weeds. Little detailed information about rate and pattern of spread has been derived from this type of source.

Marking of extremities of clonal perennials

Clonal perennials have an advantage for research purposes over annuals in that the limits of their patches are much more easily determined. Rates of spread of naturallyoccurring clones have been measured in pastures. A number of studies have planted single rhizome fragments (or other vegetative structures) in bare ground or in crops and have followed clone boundaries over time (see references in Cousens & Mortimer, 1995). These account for perhaps our most reliable estimates of rate of spread of weed patches.

Repeated mapping of fields

By overlaying maps repeated in time, we can see visually how spatial distribution changes (e.g. Chancellor, 1976). There are a few studies that allow this to be done, ranging in spatial sampling scale from 20 m grids of 1 m^2 quadrats down to 0.5 m grids of 4 cm diameter soil cores, and in time scale from two to fifteen years. Techniques used to analyse map consistency include geostatistical methods, geographic information systems, contingency tables and simple visual comparisons (Gerhards *et al.*, 1997, Wilson & Brain, 1991). At the coarsest scale, some annual weeds have been shown to consistently be most abundant in certain parts of fields (Wilson & Brain, 1991); at finer scales, patches can be highly mobile, particularly as a result of dispersal by farm machinery (Benoit *et al.*, 1992).

PREDICTIONS FROM MODELS

Published models of spatial dynamics vary considerably in both complexity and structure. In order to predict changes in both population density and spatial distribution, it is necessary for models to include processes related to population growth and dispersal. This does not necessarily mean that the inclusion of dispersal results in a more complex model with more parameters than a non-spatial model. If, for example, dispersal is the more important process with regard to weed spread, growth sub-models can be reduced considerably without significant loss in precision.

Spatial weed models range from those that consider both dispersal and growth to be continuous in space and time (reaction-diffusion models), to those in which dispersal and growth are discrete events in time and space. The published outcomes of reaction-diffusion models were used by Cousens & Mortimer (1985) to make crude calculations for an annual grass. However, dispersal often occurs at a particular time of year, and population growth processes can be considered to occur in the period between dispersal events. Integro-difference equations recognise this, making dispersal and growth discrete in time but not space (Mortimer *et al.*, 1996). Equations are required to describe both dispersal and growth. We have used a similar approach to compare different types of species (unpublished), but assuming that, for computational ease, space is discrete; however, the outcomes are almost identical to the continuous-space models, provided that spatial intervals are small enough to capture the true shape of dispersal curves.

Cellular automata (e.g. Wallinga, 1995) divide space into artificial cells of fixed size, each one capable of sustaining only a single individual; time steps are one generation and simple rules are used to determine how many (and which) surrounding cells will be colonised in each dispersal event. Given the fact that the space occupied by a plant is, in reality, density-dependent, such models lack realism in a key area of population behaviour. Coupled cellular maps, on the other hand, can have many individuals within a cell, hence a cell can be considered equivalent to a sampling quadrat. Density-dependence can be made to act within cells, avoiding the need to define the space occupied by an individual plant. This type of model uses growth equations to describe changes in cell density over time; dispersal is usually defined by numerical tables (Schippers *et al.*, 1993, Ballaré *et al.*, 1987, Auld & Coote, 1990) or by simple equations with truncation (González-Andujar & Perry, 1995). Cell size in coupled cellular map models has usually been in the region of 0.5 - 1.0 m^2, representing a very coarse scale for unaided dispersal. Even for the quite large weeds modelled to date, dispersal curves can change rapidly over 0.7 - 1.0 m: the majority of seeds will land in the source cell and very few seeds will travel more than two cells. Hence the dispersal component of these models must be regarded as very simplistic.

Most of the spatial models for weeds have been case studies of particular species, using demographic and dispersal data from experimental case studies to map the spread of new infestations in homogeneous habitats. The questions they have been used to answer have mostly concerned sensitivity to model parameters, such as herbicide efficacy, dispersal distance and relative importance of different dispersal mechanisms. Several papers have placed emphasis on the observation that predicted numbers in a population increase considerably more as a result of dispersal (and the subsequent population growth that this allows) than as a result of population growth at the source; however, this is surely self-evident and hardly requires a model. One model has been used to calculate the minimum size of suitable habitat required for population persistence. Surprisingly few of the models have been used to calculate the velocity of spread, either of the population margin or of a point on the population "wave-front". Only one model appears to have examined spread in a habitat that is heterogeneous in space or time (González-Andujar & Perry, 1995). All of the published models deal with spread from new introductions, not with spatial dynamics in populations close to their (dynamic) spatial equilibria.

Although, quite clearly, important conclusions have been reached, many more questions remain unanswered. For example, no published modelling papers have examined which species will be more spatially dynamic than others. Our own unpublished studies have compared four weed types, varying in demographic and dispersal characteristics. It would seem that demography has little effect on velocity of spread (or on crop yield loss in a field still being invaded - Maxwell & Ghersa, 1992) and that a knowledge of dispersal is the key to understanding differences in spatial dynamics among species. Although much of the impetus for examining patch dynamics comes from the interest in precision spraying, little use has been made of population models to examine, for example, questions of optimum scales for detection and application, frequency of mapping for GPS-guided sprayers; most of this is being addressed using static "snap-shot" maps.

WHERE TO FROM HERE?

Spatial dynamics is the outcome of population growth and dispersal. We have a considerable knowledge of the former, but little attention has been given to the latter. Yet, for understanding spatial dynamics, this is critical. Few generalisations about are possible from the limited weed dispersal literature, though Cousens & Mortimer (1995) presented a speculative table of dispersal distances for different mechanisms. Most attention has been given to wind dispersal, though even most of this literature concentrates on predicting distances travelled from a point source in a constant flow of air, rather than for dispersal from real (non-point-source) plants in a highly variable meteorological environment. In an arable system, the cause of greatest dispersal is the combine harvester; we know that seeds taken up at harvest can be distributed by at least an order of magnitude further than passive spread or as a result of tillage. This may, in turn, explain why some species are far less spatially dynamic than others (e.g. Chancellor, 1976). The proportion of seeds harvested will depend on the phenology of seed production and dispersal relative to crop maturity. However, we know almost nothing about weed phenology, or more specifically the effect of sowing date and harvest date on the proportion of seeds dispersed passively and the proportion entering the harvester.

Integro-difference models suggest that the shape of the dispersal curve, in particular the tail, is critical in determining velocity of spread. But what shapes are dispersal curves? We usually just fit normal or exponential curves to data that are usually inadequate for distinguishing between various functional forms. How do the shapes of dispersal curves vary with plant morphology; what is the shape and extent of the tail of the dispersal curve? For modelling purposes, a much finer scale of sampling is required than is usually adopted in dispersal studies.

Much of our future analysis of spatial dynamics will depend on models. Our review of the literature has shown, in our opinion, two main deficiencies. Firstly, the size of cells in coupled cellular map models needs to be smaller, so as to more realistically describe dispersal by mechanisms other than the harvester. Secondly, all of the modelling has been concerned with spread from a new focus of invasion. If we are to model the effects of patch spraying on existing populations, we need to model weeds that have already had the opportunity to occupy all parts of a field (i.e. closer to equilibrium).

Further empirical studies are essential. However, the values of the different types of monitoring need to be more carefully assessed. For example, repeated mapping shows us that patterns may or may not be consistent (at that scale); but they have so far not been used to give quantitative measures of spatial stability. The maps should have a sample frequency appropriate to the scale of spraying decisions; at present, most do not and their value to the debate on precision spraying must be debatable.

REFERENCES

Auld, B A (1988) Dynamics of pasture invasion by three weeds, *Avena fatua* L., *Carduus tenuiflorus* Curt. and *Onopordum acanthium* L. *Australian Journal of Agricultural Research*. **39**, 589-596.

Auld, B A; Coote, B G (1990) INVADE: Towards the simulation of plant spread. *Agriculture, Ecosystems and Environment*. **30**, 121-128.

Ballaré, C L; Scopel, A L; Ghersa, C M; Sanchez, R A (1987) The population ecology of *Datura ferox* in soybean crops. A simulation approach incorporating seed dispersal. *Agriculture, Ecosystems and Environment*. **19**, 177-188.

Benoit, D L; Derksen, D A; Panneton, B (1992) Innovative approaches to seedbank studies. *Weed Science*. **40**, 660-669.

Bergelson, J; Newman, J A; Floresroux, E M (1993) Rates of spread in spatially heterogeneous environments. *Ecology*. **74**, 999-1011.

Chancellor, R J (1976) Changes in the weeds of Upper Begbroke field (1961-76). In *Ve Colloque International sur l'Écologie et la Biologie des Mauvaises Herbes*, pp. 227-234.

Cousens, R; Mortimer, M (1995) *Dynamics of Weed Populations*. Cambridge University Press, Cambridge.

Gerhards, R; Wyse-Pester, D Y; Mortensen, D; Johnson, G A (1997) Characterizing spatial stability of weed populations using interpolated maps. *Weed Science*. **45**, 108-119.

González-Andujar, J L; Perry, J N (1995) Models for the herbicidal control of the seed bank of *Avena sterilis*: the effects of spatial and temporal heterogeneity and of dispersal. *Journal of Applied Ecology*. **32**, 578-587.

Harradine, A R (1985) Dispersal and establishment of slender thistle, *Carduus pycnocephalus* L., as affected by ground cover. *Australian Journal of Agricultural Research*. **36**, 791-797.

Maxwell, B D; Ghersa, C (1992) The influence of weed seed dispersion versus the effect of competition on crop yield. *Weed Technology*. **6**, 196-204.

Mortimer, A M; Latore, J; Gould, P (1996) From weed populations to weed communities: patch size and patch composition. In *Proceedings of the Second International Weed Control Congress, Copenhagen*, pp. 35-40.

Schippers, P; Ter Borg, S J; Van Groenendael, J M; Habekotte, B (1993) What makes *Cyperus esculentus* (yellow nutsedge) an invasive species? - A spatial model approach. In *Proceedings of the Brighton Crop Protection Conference - Weeds - 1993*, pp. 495-504.

Wallinga, J (1995) The role of space in plant population dynamics: annual weeds as an example. *Oikos*. **74**, 377-383.

Wilson, B J; Brain, P (1991) Long-term stability of distribution of *Alopecurus myosuroides* Huds. within cereal fields. *Weed Research*. **31**, 367-373.

IMPLICATIONS OF AGGREGATED WEED SEED DISTRIBUTION FOR WEED SEEDBANK STUDIES

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The weed seedbank provides us with a unique insight into past and future weed populations. Information on it's size and species content can be utilised for both predictive and management purposes. There is increasing interest in the importance of weed patches for competition modelling and weed control strategies. The dynamics of the seedbank controls the future occurrence and stability of these weed patches. Studies based on the seedbank ultimately depend on its accurate estimation. Sampling is complicated by the clustering of seeds both horizontally and vertically in the soil. Estimates that incorrectly assume homogeneity in seed distribution and assign a single seed density to a field, often have large variability and the results have limited use. Predictions of seedling emergence based on data that disregard spatial pattern, can lead to significant errors in estimating potential yield loss and the impact of management strategies. For many species, seeds are shed close to the parent plant, and as a consequence this leads to a departure from randomness in their distribution. Seed aggregation may also be modified by farm machinery and occurs at different scales. Studies have shown that, where there is little soil disturbance, patches exist over greater distances and can be correlated with large scale soil or landscape features. Where disturbance is high, patches of seeds are more microsite dependent. Weed seeds tend to conform to a negative binomial or Poisson frequency distribution and generalities have been made about the relationship between seed density and aggregation. Several indices of non-randomness have been used to measure this degree of seed aggregation, for example Lloyd's indices of mean crowding and patchiness. However, many of these indices have been criticised for their failure to utilise the spatial element of the data and the use of methods such as spatial autocorrelation have been proposed which retain this information.

Recently there has been greater emphasis given to the heterogeneous nature of the seedbank and it's implications for sampling strategies. It is generally accepted that a large number of small samples is more desirable than a small number of large samples in order to sample for the detection of clustered populations. However, high sampling intensity has inherent problems in that the process of extracting the weeds seeds from the soil samples is both time consuming and costly. This apparent conflict between the precision of seedbank sampling and the number of samples that can be realistically processed has been the basis of much work. Rapid and novel methods such as the use of image analysis have been suggested, but these require refinement and fail to assess seed viability. Alternative methods of separating the weed seeds from soil have also been developed, but their success can be dependent on soil type. A number of studies have attempted to define the optimum number of cores required to minimise unnecessary over-sampling that does not significantly add to the precision of the data obtained. The variance:mean relationship has been used as a basis for sampling protocol such as the logarithmic form of Taylor's power law. However, these relationships can only give an indication of the minimum number of cores required, as seed aggregation can affect the correlation and necessitate greater sampling intensity. Anomalies in the variance:mean relationship can also occur for species with low densities. This raises an important point that sampling protocol is ultimately dependent on the objective of the study, and whether it requires the sampling of rare species. The lack of consistency between studies regarding the optimum number of cores, may be partly attributed to seed aggregation and the timing of sampling. It has been suggested that in order to reduce the intensity of seed aggregation, for example when comparing treatments, there is also an optimum sampling time. The sampling design is also important. Where a gradient is anticipated in the seedbank due to management or other factors, stratified random sampling can be advantageous.

The necessarily large number of samples required for seedbank studies, compounded by seed aggregation, demands imaginative methods of statistical analysis and representation. Multivariate analysis, such as canonical discriminant analysis, have been proposed as being particularly well suited to seedbank studies. Aggregation of seeds, as with plants, can be clearly demonstrated by the use of mapping. Trend surface analysis is one such method that can describe gradual variation in one or two dimensions and is used to fit a surface through the data points. These methods give an immediate visual impression of seed aggregation in a way that conventional statistical analysis cannot. The relationship between aggregation in the seedbank and emerging patches of seedlings is complex and dynamic. It is important to note that seedbank mapping may not always help target control strategies and the exact location of patches of weeds. For some species there is considerable lack of correlation between the seedbank and resulting weed emergence. Cross-semivariograms and kriged maps between the seedbank and seedling populations have been used to illustrate the dependence of these correlations on factors such soil disturbance and species. There is generally less correspondence where there is greater disturbance, probably as a result of mixing and seed burial. Weed seeds may be aggregated not only in the horizontal, but also the vertical dimension. The vertical distribution of burial of weed seeds in the soil can have a profound effect on the number of seedlings likely to emerge. This raises a significant differentiation between the aggregation of weeds and aggregation of weed seeds. It is clear that in recent years many sampling strategies and methods of analysis and interpretation have been proposed for the study of seedbanks which address the problem of seed aggregation. However, as yet there remains no consensus on a comprehensive and robust protocol and this is essential for the progression of research in this area. Until then, seed aggregation and it's implications will continue to be a significant source of variability between seedbank studies.

READING LIST

Benoit D L; Derksen D A; Panneton B (1992) Innovative approaches to seedbank studies. *Weed Science* **40**, 660-669.

Benoit D L; Kenkel N C; Cavers P B (1989) Factors influencing the precision of soil seed bank estimates. *Canadian Journal of Botany* **67**, 2833-2840.

Cardina J; Sparrow D H; McCoy E L; (1996) Spatial Relationships between seedbank and seedling populations of common Lambsquarters (*Chenopodium album*) and annual Grasses. *Weed Science* **44**, 298-308.

Dessaint F; Barralis G; Caixinhas M L; Mayor J-P; Reacasens J; Zanin G (1996). Precision of soil seedbank sampling: how many cores? *Weed Research* **36**, 143-151.

Dessaint F; Caussanel J-P (1994) Trend surface analysis: a simple tool for modelling spatial patterns of weeds. *Crop Protection* **13**, 433-438.

Dessaint F; Chadoeuf R; Barralis G (1991) Spatial pattern analysis of weed seeds in the cultivated soils seed bank. *Journal of Applied Ecology* **28**, 721-730.

Li B; Watkinson A R (1993) Patterns of abundance in the weed seed bank. *Brighton Crop Protection Conference* 293-298.

ESTIMATING WEED SEEDBANK DENSITY FROM PRESENCE/ABSENCE MAPS

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ABSTRACT

A technique is described which generates a spatial map of expected weed seedbank density from weed presence/absence data. A stochastic, spatial weed population dynamics model is used to derive an empirical relationship between the observed proportion of weed presence (POP) and seed bank density. POP is treated as a continuous spatial function and estimated at each point in the field. The estimation procedure takes account of the spatial scale of variation in the presence/absence data, which is assessed using a 2-dimensional discrete Fourier transform technique.

INTRODUCTION

Cussans (1992) and Christensen et al. (1996) have discussed the concept of patch spraying as a low risk approach to reducing herbicide doses. A major challenge to it's practical implementation however is the development of cost effective techniques for generating weed density maps. Rew et al. (1997) have described a technique for acquiring classified weed density data from a survey vehicle and a similar system has been incorporated in a commercial yield mapping system. The maps produced typically show the presence or absence of the weed infestation, although data may be recorded according to qualitative class definitions e.g. "high density", "medium density", "low density". Audsley and Beaulah (1996) discuss a method of generating a map of most probable weed presence/absence by Bayesian combination of multiple uncertain observations.

Figure 1 represents a map of *Alopecurus myosuroides* Huds. presence/absence observed with the survey vehicle in an 8.6 ha field and we need a method of deducing weed density distribution from this data. Miller et al. (1991) have outlined the benefits of a mapping approach to patch spraying. Assuming that the main link between the weed infestations in consecutive years is via the seedbank, we need to deduce the local seedbank density.

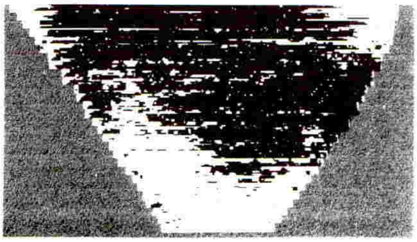

Figure 1. Presence (white) / absence (black) map of *Alopecurus myosuroides* Huds. infestation surveyed at 2 x 1m resolution in an 8.6 ha field.

It is intuitively clear from Figure 1. that both the weed plant and seedbank density in the corners of the field are likely to be higher than at the centre. If seedbank density is high there will be a greater likelihood of a weed plant germinating and therefore of being observed. This increased probability will exhibit itself as an increased proportion of weed presence vs absence. We would like to describe a technique for exploiting this relationship.

THE TECHNIQUE.

To make an objective estimate of seedbank density based on presence/absence data, we need;

a) A relationship between the seedbank density in a homogeneous area and the expected proportion of weed presence (POP), defined as: area of presence / (area of presence + area of absence).

b) A knowledge of the spatial scale of weed plant density variation.

The spatial simulation model described by Day et al. (1996) can be used to generate an empirical approximation to the relationship (a), under specified parameters. The spatial scale (b) can be deduced either by simulation or by direct observation of the presence/absence map and analysis in the spatial frequency domain. With this scale data we can then define the optimum averaging area size required to generate a map of point estimates of POP. This can then be converted into a map of expected seedbank density using the relationship (a).

The distribution of weed plants can be regarded as a modified expression of the underlying seedbank. The occurrence of weed plant/s at a point can be expressed as an *indicator variable* (Isaaks et al.,1989). If we define POP as a continuous spatial function we can estimate its value at any point by averaging indicator values within a local sample area. If we have some knowledge of the way in which the variance of the weed density distribution is related to spatial scale, we can optimise the size of the averaging area and apply appropriate weights to the indicator values.

EXAMPLE.

Step 1: The effective mapping resolution of Figure 1 is 2 x 1 m (Rew et al. 1997)

Step 2: For *A.myosuroides* there is sufficient information in the literature (see References) to parameterise the simulation model for a typical situation. In the absence of any other information for the field of Figure 1, these *standard* parameters have been used. Gaussian seed dispersal has been assumed (μ=0, σ=0.3 m). The model has been initialised with uniform seedbanks and the germinated weed patterns after 10 years simulation have been recorded. The POP (observed at 2 x 1 m resolution) has been calculated for each seedbank density. Figure 2 shows the derived relationship and we have repeated the exercise at seed dispersal σ=0.6 m to demonstrate sensitivity to this parameter. The relationship approximates to an exponential of the form:

$$POP(D) = 100[1-\exp(-A.D)]\ \%$$

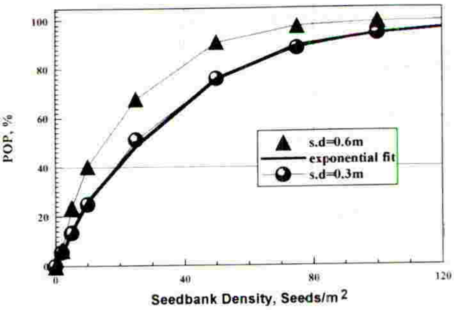

Figure 2. The relationship between the observed proportion of weed presence (POP) and seedbank density (D) derived by stochastic, spatial simulation. The thick black line is an exponential fit for σ = 0.3 m as described above with A = 0.029.

Step 3: A 2-dimensional, anisotropic, exponential probability distribution is fitted to the discrete power spectrum of the spatially mapped presence/absence data. The two parameters of the distribution θ and ϕ are representative of the spatial scale of the weed density variation, respectively longitudinal and transverse to the direction of the tramlines. For 1 ha sample areas from the field of Figure 1, the mean value of θ was 9.3 m and ϕ was 5.5 m.

Step 4: Local point estimates of POP are derived by calculating a weighted average of presence/absence indicator values falling within a chosen range of the estimated point. The optimum range is dependant on the spatial scales evaluated in Step 3. For simplicity in this example we have chosen to use an isotropic filtering process with a kernel size of 5.4 m. We have chosen a Gaussian weighting of the indicator contributions on the assumption that seed dispersal is predominantly Gaussian. Figure 3. shows the estimated point POP distribution.

Figure 3. Proportion of weed presence estimated for the field of Figure 1. White = 100 % , Black = 0.

Figure 4. Expected seedbank density, Black = 0, white = $\geq$ 200 seeds/m^2 (linear graduation).

Step 5: Having developed the point POP distribution, we can generate a map of estimated seedbank density using the relationship derived in Step 2 (see Figure 4).

DISCUSSION

It can be seen from Figure 2. that the estimate of seedbank density will be less accurate at higher density. Of more consequence may be the sensitivity of the parameter A to seed dispersal range. The reason for this sensitivity is the effect of seed dispersal on the patchiness (mean:variance ratio) of the weed distribution. Patchiness will also be sensitive to other factors such as spatial heterogeneity of environmental conditions and annual variations in mean density of the weed population (Paice and Day, in press). It may be more appropriate to deduce A from an estimate of patchiness derived from a limited quadrat sampling regime.

This work suggests a practical route towards generating the information necessary to implement high resolution patch spraying systems but raises a number of questions. How can we design field observations to test the accuracy of these seedbank density predictions? How robust are the estimates likely to be in response to human and systematic observational errors? How do we take uncertainty of germinated weed plant density into account when estimating optimum, local herbicide dose or threshold? More work is required to provide answers to these questions before this technique can be incorporated into frameworks for patch spraying decision support.

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REFERENCES AND READING LIST.

Audsley, E; Beaulah, S A (1996) Combining weed maps to produce a treatment map for patch spraying. *Aspects of Applied Biology.* **46**, 1-8.

Brain, P; Marshall, E J R (1996) Estimating cultivation effects on weed seed dispersal using Fourier transforms. *Modelling in applied biology: Spatial aspects. Aspects of applied biology.* **46**. 173-179.

Christensen, S; Heisel; and Walter, A M (1996). Patch spraying in cereals. *Procs: Second International Weed Control Congress, Copenhagen, Denmark.* 963-968.

Cousens, R; Mortimer, M (1995) *Dynamics of Weed Populations.* Cambridge University Press, Cambridge.

Cussans, G W (1992) Identifying ways of Optimising herbicide use in crops. *Procs. First International Weed Control Congress, Melbourne.* 208-214.

Day, W; Paice, M E R; Audsley, E (1996) Modelling weed control under spatially selective spraying. *Proc, Math and Contr. Applic. In Agric. and Hortic. Ed. Day W, Young PC. Acta. Hort.* **406,** 281-288.

Heisel, T; Christensen, S; Walter, A M (1996) Weed managing model for patch spraying in cereals. *3rd International Conf. on Precision Agriculture. Minnessota, Minneapolis, USA.*

Howard, C L; Mortimer, A M; Gould, P; Putwain, P D (1991) The dispersal of weeds: Seed movement in arable agriculture. *Procs: BCPC .* 821 - 828.

Isaaks, EH; Shrivastava, R M. (1989) *Applied Geostatistics.* Oxford University Press Inc., New York, USA. ISBN 0-19-505013-4

Miller, P C H; Stafford, J V. (1991) Herbicide application to targeted patches. *Proceedings of the Brighton Crop Protection Conference - Weeds -1991.* **9A-9**, 1249-1256.

Moss, S R; The seed cycle of *Alopecurus myosuroides* in winter cereals: A quantitative analysis. *EWRS, Procs.* 1990, *Integrated Management in Cereals.*

Nordbo, E; Christensen, S; Kristensen, K; Walter, M. (1994) Patch Spraying of Weeds in Cereal Crops. *Aspects of Applied Biology.* **40,**325-334.

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

Paice, M E R; Day, W (In press) A computer simulation analysis of the factors influencing weed patchiness and implications for patch spraying. *Procs. Computer Modelling in Weed Science Workshop. Copenhagen.* 1996.

Perry, J N (1996). Simulating spatial patterns of counts in agriculture and ecology. *Computers and Electronics in Agriculture.* **15:12**, 93-110.

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,** 49-55

Rew, L J ; Cussans, G W (in press). Horizontal movement of seeds following tine and plough cultivation. implications for spatial dynamics of weed infestation. *Weed Research.*

SOME ASPECTS OF THE SPATIAL DYNAMICS OF WEEDS

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ABSTRACT

This paper reviews briefly my recent work on the spatial dynamics of weeds, with particular reference to the measurement of spatial pattern by the set of new techniques termed SADIE (Spatial Analysis by Distance IndicEs). All the methods mentioned are usable through software that is available freely from the author.

Keywords: Spatial pattern, counts, maps, SADIE, clusters, association, simulation, sampling schemes, metapopulations.

The resolution of spatial data is greatest in maps, where the location of each individual is known precisely in two-dimensional space, and the sample area, usually a rectangle, is defined. For such data, there is already much methodology to study spatial pattern (e.g. Diggle, 1983). Information is less when the data are in the form of counts of individuals within spatially-defined areas or sample units; this paper focuses on such data.

Detailed spatio-temporal data when available allows metapopulation models of weed dynamics to be constructed. Perry & Gonzalez-Andujar (1993) and Gonzalez-Andujar & Perry (1995) gave examples for data in the form of counts of seeds. The models were built in explicit two-dimensional space; populations could go locally extinct and be revived only through colonization. The outcomes depended on dispersal, the scale of the environmental heterogeneity and other spatial effects. These models are now being parameterized for *Alopecurus myosuroides*.

Sampling schemes for weeds and pests (Perry, 1994) usually rely upon data based upon a count (or an incidence) in each sample unit. The information in field counts may be expressed in two mutually exclusive forms: number and location. The former relates to statistics such as the average weed population density, its variability (Clark & Perry, 1994; Clark *et al.*, 1996), incidence in sample units (Perry, 1987), the skewness of the frequency distribution of counts (Perry & Taylor, 1988), and the interrelationships between them. Sampling schemes may be derived that use some or all (Perry *et al.*, 1997) of these statistics and relationships. All relate to the properties of a list of the observed counts, without reference to where those counts were taken.

The latter form of information, on location, relates to features such as the spatial pattern of the counts and their degree of non-randomness (Perry, 1995a), patchiness in the field, the presence of clusters and gaps and their relative sizes (Perry, 1997a), and the presence of trends or edge effects (Perry & Klukowski, 1997).

SADIE (Spatial Analysis by Distance IndicEs) is a set of new techniques for analyzing spatial data (see Perry *et al.*, 1996; Perry, 1997b for a general introduction). These techniques compare the observed pattern with two extreme, baseline alternatives: crowding (Perry, 1997a), where all individuals in the sample are observed as close as the spatial resolution allows, and regularity (Perry, 1995a), where the individuals are observed spread as evenly as resolution allows. For mapped data (Perry, 1995b; Korie *et al.*, 1997a) the techniques require that the sample area be a rectangle. For count data (Perry, 1995a), there are no restrictions on where the sample units may be located in two dimensions; irregular spacing of units, not on a grid, is perfectly acceptable. By conditioning on the counts observed, the SADIE measurement of spatial pattern remains independent of the properties of the list of numbers considered above, such as variance-heterogeneity. This is entirely reasonable, for, although the set of counts of weeds in six quadrats: {0, 1, 4, 56, 484, 4095} may be highly-skewed and obviously non-Poisson, their spatial arrangement may be completely random with respect to one another. The excess variance-heterogeneity arises because of spatial pattern, but it is pattern at a smaller scale than that to which the sample unit count relates; because there is no spatial information recorded at the scale on which it manifests itself such pattern cannot be studied. Conversely, a set of counts of weeds along a line transect: {0, 0, 1, 1, 2, 2, 2, 2, 3, 3, 5}, may conform closely to a Poisson distribution, but if sampled in that order shows an obvious linear trend departing strongly from spatial randomness. SADIE techniques provide indices of non-randomness, randomization tests of non-randomness and visual diagnostics.

For example, consider the three different arrangements of 36 individuals in the 3x3 grids shown in Table 1(a-c). The counts themselves are identical; only their locations are different. The observed arrangement in (a) is clustered maximally towards the top-left of the grid; (b) was placed at random; (c) was placed such that relatively large counts were as far away from each other as possible. Although a grid is shown for simplicity, the SADIE techniques require no restriction on the arrangement of the sample units, which may be located anywhere. The baseline comparison of complete regularity would be that each unit contained exactly four individuals. The larger the distance to regularity, D, the greater the spatial aggregation. The index of non-randomness, I_a, is respectively greater than,

Table 1. Four artificial arrangements of 36 individuals in a 3x3 grid

(a) 'Aggregated'			(b) 'Random'			(c) 'Regular'		
8	6	3	2	8	5	4	3	5
5	4	2	6	3	2	2	8	3
3	3	2	4	3	3	6	2	3
D = 13.54			D = 9.064			D = 7.40		
I_a = 1.50			I_a = 0.99			I_a = 0.82		
P_a = 0.005			P_a = 0.503			P_a = 0.968		
δ = 0.354			δ = 0.150			δ = 0.039		

(d) Permuted version of (b), to match both I_a and δ		
6	4	3
2	3	2
5	8	2
D = 9.064		
δ = 0.150		

around and less than unity for aggregated, random and regular arrangements, respectively; a formal significance test is available through the probability P_a (Table 1).

The degree to which a set of observed counts occupies the edge or the centre of the area defined by the sample units is an important descriptor of basic spatial pattern. It corresponds to the role played by the arithmetic mean of a list of numbers. Perry (1996) noted that it could be represented by the distance δ, between the centroid of the counts and the centroid of the sample units. For example, the centroids of the counts for the arrangements (a), (b), (c) in Table 1 all lie above and to the left of the central cell with respective values of δ of 0.354, 0.150 and 0.039. These values of δ are related to the degree of large-scale spatial pattern in the observed arrangement, which contributes substantially to the magnitude of the index, I_a.

Furthermore, Perry (1996) provided an algorithm whereby a set of observed counts could be permuted amongst the sample units to provide a rearrangement that had the same value of both distance to regularity *D*, and of δ. Thus, the rearrangement would resemble closely the original in a spatial sense, even though the counts in corresponding sample units were uncorrelated. He showed how this result could be very useful for simulation and could provide a relatively cheap method to test putative sampling schemes (Parker *et al.*, 1997). An example is given in Table 1(d) of such a permutation for the counts in Table 1(b). Perry & Klukowski (1997) attempt to provide definitions and methodology to cope with the difficult problem of edge effects.

Often, two populations of weed species may be studied, with a count from both being available simultaneously in each sample unit. The species may be spatially dissociated (for example, if they compete fiercely but equally), occur at random with respect to one another, or be positively associated (for example, if they utilize the same rare habitat) (Perry *et al.*, 1996; Perry, 1997b). Similar data occur when the same species is sampled at the same locations but on two separate occasions, yielding measures of within-species association through time; this relates to the stability and persistence of spatial patterns. SADIE methodology has been developed to provide indices of association and tests for such data also (Perry, 1997c,d; Korie *et al.*, 1997b).

All of the above methods are encoded within software that may be used to obtain analyses of spatial pattern for field data. This software is free and may be obtained from the author by contacting him via email: joe.perry@bbsrc.ac.uk; fax: +44 1582 760981; or telephone: +44 1582 763133.

REFERENCES

Clark, S J & Perry, J N (1994). Small sample estimation for Taylor's power law. *Environmental & Ecological Statistics*, **1**, 287-302

Clark, S J , Perry, J N & Marshall, E J P (1996). Estimating Taylor's power law for weed species and the effect of spatial scale. *Weed Research*, **36**, 405-417.

Diggle, P J (1983). *Statistical analysis of spatial point patterns*. Academic Press, London.

González-Andujar, J L & Perry, J N (1995). Models for the herbicidal control of the seed bank of *Avena sterilis*: the effects of spatial and temporal heterogeneity and of dispersal. *Journal of Applied Ecology*, **32**, 578-587.

Korie, S, Clark, S J , Perry, J N , Mugglestone, M A, Bartlett, P W, Marshall, E J P & Mann, J A (1997a). Analysing maps of dispersal from a single focus. *Ecography* (submitted).

Korie, S, Perry, J N, Mugglestone, M A, Clark, S J, Thomas, C F G & Mohamad Roff, M N (1997b). Analyzing association between counts. *Journal of Agricultural, Biological & Environmental Statistics.* (submitted).

Parker, W E , Turner, S T D, Perry, J N, Blood-Smyth, J A, Ellis, S A & McKinlay, R G (1997). Development of a GIS-based tool for testing field sampling plans by modelling the within-field distribution of mealy cabbage aphid in Brussels Sprouts. *Proceedings of the 1st European Conference on Precision Agriculture.* (in press).

Perry, J N (1987). Host-parasitoid models of intermediate complexity. *Am. Nat.*, **130**, 955-957.

Perry, J N (1994). Sampling and applied statistics for pests and diseases. In: *Aspects of Applied Biology*, **37**, *Sampling to Make Decisions*, pp. 1-14. (eds. P. Brain, S.H. Hockland, P.D. Lancashire, L.C. Sim.

Perry, J N (1995a). Spatial aspects of animal and plant distribution in patchy farmland habitats. In: *Ecology and Integrated Arable Farming Systems*, pp. 221-242 (eds , D. Glen, M. Greaves & H.M. Anderson). Wiley, Chichester

Perry, J N (1995b). Spatial analysis by distance indices. *Journal of Animal Ecology*, **64**, 303-314.

Perry, J N (1996). Simulating spatial patterns of counts in agriculture and ecology. *Computers & Electronics in Agriculture*, **15**, 93-109.

Perry, J N (1997a). Measures of spatial pattern for counts. *Ecology* (in press).

Perry, J N (1997b). "Inchworm, inchworm, measuring the marigolds...": Biometry in action. Inaugural Lecture Series of the University of Greenwich. 30pp. ISBN: 1 86166 049 9.

Perry, J N (1997c). Spatial association for counts of two species. *Acta Jutlandica* (in press).

Perry, J N (1997d). Measures of spatial pattern and spatial association for counts of insects. In: *Important Aspects in Population Ecology.* Balkema, Rotterdam. *Proceedings of the 20th International Congress of Entomology, Florence, 25-31August 1996.* (in press).

Perry, J N & Taylor, L R (1988) Families of distributions for repeated samples of animal counts. *Biometrics*, **44**, 881-890.

Perry, J N & Gonzalez-Andujar, J L (1993). Dispersal in a metapopulation neighbourhood model of an annual plant with a seedbank. *Journal of Ecology*, **81**, 453-463.

Perry, J N & Klukowski, Z (1997). Spatial distributions of counts at the edges of sample areas. *Proceedings of the VI Conference of the Biometric Society (Spanish region), Córdoba 21-24 September, 1997.* (in press).

Perry, J N, Bell, E D, Smith, R H & Woiwod, I P (1996). SADIE: software to measure and model spatial pattern. *Aspects of Applied Biology*, **46**, 95 - 102.

Perry, Joe N, Parker, W E, Alderson, Lynda & Korie, Sam (1997). Simulation of 16,000 counts of aphids over two hectares of Brussels sprout plants. *Computers and Electronics in Agriculture.* (submitted).

DYNAMICS OF WEED CLUSTERS: CURRENT UNDERSTANDING AND SOME OPEN PROBLEMS

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ABSTRACT

Aggregated distribution of weeds is of interest to weed management because it offers the opportunity to control weed patches only. Simulation studies have been conducted to analyse weed cluster dynamics. Results show that weed clusters have their own dynamics that does not follow straightforwardly from the description of life-history characteristics of individual plants. Two recent theoretical results in the study of weed cluster dynamics are rephrased as hypotheses to be tested against field observations, and their potential relevance to weed patch management are discussed.

INTRODUCTION

The spatial distribution of weeds over agricultural fields is often reported to be aggregated, so herbicide use can be reduced when only weed patches are sprayed (Rew and Cussans, 1995). The reduction in herbicide use will depend on the number and size of the weed patches, and the future reductions in herbicide use will depend on how the number and size of weed patches develop over time. The term 'patch' is used to refer to weed aggregates as they appear in the field at one particular time. For studying population dynamics it is often more convenient to work with a group of spatially distributed individual weeds that descend from one ancestor. Such a group is termed a 'cluster'. The term 'weed cluster dynamics' is used to refer to the dynamics of number and size of weed clusters, including the correlations in weed positions over space and time; weed cluster dynamics might be understood as the spatio-temporal dynamics of ensembles of individual weeds.

The primary aim of this paper is to show that the description of dynamics of weed clusters does not follow in a straightforward manner from description of individual life histories of weed plants nor from the dynamics of weed numbers in the whole field. This paper also reviews some recent theoretical results in the study of weed cluster dynamics and discusses their potential relevance to weed patch management.

WEED CLUSTER DYNAMICS

The basic features of cluster dynamics of annual weeds can be illustrated in a very simple setting. Consider a two dimensional lattice that represents a homogeneous field.

Weed seeds are distributed over the lattice sites. The system is updated in discrete time steps, corresponding to one season, according to the following rules: (i) in the beginning of the season each seed germinates; (ii) if more than one plant emerges at one site, only one plant survives; (iii) each plant has a particular probability to be killed by weed control, this probability is such that the total number of weeds remains about constant and very low compared to the number of available sites; (iv) surviving plants produce seeds that are dispersed to adjacent sites. The system can be made more realistic by allowing seeds to be dormant in the soil, by describing plant growth and competition with more intricate rules, and by including dispersal of seeds to sites at various distances according to a probability distribution of dispersal distances, and so on. Several variations of the system have been studied in the context of weed cluster dynamics (Wallinga, 1995 and references therein).

Computer simulations of such systems show that: (a) the individual weeds form clusters of all sizes, there is no maximum nor a typical cluster size; (b) clusters tend to remain at the same position, that is, the cluster's position is 'stable' over time; (c) the correlation in weed positions over space and time can be described accurately by power law equations; (d) the value of the exponents in these power law equations does not depend on the specific life-history characteristics of the individual weeds (provided that dispersal over very long distances and dormancy for very long periods is relatively unimportant, that is, the probability distributions of dispersal distances and of dormancy periods should have a finite variance). The observation (d) is an important one because it gives the justification to use simplistic models as described above rather than more realistic and more complex models (Wallinga, 1995).

When weed control is absent, the system description can be modified by omitting rule (iii). The total number of weeds on the lattice will then increase and clusters will expand. Perhaps surprisingly, there are qualitatively different patterns of spread: if the tail of the seed dispersal distribution declines with distance in an exponential way or faster, the cluster expands with a closed front at a constant speed; otherwise the cluster expands by establishing new 'satellite patches' at an accelerating speed (*e.g.* Shaw, 1995).

In summary, the theoretical results show clearly that the phenomena at a cluster level have their own dynamics and that the description of cluster dynamics does not follow in a straightforward manner from the description of individual life-histories. One may have noted that the description of dynamics at the cluster level is also very different from the dynamics of a whole population (understood as changes in number of weeds in a field over time).

FROM THEORY TO EMPIRICAL OBSERVATIONS AND WEED MANAGEMENT

The theoretical results pertain to a situation where the abiotic environment is homogeneous in space and time. The environment for annual plants in a real agricultural ecosystem is relatively homogeneous when compared to a natural vegetation, but still there is some variation in the abiotic environment. When the theoretical results are taken out of the theoretical context and used in a real-life context, they are perhaps best appreciated as hypotheses that are worth testing.

A first theoretical result mentioned in the previous section was that the correlation in spatial weed positions did not depend on the specific life-history characteristics of the individual weeds. This is rephrased as a hypothesis:
the shape of the semivariogram of a weed spatial pattern is independent of the exact life-history traits of the individual weeds.
In other words, semivariograms for all annual weed species for all relatively homogeneous fields would fit one function. If this is indeed the case, it would be extremely useful because it provides a general and biologically motivated description of pattern to interpolate sampled spatial weed maps for patch spraying. At present, interpolations are made by semivariogram functions that are fitted empirically for each field for each species. More general, it is very important that the many observed semivariograms are compared and analysed for similarities.

A second theoretical result mentioned in the previous section was that an uncontrolled cluster of weeds only expands with a constant speed if the forward tail of the seed dispersal curve declines exponentially or faster, otherwise a cluster will expand at increasing rate. This is rephrased as a hypothesis:
the tail shape of seed dispersal curve determines the speed and pattern of spread.
Although there is no doubt about the importance of seed dispersal in spatial weed population dynamics, very little attention has been paid to the exact shape of the seed dispersal curve and almost no attention has been paid to the shape of the tail of this curve. Almost all studies on spread of weeds have assumed *a priori* that the seed dispersal curve can be described by a Gaussian curve or negative exponential curve (*e.g.* Cousens and Mortimer, 1995, Rew and Cussans, 1995). This implicit assumption has far-reaching consequences when making predictions about speed and pattern of spread of weeds, it may lead to severe underestimation of speed of spread and thus in underestimated risk of leaving small weed patches unsprayed. In order to justify or reject *a priori* assumptions about the shape of the dispersal curve, it would be most useful to have more detailed observations on the shape of the tail of seed dispersal curves (beyond 100 metres, like the observations reported by Shirtliffe, 1997) and to have more observations of weed spread in agricultural fields.

CONCLUSIONS

The dynamics of weed clusters does not follow straightforwardly from description of individual life-history characteristics of weeds, nor is it a sophistication of population dynamics at field level. At least in theory, the description of correlations in weed positions over time and space are independent of description of life history characteristics of the weeds (when the weed population is controlled and seed dispersal is sufficiently local). If this could be confirmed by field observations, such a generic description of correlations would be very useful for interpolating sampled weed maps. In case the weed population is left uncontrolled the clusters will expand. At least in theory, the tail shape of the seed dispersal curve determines whether clusters expand at constant speed or not. More empirical observations that consider the displacement of seeds over long distances (beyond 100 metres or so) would be most welcome.

REFERENCES

Cousens, R, Mortimer, M (1995) *Dynamics of Weed Population.* Cambridge University Press, Cambridge.

Rew, L J, Cussans, G W (1995) Patch ecology and dynamics - how much do we know? *Proceedings of the British Crop Protection Conference - Weeds*. BCPC, Farnham. pp 1059-1068.

Shaw, M W (1995) Simulation of population expansion and spatial pattern when individual dispersal distributions do not decline exponentially with distance. *Proceedings of the Royal Society of London B.* **259**, 2243-248.

Shirtliffe, S J, Entz, M H, Maxwell, B D (1997) The effect of combine harvester dispersal on seed spread of Avena fatua. *Proceedings of the 10th EWRS Symposium 1997*, Poznan. pp 24.

Wallinga, J (1995) The role of space in plant population dynamics: annual weeds as an example. *Oikos.* **74**, 377-383.

MACHINE VISION FOR PLANT SCALE HUSBANDRY

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INTRODUCTION

The desire to reduce agricultural production inputs has led to much research to improve targeting. A recent technique, spatially selective operation, is done by mapping variability within a field. This map is used to decide how to selectively treat areas of typically 5m by 5m resolution from a vehicle equipped with some type of absolute navigation system, typically GPS. An alternative approach is to sense targets, be they crop or weed, on line and treat accordingly. This allows a much finer resolution, down to individual plants and requires little prior knowledge of the field except an estimate of planting geometry. This concept, which we term plant scale husbandry, might range from mechanical hoe guidance in cereals to the targeting of parts of vegetable plants such as the base of stems with insecticide.

MACHINE VISION TECHNOLOGY

A typical machine vision system consists of a camera, a means of digitising its output, and a computer to process the resulting digital images. As the image is two dimensional, even a moderate resolution (e.g. dividing the image into 256 pixels horizontally by 256 vertically) generates a large amount of data (64 kbytes for a monochrome image of this resolution). To control some sort of machine this data has to be collected say 10 times a second giving a data processing throughput of nearly 3/4 of a Megabyte every second. This provides us with our first challenge in machine vision, processing the data quickly enough. The second, much more significant, challenge is to provide the necessary artificial intelligence to do what we humans do very easily, that is to understand the visual scenes which unfold before us. Simple arithmetic analyses are easy, for example telling which parts of an image are brighter than others. However the analyses required for any sort of intelligent activity, e.g. telling which parts are plants and which weeds, are extremely challenging. In addition, the sometimes complex solutions compound the problem of data processing rate as the resulting algorithms can be computationally intensive.

TRACKING CROP ROWS

We have developed a testbed vehicle to investigate and demonstrate some of the necessary technology for plant scale husbandry (Tillett *et al.*,1996). So far the technology has been confined to the sensing systems of an autonomous vehicle, its navigation and control, and a simple spray control system. In order to control the vehicle's path the angle of the vehicle with respect to the rows and its offset must be measured. This could be done in a naive way by measuring the rotation of each wheel and using a model of the vehicle kinematics to predict the required variables but would suffer from modelling errors and unaccounted for variations (e.g. wheel slip). Alternatively the variables could be calculated from the images collected from a camera on the front of the vehicle (Marchant and Brivot, 1995). This may give good results some of the time but suffer failures, for example where the crop pattern was absent for a section or severely contaminated by weeds. A powerful method is to combine the two techniques using a method known as a Kalman filter. This predicts from the odometry and corrects from the vision, combining the two sources of knowledge with the benefit of an estimate of the likely errors from each source. As an example of the machine vision contribution, Fig. 1 shows an image containing cauliflower rows along with the an overlay of the row lines calculated from the recovered heading angle and offset.

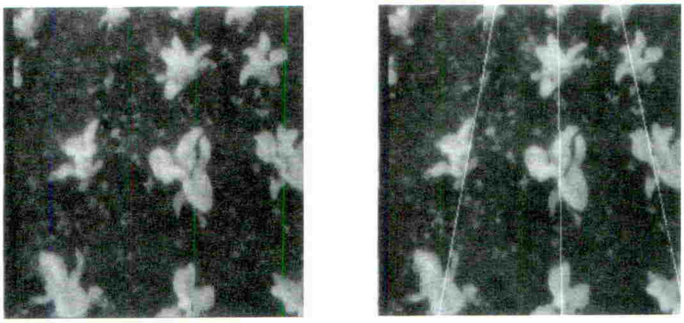

Fig. 1. Left, view from the vehicle camera. Right, recovered row lines.

As well as providing information for vehicle control, finding the rows would provide some information on weed location. For instance, vegetation outside crop rows is more likely to be weed than crop. Other clues from the planting pattern could be used, for example in a transplanted vegetable crop the plants should occur at reasonable intervals along the rows whereas weeds should be more randomly positioned.

DIFFERENTIATING PLANTS AND WEEDS

It may be possible to differentiate plants from weeds based on their appearance in the image. This is a typical case where it is fairly easy for a human but difficult for a computer program. Probably no single algorithm will work faultlessly but better performance may well be achievable by combining the result with some of the other clues mentioned above. We have developed one method which performs well on a large number of image sequences in our collection of transplanted cauliflower. The algorithm uses several techniques but relies heavily on the fact that the particular weed species present has leaves that are much smaller than the broad flat cauliflower leaves. This means that the cauliflower leaves are brighter on average and have grey levels that vary more slowly across their surface. Differentiation between vegetation and soil can be achieved comparatively simply:- vegetation reflects near infra-red much more readily than soil. If the received radiation is confined to this band using suitable filters then differentiation can be achieved simply on brightness. Fig. 2 shows the results of applying the algorithm.

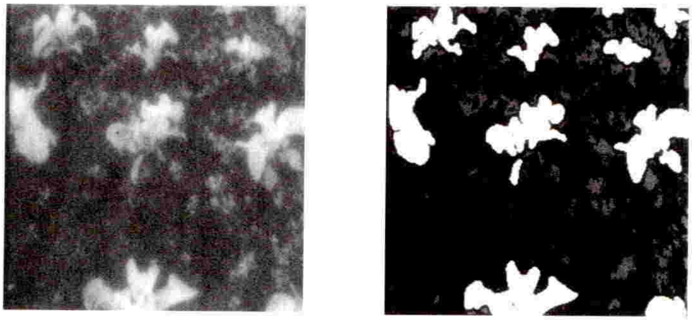

Fig. 2. Differentiation of plants and weeds. Left, original infra-red image. Right, result from algorithm, plants in white, weeds in grey, soil in black.

DISCUSSION AND FUTURE WORK

We have demonstrated some of the technology necessary for plant scale husbandry on our autonomous vehicle. This can navigate along crop rows and treat plants in a selective manner. However there is a long way to go before the technique can become a reality. We suspect that the limits of operation of the machine vision techniques are rather narrow in terms of plant growth stage, weed infestation level, and lighting conditions. We now have funding to investigate these ranges and to develop methods to extend them.

Also, we feel that operation on human guided vehicles will be a nearer term spin-off from the work. We have just started a project, in collaboration with ADAS, to develop control and sensing methods for a steerable hoe for mechanical treatment of weeds in cereals.

In conclusion, we feel that new ideas in machine vision, vehicle and implement control, and other associated sensor technologies have much to offer in the area of crop protection in the future.

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REFERENCES

Brivot, R; Marchant, J A (1996) Segmentation of plants and weeds for a precision crop protection robot using infrared images. *Proc. I.E.E, Vision, Image, and Signal Processing.* **143**, 118-124.

Tillett, N D; Marchant, J A; Hague, T (1996) Autonomous plant scale crop protection. Paper No. 96A-124 AgEng96, European Society of Agricultural Engineers, Madrid, 23-26 Sept 1996

Marchant, J A; Brivot, R (1995) Real time tracking of plant rows using a Hough transform. *Real Time Imaging*. **1** 363-371.

SPATIALLY SELECTIVE WEED CONTROL IN ARABLE CROPS - WHERE ARE WE NOW?

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ABSTRACT

Some weed species, particularly annual grasses and perennials are spatially aggregated in distribution. Recent developments in satellite location systems and in computer and sprayer technologies now provide tools that make spatially selective herbicide 'patch' spraying a practical possibility. In narrow row arable crops (eg cereals) such treatments will, for the foreseeable future, need to be based on weed maps. This paper discusses the spatial biology of weeds, reviews the effects of agricultural operations on their spatial distribution and considers their effects on the longevity of the accuracy of weed maps. It also discusses the need to convert the weed maps into treatment maps.

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.*, 1996). This is most easily seen in fields infested with tall weeds in late summer, when patches of *Cirsium arvense* (creeping thistle), *Avena* spp. (wild-oats), *Elymus repens* (common couch) and *Alopecurus myosuroides* (black-grass) are visible above the crop. 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 by turning spray booms on or off on certain tramlines. 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 advances have made it possible to start to develop spatially selective treatments.

Real-time detection and herbicide spraying of green weeds during the fallow phase of the rotation using spectral reflectance (red and near infra-red) has been developed in Australia (Felton, 1995). This technology is also appropriate for wide-row crops such as chick-pea, maize, and soybeans where it would simply identify green weeds between the crop rows. Weeds in narrow row arable crops cannot, as yet, be detected electronically, 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 to distinguish weeds from crops (eg. Gerhards *et al.*, 1995; Andreasen *et al.*, 1997) but commercial systems are unlikely in the foreseeable future. So, in these crops, sprayer control has to be based on historic maps of weed distributions, where weed detection is done by eye. This requires a separate survey to create a map. Thus, current spatially selective systems require three 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 and a sprayer to apply herbicides to the patches.

SPATIAL BIOLOGY OF WEEDS

The potential of weeds to be treated in a spatially selective way requires that they should be aggregated in distribution and that if the spatial treatment is controlled by a map, the weed distribution should be relatively static. It is clear that a number of major UK weeds are aggregated in their distribution and our work has mapped such distributions for the annual grass weeds *A. myosuroides*, *Lolium multiflorum* (volunteer rye-grass) and *Avena* spp. and for the perennial weeds *C. arvense* and *E. repens*. Other work, such as that by Gerhards *et al.*, (1995) has also shown that other annual weeds are also aggregated in distribution.

The second key biological issue relates to the stability of the weed patches. This is important 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. Quantifiable evidence for the stability of weed patches is scarce although there is much anecdotal evidence. The only detailed UK study is that reported by Wilson & Brain (1991) which monitored the distribution of *A. myosuroides* on a farm 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 (30 x 30m) 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 demonstrated that the weed patches were stable, indicating that seedling distributions in one year were good predictors of future distributions.

Our studies with *A. myosuroides* indicate that patches are relatively stable, as cultural practices seem not to move seeds more that a few metres and natural dispersion of seeds is limited (Rew & Cussans, 1995). Evidence from experiments using contrasting sized seeds (beans, barley, oilseed rape) indicated that large seeds were moved less by cultivations than smaller seeds (Rew & Cussans, 1997). Combine harvesters have the potential to move some seeds greater distances, particularly large seeds with awns, such as those of *Bromus sterilis* (barren brome) (Howard *et al.* 1991; Peters N.C.B., pers. comm.) but their effects are influenced by the percentage of seeds remaining on the parent plants at harvest The relevance of these effects to patch stability remains to be fully resolved.

Although we have information on the effects of cultivation, combine harvesters and natural dispersal on seed distribution for some of the relevant species we are not yet able to predict with any confidence how a patch will behave over time. Nor have we closely monitored the stability of natural patches. This limitation in our knowledge is constraining our ability to assess the relevance of the technology to a wider range of species. It also restricts our ability to assess how long a weed map would remain accurate, a key issue in relation to the economic viability of patch spraying.

WEED MAPPING

Navigation Systems

Global positioning satellite systems (GPS) are now being used to map many biological and geographical features of the landscape, but the need to be able to map weeds to an accuracy of c.2m requires greater precision than many other uses. The development of yield mapping systems has been helpful as it has encouraged commercialisation of more accurate mapping methods. We have created detailed weed maps of more than 20 fields using a differential(D) GPS System. However, the reliability of the navigation system was not always good enough and in some situations (eg undulating ground) failed completely. The current rapid development of this technology will, it is hoped, resolve these difficulties.

Treatment Maps

The generation of the map is possible using DGPS location systems coupled with visual observation of weeds. In our work operators used key pads connected to a lap-top computer to record the presence of weeds as a vehicle traversed the fields. There are several assessment 'windows' for creating weed maps during the year depending on the crop and weed species. In our experience one of the best opportunities is in set-aside, in early summer, as this shows the full extent of the weeds, not just survivors from earlier partially effective herbicide treatments. How to map weeds in practical situations has yet to be fully resolved but work to date indicates that it is certainly possible from combine harvesters (for pre-harvest weed detection) and from high clearance vehicles, such as self-propelled sprayers. The potential of mapping from tractors, whilst carrying out other farm operations, remains to be evaluated, but some agricultural advisors are successfully mapping weeds in winter from all-terrain vehicles. As we think observers may only be able to assess up to 12m it is not clear how to map from tramlines that are 18 or 24m apart. Thus, further development work is still needed to produce practical guidelines on how to map weed distributions most effectively.

Before the map can be used to control the sprayer it has to be converted into a treatment map. Ideally the map should identify the weeds at a range of infestation levels. We have shown that it is possible to identify three weed levels, zero weed, low density and high density. It may be possible to record more, although the ability to do so will be related to the width assessed. Appropriate herbicide doses can then be chosen for each infestation level. Results from field research, supported by modelling studies, of the effects of farming operations on weed movement, the accuracy of the DGPS system and the speed of response of the sprayer, showed that it was necessary to include *c.* 4m 'buffers' around the areas to be sprayed (Rew *et al.*, 1997). This will reduce the potential saving in herbicide in the short-term but will maintain control more effectively in the longer-term. The need for a buffer is less acute with treatments where doses are adjusted (low - high) than where there is a simple on/off system (Paice & Day, 1997).

PATCH SPRAYING

To implement the treatment map a sprayer is needed that is able to respond rapidly to the instructions, whilst in forward motion. The prototype Silsoe patch sprayer developed in this project was able to switch doses within 0.5m (Paice *et al.*, 1995) and could selectively apply herbicides from 2m sections of boom. Further commercial development of a spatially selective sprayer is now in progress. More details of sprayer design are given in the paper by Miller *et al.*, (1997).

CONCLUSION

Over the last 4 years we have shown that patch spraying can be commercially viable. Preliminary costings indicate that savings in the region of £5-10 / ha / yr are possible but these benefits will have to be offset against the cost of the sprayer, location and computing systems and the labour for mapping. We need more information on the spatial biology of more common arable weeds and on how to create weed maps on commercial farms. The development of the sprayer is advancing, as is the reliability of DGPS location systems.

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REFERENCES

Andreasen C; Rudemo M; Sevestre S (1997) Assessment of weed density at an early stage by using image processing. *Weed Research*, **37**, 5-18.

Felton W L (1995) Commercial progress in spot spraying weeds. *Proceedings of Brighton Crop Protection Conference - Weeds*, 1087-1098.

Gerhards R; Sokefeld M; Nabout A; Kuhbauch W (1995) Use of expert systems and imaging techniques for site-specific weed management. *Proceedings EWRS Symposium (Budapest)-Challenges for Weed Science in a Changing Europe*, 655-662.

Gerhards R; Wyse-Pester D Y; Mortensen D; Johnson G A (1997) Characterising spatial stability of weed populations using interpolated maps *Weed Science*, **45**, 108-119.

Howard C L; Mortimer A M; Gould P; Putwain P D; Cousens R; Cussans G W (1991) The dispersal of weeds; seed movement in arable agriculture. *Proceedings of Brighton Crop Protection Conference - Weeds*, 821-828.

Marshall E J P (1988) Field-scale estimates of grass weed populations in arable land. *Weed Research*, **28,** 191-198.

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

Mortensen D A; Johnson G A; Young L J (1993) Weed distribution in agricultural fields in: *Soil Specific Crop Management*, Robert P & Rust R H (eds), Agronomy Society of America, pp.113-124.

Paice M E P; Miller P C H; Bodle J. (1995). An experimental machine for evaluating spatially selective herbicide application. *Journal of Agricultural Engineering Research*, **60**, 107-116.

Paice M E R; Day W (1997) Using computer simulations to compare patch spraying strategies. *Proc. 1st European Conf. on Precision Agriculture (Warwick)*, (in press).

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

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**, 247-256.

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.

Wilson B J; Brain P (1991) Long term stability of *Alopecurus myosuroides* Huds. within cereal fields. *Weed Research*, **31,** 367-373.

METHODS OF CONTROLLING SPRAYER OUTPUT FOR SPATIALLY VARIABLE HERBICIDE APPLICATION

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ABSTRACT

The spatially variable application of herbicides requires the use of systems with dose control, response time and spatial resolution characteristics that are closely matched to defined criteria, if substantial improvements in herbicide use are to be reliably achieved. An experimental patch sprayer based on the use of injection metering technologies and on/off control of multiple lines in small boom sections, has been shown to give good field performance characteristics. However, the system is relatively complex, costly and difficult to implement commercially. An alternative system in which both nozzle pressure and output orifice are adjusted has been designed and built and shown to give a turn-down ratio of more than 5:1 for a given spray quality. Field experiments with the system installed on a 24 m mounted sprayer have demonstrated the ability of the system to apply both pesticides and liquid fertilisers in a spatially variable manner.

INTRODUCTION

The requirements for the spatial application of herbicides have been reviewed by Paice *et al.* (1996) and key performance parameters identified including the accuracy of the delivered dose, spatial resolution, speed of response, the ability to operate over a wide range of delivered dose rates and with variable herbicide mixtures. Requirements for optimal patch spraying performance can be summarised as follows:

accuracy of delivered dose to better than ± 5%of target
spatial resolution to be in the range 4.0 to 6.0 m
response time between delivered dose levels to be less than 1.0 s
herbicide to be delivered to target areas over a of dose rate range of 5:1
an ability to work with a wide range of herbicide formulations

The features of a number of possible technologies for making such spatially variable applications were also analysed by Paice *et al.* (1996). The range of dose rates that can be applied with a given size of conventional hydraulic pressure nozzle by changing the liquid pressure is limited to typically ± 20% of a nominal output because of the variations in spray volume distribution pattern (patternation) and droplet size distribution within the spray (spray quality). Giles and Comino (1990) have described a technique whereby the turn-down ratio of systems using hydraulic pressure nozzles has been extended without degrading patternation or spray quality. Fast acting solenoid valves mounted immediately upstream of each nozzle are actuated with a rectangular wave signal having a frequency of approximately 10 Hz and a duty cycle in the range 10 to 70%. Other systems have selected alternate nozzles by switching of multiple boom lines.

Twin fluid nozzle systems can also be used to give a variable flow rate at a defined spray quality by adjusting both the air and liquid supply pressures. This type of nozzle system is therefore well suited to spatially variable herbicide application (Miller and Combellack, In press, Paice *et al.*,1996). Published performance data for commercially available systems indicates that such nozzle systems can achieve a turn-down ratio of approximately 3:1 although experimental units have achieved a wider range. The sprays produced by twin fluid nozzles have droplets with "air-inclusions" and therefore cannot be directly classified with respect to spray quality using existing published protocols.

By changing feed rate and rotational speed, spinning discs and cages can also produce a range of outputs for a given spray quality. However, such systems have not been widely developed in Europe for treating arable crops using boom sprayers and hence are unlikely to form a basis for commercial patch sprayer design.

Paice *et al.* (1996) identified patch spraying systems based on injection metering control as being the most likely to fully meet the performance requirements for spatially selective herbicide application. Recent work has aimed at defining the likely performance of different designs of injection metering system (Antuniassi *et al.*,In press) and the implications for patch sprayer control. Much of the analysis and evaluation of patch spraying approaches has been based on an experimental unit which used a combination of injection metering and multiple boom line control (Paice *et al.*, 1995) to apply treatments at a spatial resolution down to 2.0 m x 2.0 m.

AN EVALUATION OF PATCH SPRAYING APPROACHES

An experimental patch sprayer has been successfully used to apply a range of herbicide formulations in field scale trials at a number of sites (Miller *et al.*, 1995). Sprayer control was based on an injection metering system which used cylinders to contain liquid chemical formulations. Calibrated gear pumps were used to deliver water from the pressure side of the sprayer circuit to the base of the metering cylinders hence displacing the active formulation at a rate depending on the defined dose rates on a treatment map, the position on the map and the forward speed of the sprayer. Experiments with the unit showed that it was able to deliver a dose rate to an accuracy of better than ± 5% over a turn-down ratio of more than 20:1 and that dynamically, a step change of 100% in output could be achieved in less than 0.5s (Miller *et al.*, 1995).

The control treatment map was carried in a conventional portable computer mounted in the tractor cab and interfaced with the sprayer control system via a Controller Area Network (CAN) system. In-field location was initially based on the distance travelled down tramlines but later used the Global Positioning System (GPS). Most treatment maps were derived from weed patch maps obtained with purpose-built equipment (Miller *et al.*, 1995) with an allowance around detected patches to account for errors in field location (while mapping and spraying) and the dynamic response characteristics of the sprayer.

Experience with this system identified weed patch mapping and treatment map generation as key areas requiring further work. Patch detection from tractors, sprayers and combine harvesters has been shown to be feasible and to have the potential to form the basis for treatment map generation using a range of geostatistical and mathematical modelling techniques. A critical analysis of the required inputs for different treatment map generation systems is now required with an appropriate assessment of the quality of map produced.

The work has generated considerable commercial interest and methods of developing commercially viable systems are now being sought.

DESIGN OF AN ALTERNATIVE SYSTEM

A collaborative project with commercial and research interests has aimed to design, construct and evaluate a patch spraying system that would be directly compatible with existing sprayer designs and, if appropriate, could be retro-fitted to existing machines. The resulting system was based on a commercial unit which provided both in-field location via a GPS system and the management and storage of a treatment map in a tractor-mounted console (Massey Ferguson "Field Star"). Supporting software enabled treatment maps to be generated on a farm office computer and down-loaded to the tractor console via a data card.

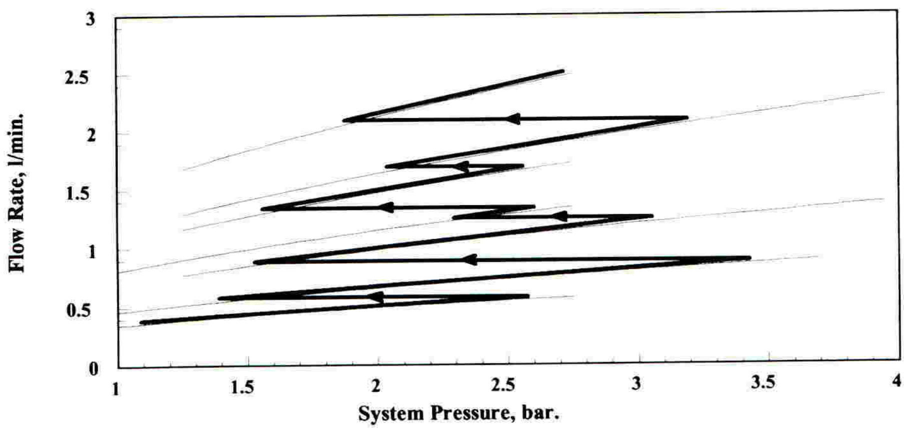

Figure 1. A typical path of increasing demand flow rate through the seven ranges of a three nozzle system.

The control principle was to switch nozzle orifice sizes and vary the pressure at the nozzle such that output could be varied almost continuously. At each field location, at a frequency of 1 Hz, the tractor based control system sent a message to the sprayer containing the required application rate and the forward speed. The control system on the sprayer selected the nozzle(s) to be used and the spraying pressure to give an appropriate flow rate at a given spray quality (Figure 1).

The switching of nozzles and the control of spray pressure was implemented using a compressed air control system powered by an air compressor driven from the pump drive shaft. Each nozzle on the boom was fitted with a commercial pneumatic on/off valve which also acted to fail safe and prevent the nozzles from dripping. These valves were activated by small air lines mounted along the boom. Spraying pressure was also controlled pneumatically via a pressure regulating valve and diapraghm control unit. An original design used three nozzles at each spraying station on the boom giving a continuously variable output over a wide range of flow rates (see Figure 1). In practice, it has been found that good performance can also be obtained with two nozzles at each position along the boom.

The patch spraying unit that has been developed is directly compatible with existing sprayer and tractor control systems. It has been used successfully to apply herbicides, fungicides and liquid fertilisers in a series of evaluation trials involving spatially variable application.

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REFERENCES

Antuniassi, U R; Miller, P C H; Paice M E R (In press) Dynamic and steady state dose responses of some chemical injection metering systems. Proceedings Brighton Crop Protection Conference - Weeds.

Giles, D K; Comino, J A (1990) Droplet size and spray pattern characteristics of an electronic flow controller for spray nozzles. *Journal of Agricultural Engineering Research,* **46**, 55-70

Miller, P C H; Combellack, J H (In press) The performance of an air/liquid nozzle system suitable for applying herbicides in a spatially selective manner. Proceedings 1st European Conference on Precision Agriculture.

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

Paice, M E R; Miller, P C H; Bodle, J (1995) An experimental machine for evaluating spatially selective herbicide application. *Journal of Agricultural Engineering Research*. **60**, 107 - 116.

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

Stafford, J V; Miller P C H (1993) Spatially selective application of herbicides. Computers and Electronics in Agriculture. **9**, 217-229

THE BIOLOGY UNDERLYING WEED MANAGEMENT TREATMENT MAPS IN MAIZE

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ABSTRACT

Row-crop weed infestations occur as spatially aggregated or patchy populations in fields. Within these patches, seedbank and emerged seedling density varies, with high density patch centers and low density patch edges. We hypothesize that high density patch centers account for the persistence of patchy populations. Preliminary results of our own and of other work indicates strong associations of weed populations and field-site characteristics. These associations may result from direct influences of the site on species fitness and fate or indirectly through modification of mortality intensity. In addition, a strong negative correlation between weed density and response to weed management has been observed. As an outgrowth of this work, algorithms are being developed to calculate site-specific weed management treatment maps.

INTRODUCTION

On the scale of a grower's field, weed populations are spatially aggregated and 'patchy' (Johnson et al., 1996; Marshall, 1988; Mortensen et al., 1993). Patchy weed populations imply that portions of the field are weed-free while other areas have weeds occurring at various densities and are constrained in space. Subsequently, weed patches themselves have been studied in order to understand the nature of their occurrence.

The organization of weed patches in a grower's field could be classified either as mainland-island, source-sink, or metapopulation structures (Cousens and Mortimer, 1995). Two important parameters used to define spatial structure and behavior of a population are colonization and extinction rates. These imply that weed patches in the field are either empty (to be colonized) or full (at carrying capacity, to become extinct). However, these processes occur on a temporal scale much longer than that of individual weed patches. While colonization and extinction of patches must occur in fields (Ghersa and Roush, 1993), established populations appear to be the rule rather than exception in the maize cropping system. For this reason behavior of established populations (patches) has been the focus of our work (Gerhards et al., 1997; Johnson et al., 1996).

Patch characterization and stability

Results from five years of field research indicate that patches are rather persistent, that patch centers are spatially stable, and that within-patch density and patch edges vary significantly from year to year in part as a function of intensity of mortality as well as soil and crop environmental variation. Significant variation in density exists across individual weed patches in growers' fields (Cardina et al., 1995, Johnson et al., 1996). Within these patches, seedbank and emerged seedling density varies with high density patch centers and low density patch edges. We have also observed that patch shape is anisotropic with patch length parallel to the predominant direction of implement traffic.

Stability of patches implies that patch location and within-patch density are constant from year to year (Gerhards et al., 1997; Johnson et al., 1996; Wyse, 1996). However, such stability analyses have been very descriptive. Intensive surveys of weed seedling populations in four eastern Nebraska corn and soybean fields over four years have provided a valuable database on which to perform such stability analyses. Based on chi-square and Spearman rank statistical tests of independence, stability of weed seedling populations was quantified (Wyse, 1996). The greatest degree of stability was observed for common sunflower (*Helianthus annuus* L.) and velvetleaf (*Abutilon theophrasti* Medik.), followed by foxtail species (*Setaria sp.*), pigweed species (*Amaranthus sp.*), and eastern black nightshade (*Solanum ptycanthum* Dun.) when pooled over four study sites. Overlaying weed distribution maps from two of these fields over four years indicated that common sunflower, velvetleaf, and hemp dogbane (*Apocynum cannabinum* L.) patches were persistent in direction and location (Gerhards et al., 1997). However, foxtail distribution and density over the four years continuously increased in one and decreased in the other field.

Because of variation of within-patch density and patch edges and since, in some cases spatial patterns may not exist, patch stability has been difficult to quantify. It is clear that the whole field distribution of patches is site-specific, reflecting the long-term management history and species spectrum occurring in a field. In spite of this variation, weed patches can be visually relocated year after year in the same field (Wyse, 1996). This suggests that some component of the weed patch is more stable; the patch center.

Site-specific plant associations

Annual grass weed populations in maize fields were correlated with high elevation while broadleaf species of common sunflower and velvetleaf were associated with areas of high organic matter (Dieleman et al., 1997b). In these fields, higher elevations describe regions with high sand content and low organic matter. Distributions of field site characteristics and weed populations appear to be linked. Mechanisms underlying these associations are unclear at this time. We know that extent of mortality and fitness reduction of a particular weed management approach interacts strongly with site characteristics. For example, the herbicide rate required to provide lethal plant available concentrations in the soil varies significantly with soil texture, organic matter content and pH (Johnson et al., 1997). In addition, niche separation in high elevation sandy regions and in organic matter rich depressions of fields may also contribute to the observed associations. The extent to which one or the other of these two forces contribute to these associations is poorly understood and in need of further study.

Interaction of weed density to weed management events

From preliminary research with common sunflower and velvetleaf, a strong negative relationship has been consistently observed between within-patch density and resulting weed mortality. As the number of individuals within a patch increases, more individuals appear to survive the imposed mortality event (Dieleman et al., 1997a). For example, common sunflower densities before an application of either 1/2 or 1X bentazon ranged from 100 to 400 plants. More sunflower individuals were present in higher density patches two weeks after application of 1/2X of bentazon than at lower densities, while the 1X rate was more effective at reducing the number of survivors overall. Similar results have been reported for other species, for a range of soil-applied (Hoffman and Lavy, 1978; Winkle et al., 1981) and foliar-applied (Dieleman et al., 1997a) herbicides, and mechanical methods of control (Buhler et al., 1992). There appears to be a critical density below which no survivorship is observed. This critical density increases as the intensity of mortality increases. Results of these component studies are consistent with our observations of patch stability on-farm. A higher intensity of mortality is required to limit weed seedling populations in high density centers suggesting something other than uniformly implemented weed management systems may provide more effective long term population regulation. Management systems with something less than high mortality intensity applied to high density patch centers will have a high probability for increased plant fitness and survival to reproductive maturity contributing to patch persistence.

SUMMARY

Results of descriptive patch studies in which density variation and distribution has been characterized suggest a fair degree of spatial stability of weed patches in the maize study system. To some extent evidence in our study system indicates that these patchy populations are associated with site characteristics through direct influences on species (plant or seedbank) fitness and fate and indirectly through modification of mortality intensity. Finally, a strong negative relationship exists between weed density and resulting mortality and fitness reduction. We are currently in the process of developing algorithms for weed management treatment maps. The approach is information-intensive relying where spatially referenced measures of site and weed and crop demography are used to derive spatial maps of density-dependent and site-specific mortality functional relationships. Too date the approach is empirical, deriving functional relationships from sites in which weed and soil attributes have been previously measured. While we believe the approach has the potential of providing improvements in maize management systems, a number of questions remain unanswered and are in need of attention. Those questions include:

How representative of all farm fields are the relatively few that have been intensively studied?

How extendable are soil association and patch fate findings made at one study site to adjacent farm sites?

How accurate does weed density/infestation level forecasting need to be?

How much of the variation in weed by soil/site association can be explained by niche separation vs. site-specific mortality modification?

REFERENCES

Buhler, D D; Gunsolus, J L ; Ralston, D R (1992) Integrated weed management techniques to reduce herbicide inputs in soybean. *Agronomy Journal* **84**, 973-978.

Cardina, J; Sparrow, D H; McCoy, E L (1995) Analysis of spatial distribution of common lambsquarters (*Chenopodium album*) in no-till soybean (*Glycine max*). *Weed Science* **43**, 258-268.

Cousens, R; Mortimer, M (1995) Dynamics of Weed Populations. Cambridge University Press, New York, NY. 332 pp.

Dieleman, J A; Mortensen, D A (1997a) Influence of high seedling densities of common sunflower and velvetleaf on weed management efficacy. *Weed Science*, in preparation.

Dieleman, J A; Mortensen, D A; Buhler, D D (1997b) Multivariate approaches for linking field-scale variability of soil properties and weed populations. WSSA Proc. **37**, 46.

Gerhards, R; Wyse-Pester, D Y ; Mortensen, D A; Johnson, G A (1997) Characterizing spatial stability of weed populations using interpolated maps. *Weed Science* **45**, 108-119.

Ghersa, C M; Roush, M L (1993) Searching for solutions to weed problems: do we study competition or dispersion. *Bioscience* **43**, 104-109.

Hoffman, D W; Lavy, T L (1978) Plant competition for atrazine. *Weed Science* **26**, 94-99.

Johnson, G A; Cardina, J; Mortensen, D A (1997) Site specific weed management: current and future directions. pages 131-147 In The State of Site-Specific management for Agriculture, (ASA – CSSA – SSSA, eds.) Madison, WI.

Johnson, G A; Mortensen, D A; Gotway, C A (1996) Spatial and temporal analysis of weed seedling populations using geostatistics. *Weed Science* **44**, 704-710.

Marshall, E J P (1988) Field-scale estimates of grass weed populations in arable land. *Weed Research* **28**, 191-198.

Mortensen, D A; Johnson, G A; Young, L J (1993) Weed distribution in agricultural fields. Pages 113-124 IN Soil Specific Crop Management, (ASA-CSSA-SSSA, eds.), Madison, WI.

Winkle, M E; Leavitt, J R C; Burnside, O C (1981) Effects of weed density on herbicide absorption and bioactivity. *Weed Science* **29**, 405-409.

Wyse, D Y (1996) Characterizing the Stability of Weed Seedling Populations. M.S. thesis, University of Nebraska, Lincoln, NE. 122 pp.

PATCHY WEED CONTROL IN AGRICULTURAL PRACTICE

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Field observations indicate an uneven weed distribution and a marked tendency of several weed species to form aggregated spatial patterns. Spatial weed distribution can be permanent over many years, but with changing abundance. This uneven distribution of weeds can be related to certain aspects of weed biology, to spatial variability of specific site factors and to field management. From an economic and technical point of view the observed patchy weed distribution is often above economic threshold on the whole field and the weed free areas are rather small. Sometimes weed species with low economic threshold (e.g. *Galium aparine*) are distributed over the whole field. In these cases patch spraying is not realistic.

Patch spraying is a new approach to minimize the amount of herbicides in order to reduce farmer's costs and environmental contamination. Patch spraying can be done by using different herbicides or no herbicides at all. Using variable dosages according to growth stage of weeds or soil conditions is an additional option in this concept. Patch spraying requires the solution of two basic problems: weed identification and sprayer control with high spatial precision. There are two overall concepts. One can be described as the real-time or on-line approach: A weed sensing system mounted on the tractor controls spot herbicide application in real-time. Today's technique allows us only to distinguish between photosynthetic and non-photosynthetic material. Systems which are able to distinguish between weed species or weeds and crops are not available in practice yet. Problems arise from background structure, variability of light, crop and weed development and overlapping of plants. Especially for weeds with low economic threshold a high accuracy in weed detection is necessary and it is most likely that the required hardware for the detection of weeds in real-time won't be available in the near future. Another approach is the mapping concept which includes two separate steps. The first is the generation of weed maps and the second is the weed control according to these maps. The concept requires a positioning system with high accuracy for weed location and sprayer control (e.g. Differential Global Positioning System). One of the most important questions in this concept is how to determine weed distribution quickly and economically. In the beginning of the growing season farmers usually have not enough time to walk across their fields to estimate weed species and weed distribution in a sufficient small grid. But at the moment there seems to be no other realistic possibility than weed mapping by field systematic observations. The required data for generating weed maps can be derived from actual field walking, weed maps from previous years, aerial photography, remote sensing data, monitoring of weeds during routine field work (e.g. soil management, harvesting), soil properties and farmer's experience. All these data should be recorded in a weed data base and prepared for map generation by a Geographical Information System. In the long term, herbicide application maps can be generated with less annual work for weed recording, if a basic data pool from several years is available.

A the present moment the consequences of patch spraying in the current year on weed infestation in following crops are not clear. The omission of chemical weed control on areas with weed densities below the economic threshold can result in a higher seed formation followed by a higher weed population in future crops. The objective of our studies is to determine the distribution pattern of relevant weed infestations (weed densities above economic threshold levels) on selected agricultural fields and to demonstrate patch spraying based on these weed distribution data.

In our investigations from 1994-1997 we found for grass and broadleaf weeds (> 38 species) in all cases a patchy distribution (Lloyd`s index of patchiness (PI) > 1). Often, grass weeds showed a higher PI than broadleaf weeds. The greatest PI was estimated for *Cirsium arvense* and the smallest for *Chenopodium album* and *Viola arvensis*. The aggregated areas of different broadleaved weed species were not congruent. The patches of the species were often distributed over the whole field. Consequently, the economic threshold was exceeded on the whole field and a overall herbicide application became necessary.

In cases where less than 10 % of the field have weed densities above thresholds, patch spraying from an economic and technical point of view is not practical. Based on weed distribution application maps for herbicide use were generated. The spray area must be greater than weed patches to have security zones around the weeds in order to avoid misapplication caused e.g. by inaccuracy of positioning. Case studies showed that patch spraying according to weed maps is possible by using conventional sprayer technique. A comparison of treated and total field area gives an impression on the potential of herbicide reduction. The success of patch spraying was estimated by monitoring weed densities in the growing period until harvest.

From our results it can be concluded that the potential for herbicide reduction by patch spraying is greater for grass weeds than for broadleaf weeds. Our results showed potential savings of herbicide use ranging from 0 to 80 %. In further investigations it should be clarified under which conditions (field size, distribution pattern of relevant weed infestations, weed densities above economic threshold levels, monetary loss due to weed competition, costs and benefits of patch spraying) patchy weed control can be successfully integrated in precision farming. But an overall short-term success of this concept with a substantial economical benefit to the farmers cannot be expected. Nevertheless, under specific circumstances patch spraying will in the long run reduce costs and can contribute to a more sustainable agriculture.

CONCLUSIONS

- There is a marked tendency of weed species to occur in patches.
- Based on geostatistical methods weed maps can be created for agricultural fields.
- For both environmental and economic aspects, patch spraying seems to be a successful way of reducing herbicide use.
- In future, the patch spraying concept will become more important in agricultural practice.

For further reading

Nordmeyer H; Häusler A; Niemann P (In press). Patchy weed control as an approach in precision farming. *Proceedings 1st European Conference on Precision Agriculture*, Warwick.

Nordmeyer H; Häusler A; Niemann P (1996) Weed mapping as a tool for patchy weed control. *Proceedings Second International Weed Control Congress*, pp. 119-124, IWCC, Copenhagen.

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 Second International Weed Control Congress*, pp. 1103-1108, IWCC, Copenhagen.