Session 8B

Patchy Distribution of Weeds - Ecological Problem and Agronomic Opportunity

Chairman	Mr M J May
Session Organiser	Mr G W Cussans
Papers	8B-1 to 8B-4

PATCH ECOLOGY AND DYNAMICS - HOW MUCH DO WE KNOW?

REW L J & CUSSANS G W, IACR - Rothamsted, Harpenden, Herts., AL5 2JQ

ABSTRACT

The distribution of arable weeds is patchy, and many patches appear to be more or less stable. Factors that effect the stability of weed patches, such as natural dissemination, soil cultivation, combine harvesting, herbicides, seed persistence and predation are reviewed. In general the vast majority of seeds remain close to the source (<2 m) and such small scale movement is predictable to a reasonable level of accuracy. However, movement of a small minority of seed over far greater distances is more difficult to quantify, but may provide the genesis of a new population. Simulation and predictive models are needed to assist our understanding of patch ecology and dynamics.

INTRODUCTION

In the past, the aggregated distribution of weeds has largely been ignored by researchers and farmers, who have chosen to assume that weed distribution is uniform or regular. However, it is generally accepted that weed distribution is patchy, or aggregated, and more researchers are currently addressing spatial heterogeneity. Patchy distribution of grass weeds at field scale has been recorded (Marshall, 1988; Rew *et al.*, in press). Furthermore, Wilson & Brian (1991) mapped the distribution of *Alopecurus myosuroides* L. on seventeen fields and recorded a patchy distribution that remained generally stable over ten years.

The lack of work addressing the spatial distribution of arable plants is probably a result of past emphasis on greater crop yield and profitability. Herbicides were relatively cheap and it was considered more important to understand herbicide activity, and sometimes the physiology and life cycle of the target species, rather than the ecology of the agroecosystem. Currently, the emphasis is changing towards more precisely targeted agrochemicals, both in terms of choice and application, due to changes in the world market; development of resistance to particular chemical groups; increasing problems with pesticide residues and nitrogen leaching amongst other things.

The move towards precision agriculture, in terms of tailoring input requirements to individual fields must be matched with an understanding of how and why such spatial heterogeneity exists and persists. Agricultural practices are intended to ensure homogeneity and yet we observe patchy weed distribution despite years of uniform treatment, although many patches appear to be more or less stable. Why? What causes weeds to occur in patches that then appear to be stable?

Density dependence should ensure that seed (or rhizome) production per plant is least in the densely populated centres of patches, and greatest at the edges where plants are at low densities. Thus, old patches should spread from the edges and new patches develop. However, the general stability of patches suggests that other factors are involved. The small scale movement of the majority of seeds by different agricultural practices can be quantified with a reasonable level of accuracy. Other factors are more difficult to quantify, such as: lodging of seeds on agricultural machinery, and the distance they are transported before being dislodged; the predation rate of seeds in arable ecosystems; if herbicides are more or less likely to kill a plant standing alone, or in a patch of many plants; how far apart individual obligate out-breeders, such as *A. myosuroides*, can be before pollination and fertilization is unlikely. Knowledge and quantification of all such factors is integral to the understanding of patch dynamics.

Natural seed dissemination

Primary dissemination of arable species with no specialized dissemination structure is generally limited (Verkaar *et al.*, 1983; Blattner & Kadereit 1991). Studies on *Bromus* spp. (Howard *et al.*, 1991) and *B. sterilis* and *Anthriscus sylvestris* (Rew, 1993) have shown that the majority (^90%) of seeds disseminate within 1 m of the parent plant.

Movement by cultivations

Studies on vertical movement of seeds in the soil, have shown that seed distribution is not uniform throughout the soil profile (Soriano *et al.*, 1968; Froud-Williams, 1983). Ploughing has been observed to incorporate seeds deeper into the soil than tine cultivation (Moss, 1988). Such information has important implications for weed control. Species with short-lived (short persistence) seeds e.g. *Bromus* spp. can be controlled by ploughing, which buries the seeds too deeply for successful seedling emergence and survival (Froud-Williams *et al.*, 1980) with the possible exception of *B. diandrus* (NCB Peters, pers. comm.)

Horizontal movement of seeds by cultivators obviously has important implications for seed spread and the potential for new weed infestations. Experiments designed to investigate this have found low levels of movement (< 1 m) by cultivators (Fogelfors, 1985; Howard *et al.*, 1991). EJP Marshall & P Brain (pers. comm.), used plastic beads to simulate seeds and found the majority of beads remained within 2 m of a 1 m^{-2} source area following tine, harrow and seed drill, although some individuals were observed up to 15 m away. Our own unpublished studies investigated the movement of three different sized seeds, when subject to one pass with tine or plough, followed by harrow and seed drill. Although smaller seeds (oilseed rape) moved significantly further than larger seeds (beans), approximately 90% of all seeds remained within 1 m of their start point. Two passes with a tine cultivator, harrow and seed drill, all in same direction, reduced this to approximately 80% within 1 m. For no treatment were seeds observed more than 3.5 m in forward direction or 0.2 m backwards (Figure 1). From such data estimates on the shape of the distribution curve and the movement of a "front" (the furthest 2.5, 1 % etc.) can be made and included in dispersal models.

Fields are often entered from the same point and have one axis longer and straighter than the others, it is therefore likely that the first cultivation would run in the same direction in successive years, thus spreading the seeds. However, if two tine cultivations are performed consecutively, it is possible that the second cultivation would run in the opposite direction (the driver starts the second run where the first was finished) or at 90 degrees. Either practice would restrict the spread of weed patches. Farmers who alternated the end of the field in which cultivation commenced between and within years, would further restrict seed spread and stabilize or retain patch morphology.

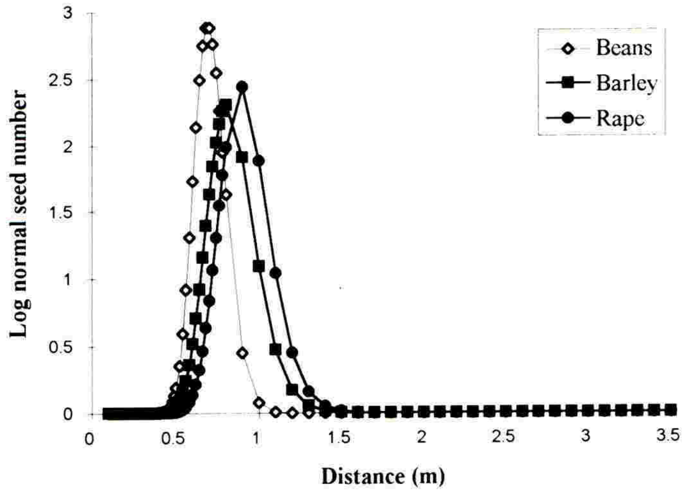

Figure 1. Distribution curve of seeds following cultivation with tine or plough, power harrow and seed drill. Data fitted to log normal distribution.

Not all seeds will be moved with the main bulk of the soil. Some seeds will become lodged on parts of the machinery to be dislodged later, either in the same field or possibly in another. Hofmeester (1990) found that the amount of soil on machinery was in a steady state, due to exchange between fresh soil from the field and soil on the machine. Further work is required, as the movement of a few seeds may have more important ecological implications than the movement of the majority, as they could be the genesis of new populations.

Movement by combine harvesters

The percentage of weed seeds left on plants at the time of cereal harvest is generally small. More seeds will be left on plants in crops harvested early in the summer, such as winter barley than in later harvested crops. Moss (1983) recorded <5% *A. myosuroides* remaining at harvest in winter wheat, although two winter barley fields had shed only 50% prior to harvest. At Rothamsted in 1994, 7% of *A. myosuroides* seeds remained on the panicles in winter barley compared with less than 3% in winter wheat.

Howard *et al.* (1991) investigated the dispersal distance of *B. sterilis* and *B. interruptus* seed with a small Claas Compact combine. Painted seeds were added to the auger at set intervals. Volumetric grain samples were taken from material about to enter the storage tank. The swath containing the painted seeds was deposited on to a polythene sheet and hand sorted. The data fitted a Gaussian distribution, with mean distance 1.9 m behind point of introduction, with a maximum distance of 20 m. However, the combine was driven at 1.75 km hr^{-1}, a more normal combine speed would be 7-8 km hr^{-1}, thus moving the mean distance closer to the point of entry and also increasing the length of the distribution tail. Seed size and shape affected the quantity of seed recorded in the grain with two times more *B. sterilis* seeds recorded than *B. interruptus*, 34 and 15% respectively. The potential of combine harvesters for long distance movement has also been recorded by other researchers (Ballaré *et al.*, 1987; McCanny & Cavers 1988).

Our experiment investigated the movement of *A. myosuroides* seed from 10 X 10 m plots by a Claas combine harvester (5 m cutter bar). In two plots the area beneath the swath was removed with a vacuum cleaner and the resulting samples sorted and germinated. The remaining plots (6) were cultivated (the same direction as combining) and seedlings counted the following spring (Figure 2). 80 and 72% of seedlings respectively, remained within the original plot, although individuals were observed up to 50 m away.

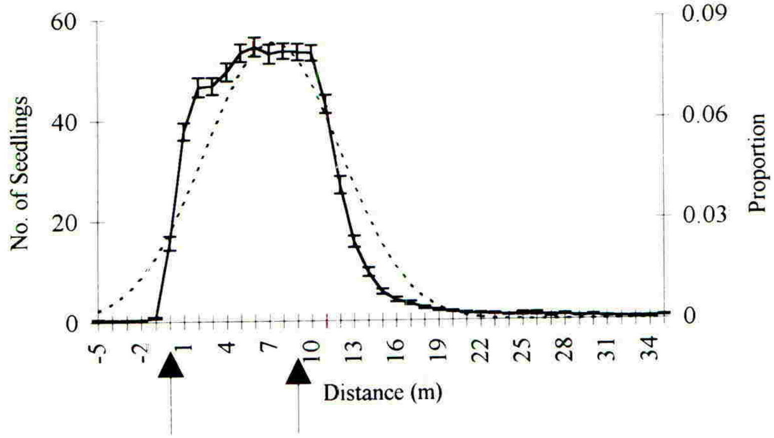

Figure 2. Distribution of *A. myosuroides* seedling following combine harvesting and cultivations, all in the same direction. Arrows indicate 10 m wide source plot. ---- Data fitted a normal distribution.

The possible role of herbicides

Crop/weed interactions and their effect on crop yield, and the cost effectiveness of herbicide control has been well researched. Competition generally acts to complement the function of herbicides, although there are circumstances where density dependent relationships have been observed (Courtney, 1994). The relationship between weed density and crop yield depends on many different factors, including crop density, species composition, soil type, site, weather and herbicide efficacy.

It has been suggested that herbicide efficacy could be reduced with increased weed and crop density due to either competition for soil acting herbicides, or reduced interception of foliar acting herbicides. However, an experiment investigating weed control and crop biomass responses of spring barley and oilseed rape, sown at a range of densities, showed that herbicide efficacy remained constant at all densities (Courtney, 1994).

Species tolerance in terms of herbicide competition has also been observed. Tom (see Courtney, 1994) investigated the herbicide tolerance of various species at different densities, albeit in sand culture. He observed that the species more susceptible to herbicide at low doses showed increased tolerance with increased weed density. Although, conflicting results were observed in two field experiments in Sudan (Tom & Courtney, 1993). In addition, Tom (see Courtney, 1994) observed no difference in the subsequent growth of surviving plants. However, seedling growth and recovery at lower herbicide application rates was favoured by low densities and reduced intra-specific competition. This may have implications for reduced herbicide regimes, and could play a role in herbicide resistance.

Herbicide resistance to one or more chemicals has been recorded in at least 25 annual grass species worldwide. Resistant *A. myosuroides* populations have been recorded in 23 counties of England, and in a small number of *Avena sterilis* spp. *ludoviciana* populations. Some of the *A. myosuroides* populations are resistant to a specific group of chemicals, whereas most show cross resistance to several different chemical classes (Moss, 1990). Similar multiple-resistance patterns have been observed in populations of *Lolium rigidum* in Australia (Hall *et al.*, 1994). Resistance affecting a wide range of herbicide classes is, obviously of great concern, and may be due at least partly to the presence of multiple mechanisms of resistance. In the absence of reliable and cost effective chemical control of such weeds in crops farmers will be forced to change their management strategy, and use other cultural techniques such as sowing date, crop rotations and tillage regime to control their weeds (Moss, 1995).

More information is needed on the interactions between evolution of resistance and spatial ecology. In most cases evolution appears to have been by "parallel evolution" rather than by spread from a single source and thus, influenced only in a general way by the spatial dynamics of the weed. However, it seems intuitively reasonable to suppose that resistance conferred by "rarer" mutations would spread by "founder effect evolution".

Pollen viability and dispersal curve

Few studies have reported on the period of time for which pollen is viable and the shape and length of the dispersal curve, although predictions can be made from work on fungal spore dispersal. The shape of the dispersal curve is obviously most important for obligate out-breeders. It is possible that although the dispersal curve of the majority of the pollen is short, the minority move a considerable distance, and there are sufficient weed populations in major arable areas to create a low background level of pollen.

Mulugeta *et al.* (1994) collected 50% of *Kochia scoparia* pollen within 1.4 m of the source, and estimated that 99.9% would be deposited within 154.4 m. Our experiments designed to measure the flow of *A. myosuroides* pollen from a point source, collected 50% of pollen within 2 m then levelled out at approximately 5% between 8 and 32 m. This was a preliminary study and further experiments have been planned.

Viability of *K. scoparia* pollen was observed to range from 1 -12 days (Mulugeta *et al.*, 1994). Initial work on *A. myosuroides* pollen viability has failed to provide a conclusive answer (JL Rhoden, unpublished data).

Seed persistence

The spatial pattern of seeds in the soil is a result of dispersal processes: natural dissemination, agricultural machinery and animals. The spatial pattern may also be influenced by the persistence of seeds in the soil. Species such as *A. myosuroides*, *B. sterilis* and *Galium aparine* have short seed persistence and most seeds germinate in the first year; seeds of other species such as *Papaver rhoeas*, *Aethusa cynapium*, *Chenopodium album* and *Sinapsis arvensis* persist much longer.

It seems possible that species with short seed persistence, where a high proportion of the population is derived from seed of recent origin, could show a stronger tendency to aggregation than seed with longer persistence, which have a greater chance of being moved away from the original source. However, Dessiant *et al.*, (1991) observed patchy or clustered distribution of 17 arable weed species, in the soil seed bank, with both short and long seed persistence. They observed two different types of aggregation which was due to biological and agricultural factors, rather than seed persistence; albeit that the sample area was small (300 soil samples on 7.5 x 10 m area).

Seed predation

A large proportion of seeds are "lost" in the first few months after shedding. Moss (1980) recorded only 32% of viable seed remaining after 10 weeks in a winter wheat crop. Some of the loss was accounted for by seed germination but the majority was attributed to seed predation and fungal attack.

Polyphagous beetles (*Amara* and *Harpalus* spp.) show some form of foraging strategy, they are attracted to areas (25cm^{-2}) of high seed density and show seed preferences (DA Kendall, pers. comm.). If such small scale location of seed clusters is possible it could suggest that small areas of seed (eg. an individual plant's seed) would be located as frequently as a large patch. If the same feeding rate occurred regardless of patch size, the chance of a small patch being eaten is greater than a large patch due to quantity of seeds. This would act to stabilize large patches.

Modelling the ecology of weed patches

Many of the earlier crop-weed threshold models assumed spatial homogeneity and ignored spatial heterogeneity or patchiness of weed distributions (van Groenendael, 1988).

The spatial distribution of weeds can have a substantial effect on the calculated economic weed threshold, as the yield loss incurred from a dense patch of weed in a small area of the field would cause less yield reduction than the same number of plants distributed uniformly over the whole field. Thus, spatial parameters should be incorporated into models to allow for this (Brain & Cousens, 1990; Thornton *et al.*, 1990).

Schippers *et al.*, (1993) incorporated demographic processes and agricultural operations into his spatial model of *Cyperus esculentus* tubers, at field level. Farming operations were responsible for the majority of movement. Validating such models with actual field data is important. Some models have suggested that patches are not stable in time. However, sampling over a ten year period at a mixed farm in Oxfordshire showed otherwise, albeit only on *A. myosuroides* (Wilson & Brain (1991). Furthermore, our work mapping the spatial distribution of five cereal fields infested with *Elymus repens* showed (as would be expected) that there is no easily defined pattern (Rew *et al.*, in press) nor with *A. myosuroides, Avena fatua* or *L. multiflorum* (LJ Rew, unpublished). This is presumably because of the vastly different management histories and soil characteristics of fields. Therefore, in order to predict movement or fluctuations of patches within a field, each field would need to be mapped individually, either by sampling the whole field (Rew *et al.*, in press) or part of it using in a grid system (Mortensen *et al.*, 1993;).

Mortensen *et al.*, (1993) created a spatial map of weed distribution using a interpolation technique, kriging, to estimate the weed population between the sampled points. The same sampling technique was then used by Johnson *et al.*, (1995) to provide spatial distribution data in order to evaluate potential herbicide savings.

This apparent anomoly between models suggesting patches are not stable, while observations suggest the opposite could be explained by two different hypotheses: density dependence and continuous distribution of weeds over space or, by a stationary stochastic spatially discrete distribution. In order for the first hypothesis to achieve stable patches it would have to be assumed that the relative growth rate of the population is lower at low densities, providing an advantage for weeds within the old patch rather than those in a new patch or at the edge of an established patch. The second hypothesis does not assume continuous distribution. A probability is given for a seed to disperse outside a patch, and a probability for the seed being eaten, or seedling killed. Thus, the few small patches have a much greater chance of being eaten/killed than those in the original patch, due to the larger number of seeds that fall within the original patch (J Wallinga, pers. comm.). Using the latter theory Wallinga, (1995, and submitted) has shown that weed distributions are clustered and the position of the clusters are relatively stable over time.

CONCLUSION

Weeds do not occur uniformly or randomly, they appear in aggregations or patches (Marshall, 1988; Wilson & Brain, 1991; Mortensen *et al.*, 1993; Rew *et al.*, in press). The majority of movement by natural dissemination and cultivation moves seed less than 1 m. This type of movement can be seen as classic "phalanx spread" (Lovett-Doust, 1981), because the mean movement distance is short and the leading edge or "front" is small. In contrast, "guerilla spread" is caused by the small percentage of seeds that are moved unpredictable distances, whether by the combine, on machinery or by animals. The moving front of guerilla spread is difficult to quantify, but long distance combine movement has been recorded (Ballaré *et al.*, 1987; McCanny & Cavers, 1988; Howard *et al.*, 1991).

Phalanx spread is quantifiable and therefore can be incorporated into spatial and population models (Schippers *et al.*, 1993). Many factors that could be termed as guerilla spread are difficult to quantify. Although, only a very small percentage of the total seeds have the potential to be affected by guerilla movement, the implications of one seed starting a new population are important. However, it may be that after further investigations on guerilla spread some of the factors require a "weighting risk" when included in a comprehensive spatial model. For example Moss (1983) observed that *A. myosuroides* seed viability tended to be lower at the beginning and end of the shedding period. Thus seed dispersed by the combine, at the end of the shedding period, may have lower viability and therefore a lower chance of germinating and creating a new patch.

More research is required to understand patch ecology and dynamics because it is such an important element of weed ecology, as well as having important implications for the future of agriculture. The financial pressures exerted on the farming community are unlikely to diminish, and the problem of herbicide resistance will continue, along with increasing public sector concern over environmental issues such as pesticide contamination to water courses. Thus, there may be clear advantages in reducing herbicide applications by patch spraying, regardless of economics. However, the approach would gain support more quickly if the price of herbicides increased relative to the crop value.

Weed distribution is currently patchy despite years of uniform overall treatment. However, do we really know what will happen if we start spraying only the patches? Several studies have shown that there could be considerable herbicide savings from patch spraying. Johnson *et al.*, (1995) studied weed distribution in 12 Nebraskan fields and found 30% of interrow areas free of broadleaved weeds and 70% free of grass weeds. It was calculated that real-time spraying would reduce herbicide use by 30-72% if discrimination between plant species within the row was possible. A study of five fields in England, found between 3 and 79% of fields infested with *E. repens*. Patch spraying using these historic maps provided considerable herbicide savings (27-95%) even with the inclusion of "buffer areas" around the data to allow to navigation error and movement by agricultural practices (Rew *et al.*, in press).

At best spraying only the patches, with "buffer areas" to allow for predictable phalanx movement, would allow the slow development of new patches; at worst it could lead to a more homogeneous weed distribution. Although the latter scenario is unlikely it does emphasize that we must increase our understanding of the patch ecology and dynamics in order to be able to predict and therefore manipulate the system effectively.

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EXPANDING ECONOMIC THRESHOLDS BY INCLUDING SPATIAL AND TEMPORAL WEED DYNAMICS

B. D. MAXWELL & C. T. COLLIVER
Plant, Soil & Environmental Sciences Dept., Montana State University, Bozeman, MT, USA, 59717

ABSTRACT

Our ability to predict weed population temporal dynamics has improved through detailed demographic studies. The result of these studies has been the evolution of the concept of economic density thresholds to consider the future impact of weeds by creating models that predict the temporal dynamics of weeds. However, the models rarely consider the spatial component of weed population dynamics and therefore may underestimate density thresholds for weed control if weed distribution is aggregated within fields. Weed management is currently being refined with the ability to spatially locate weeds. Simulations indicated that profit maximization occurs when using site specific weed density thresholds rather than whole field thresholds. The simulation results also indicated that very low density thresholds generally had higher economic returns when using site specific thresholds, whereas the opposite was true for whole field thresholds.

INTRODUCTION

The concept of economic density thresholds has evolved to consider the future impact of weeds by developing models that predict weed population dynamics over time. However, the models rarely consider the spatial component of weed population dynamics and therefore may under estimate density thresholds for weed control if weed distribution is aggregated within fields. It is, therefore, critical to examine several questions: 1) Are weeds aggregated? 2) How can aggregation be quantified? 3) What are the spatial dynamics of weed patches? 4) What are the factors that regulate weed patch spatial dynamics? 5) How can an understanding of weed population spatial and temporal dynamics be used to refine weed management strategies? The objective of this paper is to examine these questions from a theoretical perspective using a partially validated simulation model and some limited data on spatial distribution of wild-oats (*Avena fatua*).

Most weed species have been observed to be patchy in fields, however there are few examples of quantification of aggregation (Marshall, 1988). Auld and Tisdell (1987) and Thornton *et al.* (1989) demonstrated that there can be a significant impact of weed patchiness on crop yield loss estimation. The negative binomial distribution function was used to characterize the spatial distribution of weed densities in fields (Brain and Cousens, 1989; Wiles *et al.*, 1992; Mortensen *et al.*, 1993). The magnitude of a single parameter (k) in the negative binomial distribution function can be used to quantify the degree of aggregation (patchiness) of the weed population and can be related to the economic impact of aggregation (Wiles *et al.*, 1992). Cardina *et al.* (1995) provided a review of "classical" statistic techniques including Lloyd's Mean Crowding Statistic (Lloyd, 1967), Patchiness Index and Index of Dispersion (Ludwig and Reynolds, 1988) that can be used to characterize the degree of weed aggregation where the dependent variable is weed density. These quantifications of weed patchiness do not facilitateor do not result in weed density maps which are critical for predicting spatial population dynamics and subsequent long-term thresholds (Cardina *et al.*, 1995; Maxwell, 1992).

Two widely used statistical techniques, semivariogram analysis and trend analysis, have emerged as useful techniques for detecting within patch variability and direction specific patterns while retaining the ability to create weed density maps that can be used for management (Mortensen *et al.*, 1993; Donald, 1994; Colliver and Maxwell, 1995). Cardina *et al.* (1995) provided a clear explanation of the assumptions and utility of these spatial statistic approaches applied to weed populations. These statistical approaches will be useful in the design of future site specific management strategies and development of long-term economic optimum weed density thresholds. However, these characterizations will require concurrent research to develop a more complete understanding of the mechanisms that govern weed spatial dynamics (Maxwell, 1992).

MATERIALS AND METHODS

A simulation model for a small grain production field recently infested with a wild-oat (*Avena fatua*) population was constructed to examine the relative importance of weed seed dispersal versus environmental heterogeneity in determining weed patch spatial dynamics (Maxwell, 1995).

The simulated field is 18 m wide and 22 m long and includes 3 strips, each 6 m wide representing the path (width) of machine movement. The small field size is a study constraint that increased the efficiency of simulation time. The simulated period was held to a maximum of 10 years to reduce the edge influence on the results. Tillage, weed control and combine machines move along the same direction and over the same strip every year in the simulated field. The simulated field is divided into a grid forming map units that are 400 cm^2 (20 cm X 20 cm). Each map unit is modelled as an independent weed (Nw) and crop population, where the weed population density follows logistic growth:

$$Nw_{t+1} = Nw_t e^{r(1-Nwt/K)}$$

where Nw_{t+1} is the weed population in the next generation (year), Nw_t is the current generation (t), K is the maximum potential weed density and r is the population growth rate. Population growth rate (r) was assumed to vary across the field at a scale and pattern similar to weed patchiness if only natural dispersal was allowed to occur. This was an arbitrary assumption, but other patterns of weed growth rates at a range of scales produced no significant impact on the simulation results. Population growth rate can also be set to vary randomly over time in a normal distribution around the spatially specific growth rate r with a standard deviation of 30% of r. Varying r over time simulates variability in the environment (climate, biotic variables, etc.) and establishes a Monte

Carlo simulation. The simulations considered in this paper do not include temporal variability in r.

The impact of the weed (Nw) and crop density (Nc) on the crop yield (Yc) was incorporated into the model using an equation adapted from Cousens (1985);

$$Yc = Yc_{max}[Nc/(1 + Nc + \alpha\ Nw)]$$

where Yc_{max} is the maximum potential yield in kg/ha, and α is an equivalence ratio or competition coefficient.

Migration of weed seed between grid map units with coordinates x and y to surrounding map units with relative coordinates was assumed to occur by cultivation with a disc prior to planting the crop and through the combine at harvest time. Both machines were assumed to be 6m wide. Distribution of seed from a given map unit (x,y) to surrounding map units defined by opposite corners of a rectangular area on the field map with relative location of x-2,y to x+2, y+4 following the disc operation was based on the following three-dimensional probability distribution:

$$p_x = \begin{cases} 1/[SQR(2 * \pi) * s_t] * EXP[-.5 * (i/s_t)^2] \\ \text{for } i = x-2 \text{ to } x+2 \end{cases}$$

$$p_t = \begin{cases} (p_x - p_x/de * y) * q_t \\ \text{for } j = y \text{ to } y+4 \end{cases}$$

$$Nw_{t,i,j} = (p_t * Nw_{t-1,x,y}) + N_{t-1,\ i,j}$$

where p_x is the proportion of seed that will be dispersed in the x-direction normal distribution, s_t (0.444) is the variance in the distribution in the x-direction, de (3.9324) is distance (map units) in y-direction, q_t (0.613) is the maximum proportion in the y-direction distribution at a given x value. The parameter p_t is the combined x and y-direction proportion (probability) of seed moving to cells adjacent to x,y. The number of weed seed in the adjacent cells $Nw_{t,i,j}$ at time t (after tillage operation) with coordinates of i and j, is then calculated as the product of the probability p_t and the number of seed in the map unit $Nw_{t-1,x,y}$ added to the seed that were already present in $Nw_{t-1,i,j}$. Parameter values were estimated by fitting to data from observations of seed surrogate distribution as a result of a disc operations (Lindquist and Maxwell, 1991).

Distribution of seed as a result of a combine operation was based on: 1) the proportion of seed picked up by the machine (p_{up}), 2) the proportion of seed that gets partitioned into the bin with the crop (p_{in}), and 3) the probability of distribution to surrounding map units p_c, so that the amount of weed seed ready for distribution back on to the field by the combine (Nw_{tot}) is calculated as follows:

$$Nw_{tot} = \begin{cases} (\Sigma Nw_{x,y}) * p_{up} * (1 - p_{in}) \\ \text{for } x = 1 \text{ to } 30 \end{cases}$$

The distribution of the seed from the combine is calculated as a 3 dimensional probability distribution similar to the disc operation, where a proportion of the seed, Nw_{tot}, goes to cells adjacent to their origin from a mid point in the x-direction (m) perpendicular to combine movement. The y-direction (same direction as combine movement) proportion, in this case is based on a Poisson distribution and is combined with an x-direction normal probability distribution function as follows:

$$p_y = \begin{cases} [\lambda^z * EXP(-\lambda)]/y_{sum} \\ \text{for } y = ys \text{ to } ys + dp\text{-}1 \end{cases}$$

where ys (the starting y-position of seed distribution behind the combine) is $j - \lambda$, and j is the y-direction position of the combine and λ is an integer that is 30% of the maximum seed distribution distance from the combine (dp). The parameter z is the number of map units from the start of distribution to the y-position of the combine as it moves over the grid. The y_{sum} parameter was used to identify the y-position in the Poisson probability distribution and is calculated as the sum of the previous $y_{sum} * z$. The x-direction portion of the probability distribution is calculated and combined with the y-direction probability distribution as follows:

$$p_x = \begin{cases} 1/[SQR(2\pi)*s_c] * EXP[-0.5*((x - m)/s_c)^2] \\ \text{for } x = 1 \text{ to } 30 \end{cases}$$

$$p_c = p_y * p_x$$

$$Nw_{t,i,j} = (p_c * Nw_{tot}) + Nw_{t-1,x,y}$$

where s_c is the variance of the normal distribution in the x-direction, and $Nw_{t,i,j}$ is weed seed from the combine that is added to the previous amount of seed $Nw_{t-1,x,y}$ in a map unit adjacent to the origin of the seed.

Annualized net return (ANR) in units of $US/ha was calculated based on weed free or maximum potential yield, yield loss due to weed density, crop price, herbicide and application cost and crop production costs not associated with weed control, as described by Lindquist *et al.* (1995).

Two weed distributions were used as starting conditions for simulations. The first distribution was an arbitrary assignment of 20 seeds to each of 6 map units widely dispersed over the map. The first distribution simulated a field at the time of introduction of wild-oats and the second was a high infestation segment of a dryland barley field where wild-oats were mapped in 1994.

RESULTS AND DISCUSSION

Two sets of simulations were conducted to determine the economic advantage or disadvantage of site specific weed management over a ten year period where there were spatially variable weed population growth rates. Two management options were compared based on the ANR that resulted from weed management decision rules based on determining weed density thresholds at the whole field scale or the weed patch scale. In addition to identification of thresholds at the two different scales, herbicide application for weed control was either applied at the whole field or patch scale in response to the identified threshold at the coinciding scale. The first set of simulations were based on a new invasion initial weed distribution, and the weed population was allowed to grow without management until it exceeded the threshold.

The maximum ANR that resulted from continuous use (over 10 years) of a weed management decision rule based on a whole field threshold of approximately 10 wild-oat plants/m^2 was \$24.15/ha (Figure 1). The maximum ANR from using the patch threshold decision rule with the same initial conditions was \$41.96/ha which was a 174% increase in dollar return. The profit was maximized with the patch decision rule and herbicide application approach at threshold densities between 2 and 8 plants/m^2.

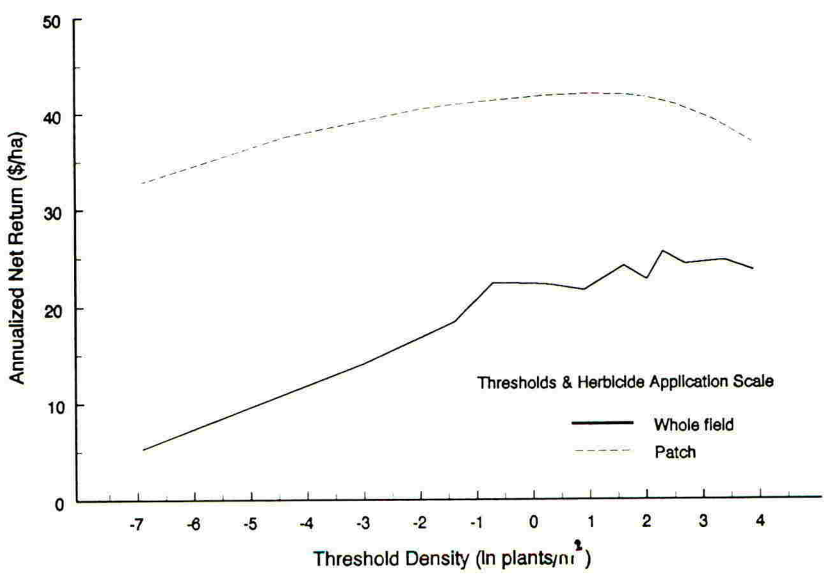

Figure 1. Simulated ANR for a 10 year period for two different decision rules and herbicide application approaches based on thresholds (natural log of weed density) identified at different scales when the initial weed distribution is a new infestation.

The second set of simulations compared the whole field and patch threshold decision rules and herbicide application approaches when the initial weed distribution was an actual high infestation. In this case, the maximum ANR for the whole field threshold decision rule was $11.19 /ha, and the patch threshold decision rule was $27.87/ha (Figure 2). The profit maximizing threshold was again approximately 5 wild-oat plants/m^2 at both scales and the economic advantage of managing at the patch rather than whole field scale was more than 2 fold.

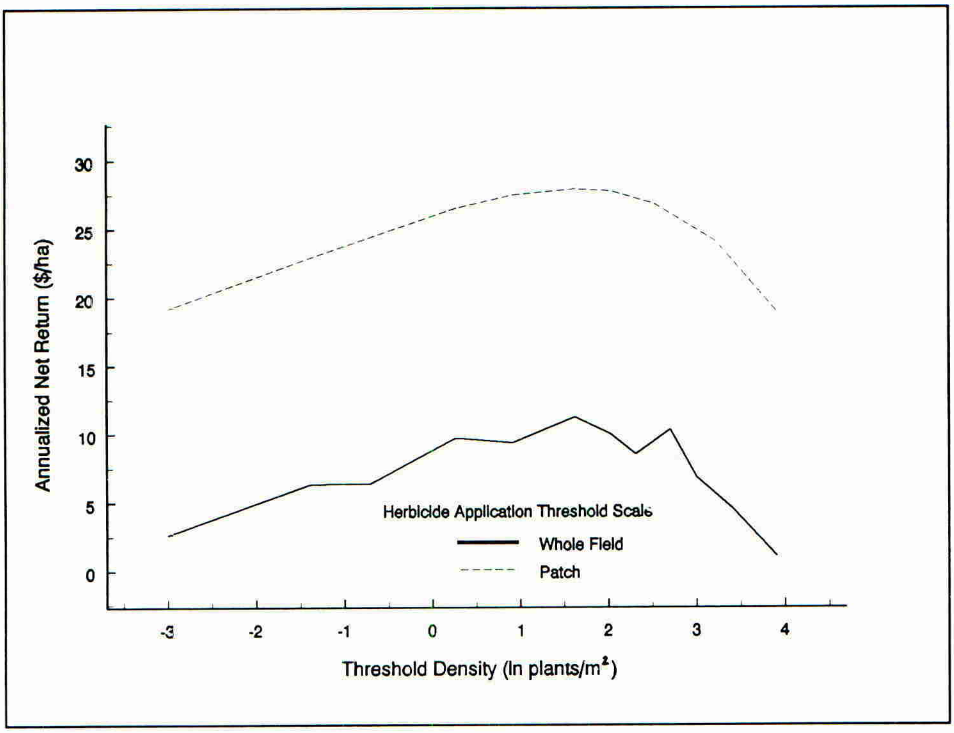

Figure 2. Simulated ANR for a 10 year period for two different decision rules based on thresholds (natural log of weed density) identified at different scales when the initial weed distribution was an observed high density infestation of wild-oats.

The economic advantage of using a patch scale threshold decision rule primarily comes from reduction of herbicide cost for controlling weeds. This advantage is therefore accompanied by the environmental advantage associated with reduced pesticide use. The simulations also provide insight into the interactions between weed threshold determination, spatial and temporal dynamics. Prediction of weed population spatial dynamics is crucial for development of economic and environmentally optimum management strategies that support sustainable agricultural production.

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THE PATCH SPRAYING OF HERBICIDES IN ARABLE CROPS

P C H MILLER; J V STAFFORD; M E R PAICE
Silsoe Research Institute, Wrest Park, Silsoe, Bedford, MK45 4HS

L J REW
Institute of Arable Crops Research - Rothamsted, Harpenden, Herts, AL5 2JQ

ABSTRACT

Spatially selective spraying systems for applying herbicides to mapped weed patches at variable dose rates and/or using different herbicide mixtures across the field have the potential to give substantial financial and environmental benefits. Approaches to weed patch detection, treatment map generation and sprayer control are reviewed with particular reference to an experimental sprayer using injection metering control. This system has been developed and used successfully in field trials with a range of commercially formulated herbicides. Results from detailed studies with the system have shown that it is able to deliver a constant dose rate within a tolerance of ± 5% over a total turn-down ratio of more than 20:1 for a single pump unit and that dynamically, the system can adjust to a 100% change in concentrate formulation flow demand in less than 0.5 s.

INTRODUCTION

The recent development of techniques for determining in-field location with reasonable reliability and accuracy has provided the ability to monitor and adjust the inputs to arable crops on a spatially variable basis rather than treating whole field areas uniformly. Systems for generating yield maps from combine harvesters are now available commercially and methods of using this yield map information as the basis for management decisions and the adjustment of key inputs to arable crops are currently being investigated.

The application of herbicides is one of the input systems that has the potential to give substantial financial and environmental benefits from such a spatially variable, "Precision Farming" approach (Rew *et al.*, 1995). This is because :

(i) there is evidence to show that the distribution of many weed species, particularly grass weeds in cereal crops, are patchy and that the patches are relatively stable over a number of growing seasons; and

(ii) given a map of weed species composition and population density(ies), a structured treatment map can be generated accounting for the competitive effect of weeds on crop yield and the response of weeds to different applied herbicide doses. The treatment map will specify the herbicide active ingredient (or mixture) to be applied and the dose rates for optimum response.

Wilson and Brain (1990) reported that, over a ten year period, blackgrass (*Alopecurus myosuroides*) grew in well defined patches on a commercially operated farm. The patches were stable and there was little evidence of new patches forming under conventional herbicide treatments. Marshall (1988) found that three grass species - barren brome (*Bromus sterilis*), common couch (*Elymus repens*) and meadow brome (*Bromus commutatus*) grew in definite patches within a wheat crop.

Weed density has a direct effect on crop yield with the magnitude of the yield reduction dependant upon species. Wilson (1989) reported that wild oats (*Avana fatua*) and mayweed (*Matricaria spp*) cause a 2% reduction in yield in cereal crops at densities as low as 1 to 2 plants/m^2 whereas other weeds such as red dead nettle (*Lamium purpureum*) and field pansy (*Viola arvensis*) only give substantial yield losses at weed densities of above 20 plants/m^2.

APPROACHES TO PATCH SPRAYING

One possible approach to patch spraying is to detect the weeds at the time of spraying using an appropriate sensor on the sprayer/spraying vehicle and to use a direct link to the control of sprayer output. Such a sensor would need to be able to distinguish between weeds and crop as well as between weeds and soil. Thompson *et al.* (1991), reviewed the possible methods for distinguishing weed from crop in arable situations and concluded that it was not practical with current technologies to design a spraying system based on such a real time automatic weed detection approach (see discussion of weed detection below). The use of a map-based sprayer control system was therefore proposed and this concept is described by Miller and Stafford (1991). It provides the ability to:

(a) detect weed patch positions over the growing season and particularly to undertake the weed detection operation when weed/crop conditions are favourable to discrimination between weed and crop;

(b) edit the weed map to create a treatment map which can be used as the basis for controlling the sprayer.

The treatment map will specify the dose rate and mixture of herbicides to be applied to each unit area of the field. The transformation of a weed map to a treatment map enables:

(i) margins or buffers to be added if necessary to account for:

 (a) field location errors while mapping;
 (b) field location errors while spraying;
 (c) errors or uncertainty while mapping weed patches; and
 (d) delays in the sprayer response;

(ii) an input relating to the specification of dose rates and mixtures of herbicides to be used based on information relating to the competitive effect of the weed and the likely response to the herbicide.

It is recognised that there is an interaction between the performance of the weed patch detection systems and the strategies to be employed for controlling the sprayer. If, for example, the weed patch detection system is capable of providing accurate and reliable data based on detailed high resolution surveying techniques, then it may be appropriate to turn the sprayer off completely in areas of the field where no weeds have been mapped. If for practical means, a weed map is generated with a lower level of confidence in respect of absolute accuracy and resolution, then it may be appropriate to treat patch areas with a relatively high dose of herbicide or mixture and apply a base insurance dose of herbicide or a lower cost active ingredient over the whole of the field area. The control decision relating to switching the sprayer on/off, changing the herbicide mixture or varying the applied dose will therefore be a function of the specification of the weed detection system, the characteristics of the sprayer and the agronomic requirements.

The herbicide savings that can be made from using patch spraying are likely to increase with increasing resolution of weed detection and spraying treatment. However the provision of input data at the higher resolution and the more complicated sprayer design required for the higher resolution treatments will tend to increase costs such that for many situations there will be a practical optimum resolution. An experimental patch sprayer (Miller and Stafford, 1991; Stafford and Miller, 1993) has been constructed based on resolution of 2 m x 2 m which was selected as the highest resolution that could be justified in any practical design (Paice *et al.*, 1995a). Computer simulation models and the structured analysis of field data are now being used to define the level of resolution that should be aimed for in a practical sprayer design in both the transverse direction and the direction of travel. Preliminary results from this work suggest that a transverse resolution of 4.0 m or greater is likely to be practical in most applications (Day *et al.*, 1995; Rew *et al.*, 1995).

IN-FIELD LOCATION

A location system is required during the weed patch map generation process and to provide real time location for the spray vehicle so as to match sprayer output to weed patch positions.

Many cereal crops are grown using tramlines which provide a recognisable and semi-permanent grid across the field. An initial approach to weed mapping and patch spraying therefore used dead reckoning location based on a field tramline count and the position along a given tramline obtained by integrating the output from a wheel or radar speed sensor system. Provision was made to calibrate the unit in-field and results showed that typically an accuracy of ± 1% could be obtained on level terrain but that this degraded to ± 2.5% on fields with substantial slopes (Rew *et al.*, 1995). The dead reckoning system has important advantages relating to simplicity and relatively low cost but disadvantages due to:

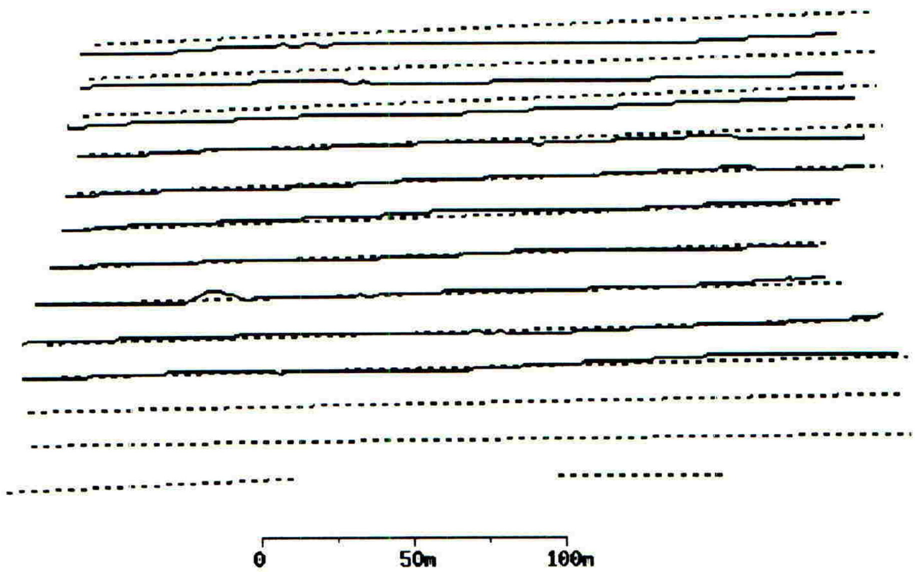
(a) the location error being cumulative; and

(b) an inability to operate in fields with other than straight tramlines - an important limitation particularly in many headland areas.

A number of alternative in-field location systems have been proposed for spatially variable field operations based on laser beacons, radio masts and local radio stations but few of these have been developed commercially for agricultural applications.

The global positioning system (GPS) based on a constellation of satellites placed in orbit by the US Defence Department is now becoming established as the location system for many precision agriculture systems. In order to obtain sufficient resolution for dynamic location, the GPS system must be used in differential mode. This uses two receivers; one based at a known location and the other on the spray vehicle. A radio link then transmits position correction data from the fixed to the mobile receiver. Results from field tests with this system have shown that a resolution of 2 m is achievable although there are large temporal variations due to the changing geometry of the satellite constellation and due to "shadowing" effects of trees, buildings, terrain and other obstacles. The results of a dynamic test with a five channel receiver following field tramlines 12 m apart is plotted in Figure 1.

Figure 1 : Field tramlines as surveyed (- - - - -) and determined by differential GPS (——).



WEED DETECTION AND MAP GENERATION

Automatic weed detection

Thompson *et al.* (1991) reviewed the possible methods for distinguishing weed from crop in arable situations and concluded that two possible approaches were relevant, namely:

(a) to use image analysis techniques to identify geometric differences between weeds and crop using factors such as leaf shape, plant structure and/or the position of plants with respect to the crop row; and

(b) using spectral reflectance characteristics.

For cereal crop canopies, the problem of weed and crop plants being obscured by neighbouring plants was found to be a major limitation to accurate and reliable detection even at relatively early growth stages. For image analysis systems, a resolution of the order of 1 mm^2 per image-pixel was required and this meant that a standard 512 x 512 pixel conventional video camera could view less than 1.0 m^2. Image analysis systems were therefore likely to be costly and/or unable to achieve the required level of performance. Spectral reflectance techniques have been used successfully to distinguish plants from bare soil (Hooper *et al.*, 1976) but to date it has not been possible to establish robust and consistent thresholds for reflectance characteristics in growing crops that will enable accurate and reliable weed detection in crop canopies. A possible exception is when weeds such as couch (*E. repens*) remain green in a senescing crop (Hagger *et al.*, 1984).

Although research is continuing to explore and evaluate combinations of new and existing approaches to automatic weed detection, this work is unlikely to give practical systems that can be used with the first generation of commercial available patch sprayers.

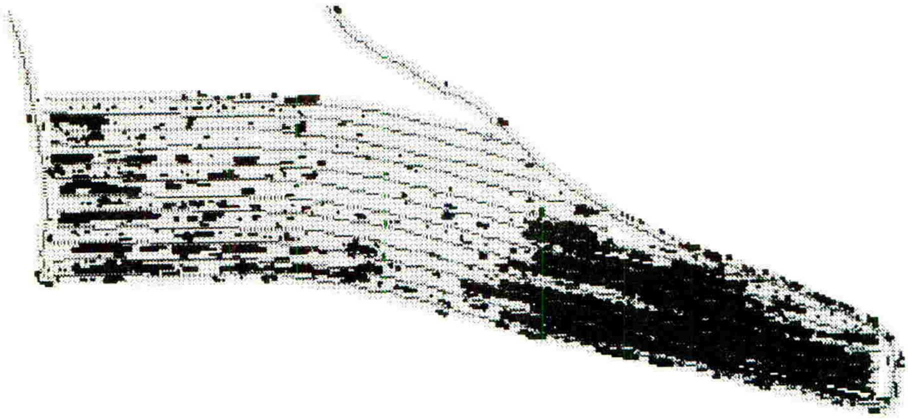
<u>Manually based systems</u>

The ability to combine field location with manual weed recognition provides the basis for a number of approaches to weed map generation. For experimental work, two survey vehicles have been used (Rew *et al.*, 1995). Both work on the principle of systematically travelling along tramlines and using a push-button system for the operator(s) to record weed patch positions into a program running on a notebook computer. Field location has been obtained either by monitoring ground wheel pulses (dead reckoning) or by using GPS and the software creates a map in real time based on the manually recorded weed patch data and the calculated field location.

One of the survey vehicles was based on a specialised high clearance spraying vehicle and used two weed detecting operators looking along a 12 m boom divided into 2 m sections to match the requirements for the experimental patch sprayer. The vehicle was driven down tramlines by a third operator at a speed of approximately 1.5 m/s. When using dead reckoning for field location, two reference lines were marked out in the field at right angles to the tramlines and at a measured distance apart (typically 50 m). By recording the positions of these reference lines in each tramline the computer program was able to scale and position each recorded tramline to give a map of the field without the need for any pre-surveying of the area. The dead reckoning principle cannot be used for headland tramline areas but GPS field location has been used to record both headland tramline areas and fields where the tramlines are not straight (Figure 2). The second survey vehicle used similar principles but with dead reckoning only and was hand-pushed by a single operator. This was used mainly at early stages of crop growth.

A backpack GPS system and hand-held computer system has also been developed for logging weed patch positions within a field (Stafford and Le Bars, 1995). With this system, the operator has a map of the field boundary displayed on the computer screen together with the current position. For recording weed patches there are options relating to the input of geometrically shaped patches or to walk round an irregular patch to define its position. Weed type and patch density are entered from a menu based system. Although the system can be used for an initial rigorous survey of a field, it is also useful to update a pre-recorded weed map which can be displayed on the computer screen and provides the operator with a means of updating the map to account for seasonal effects. The boundaries of a field can also be input at the start of a surveying operation by walking round the field.

Figure 2 : Field weed map obtained with the survey vehicle using GPS location.



A combine harvester fitted with a GPS field location system for yield mapping purposes also provides an opportunity to log weed patch positions, particularly for those weeds which are easily seen at harvest time. An initial study mapping couch grass in a wheat crop showed good agreement between a weed map generated by the combine harvester and obtained from using a backpack weed mapping system.

METHODS OF CONTROLLING SPRAYER OUTPUT

Paice *et al.* (1995b) have reviewed the application control requirements for patch spraying of herbicides and have concluded that pressure control systems are not appropriate because changes in applied dose rate of more than ± 20% cannot be achieved without changing forward speed, nozzle orifice size or spray quality and distribution pattern. The turn-down ratio of an application system is therefore a key performance parameter and has components relating to:

(i) the range of dose rates that are likely to be required for any given application - the need to apply full dose to areas of high weed density and 20% of full dose (as an insurance treatment) to areas with nominally no weeds implies a turn-down requirement of 5:1;

(ii) the need to compensate for forward speed variations of typically ± 20% of a nominal value.

This means that an overall turn-down ratio of at least 7:1 is likely to be required for a patch application system. Current designs of spraying system based on twin-fluid nozzles and rotary spray generation devices are capable of achieving turn-down ratio's in the order of 3:1 for a given spray quality and with operating variables in a practical range and hence such systems may provide the basis for practical patch spraying system designs. Turn-down ratios of 3:1 may also be achieved by multiple switching from three different spray lines mounted on a boom. However, other performance considerations particularly relating to spray volume rate, cost and complexity may limit the acceptability of such approaches.

Other important performance requirements for a patch spray application system are related to:

(a) accurate control of delivered dose;
(b) spatial resolution and rapid response times;
(c) the ability to change the mixture of herbicides applied to patch areas; and
(d) minimising the need to dispose of any unused dilute herbicide in the sprayer tank or pipework.

Injection metering of concentrated liquid herbicide formations into the pressure side of a conventional sprayer circuit has been identified as one system that can meet many of the requirements relating to patch spray application (Paice *et al.*, 1995a; Stafford and Miller, 1993) particularly with respect to the application of different herbicide mixtures. Such a system operated with a closed transfer device may also have advantages in minimising the risk of operator contamination during the loading operation. With an injection system driving a multi-section spray boom, a higher turn-down ratio capability is required to account for the variation in active boom width and the range of dose rates associated with different herbicide formulations. These factors could impose a requirement for an additional turn-down ratio in the order of 30:1 to give an overall turn-down ratio of 180:1 which is very unlikely to be achieved by a single metering delivery unit.

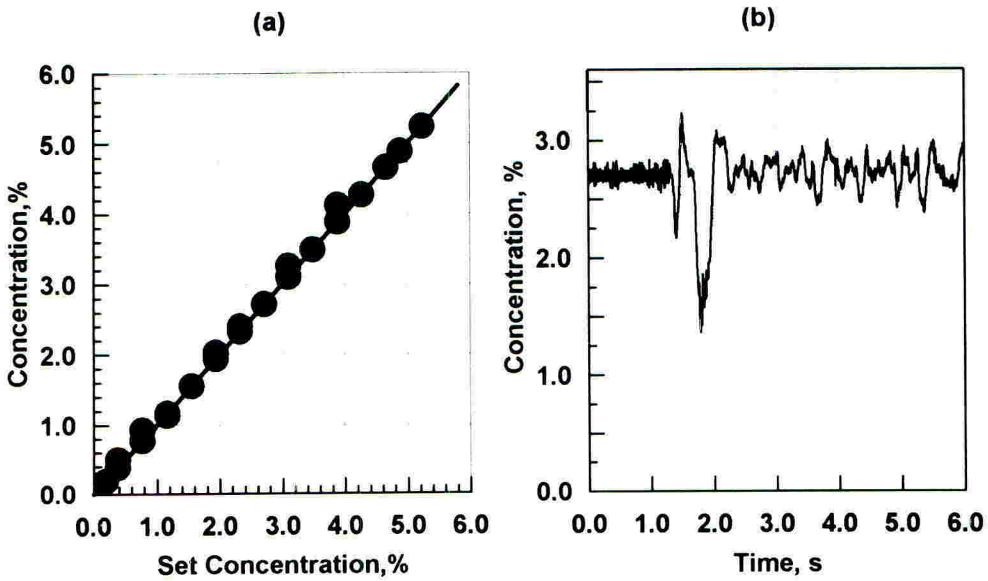
An experimental patch sprayer has been built (Miller and Stafford, 1991; Stafford and Miller, 1993; Paice *et al.*, 1995a) for full scale field evaluation has used a combination of injection metering and on/off application control strategies. An injection metering system, initially proposed by Frost (1990) with a metering cylinder to carry the herbicide has been used as the basis of the system. Two metering cylinder injection units supply herbicide formulations to separate mixing chambers, manifolds and parallel boom lines. Each manifold distributed the flow to six 2 m nozzle sections via narrow bore pipes (Miller and Stafford, 1991) and individual, on/off solenoid valves. System control and monitoring functions were distributed around the nodes of a Controller Area Network (CAN). These were defined as:

- a personal computer (mounted in the tractor cab) displaying the treatment map and logging spraying data;
- an operator's control box providing on/off and override controls;
- a dead reckoning interface monitoring forward speed by wheel rotation or doppler radar;
- a satellite navigation interface monitoring field location by differential GPS;
- two micro computer controllers interfacing with sensors, applying control algorithms for each injection metering system.

The control system is configured such that the performance of the complete system can be recorded for every 0.5 m of forward travel and the ability to keep such records may be an important component in the future development of patch spraying systems. The flow rate of the concentrated herbicide formulation when the sprayer is operating is a function of the dose rates specified on the treatment map, the number of boom sections delivering the herbicide and the forward speed of the unit.

Experiments have been conducted to determine both the steady-state and dynamic responses of the injection metering system and these results have been reviewed with regard to the specification for operation in conjunction with a patch spraying system. The steady-state response characteristic was quantified by loading the system with a concentrated tracer dye solution (0.2% Orange G - Merck Ltd) and measuring the dye concentration the liquid delivered to the spray nozzles for a number of settings in the full range of dose rate and forward speed values. Dye concentrations in the flow from the nozzles was determined by spectrophotometry using samples of the original dye solution as a reference. The results shown in Figure 3a indicate that an accuracy of better than ± 5% of the set dose rate could be achieved over a sprayer speed range of at least 1.0 to 3.5 m/s and for dose rates from 0.75 to 5.0 l/ha - a turn-down ratio of some 25:1. Although this could probably be extended by changes to the pump instrumentation and control algorithm, values of greater than 50:1 are unlikely to be achieved at the required accuracy.

Figure 3 : Measured concentrations delivered by the injection metering system (a) at steady state; (b) dynamically.



The dynamic response characteristic of the injection metering was examined by loading the cylinder with a 4.0 M solution of sodium chloride and monitoring the electrical conductivity of the liquid flow to the nozzles immediately downstream of the injection point (Paice *et al.*, 1995a). The system was again calibrated using solutions of known concentration and the output from the calibrated transducers were logged directly at a rate of 50 samples/s using a computer based data logger. Figure 3b shows the concentration in the spray line measured downstream of the mixing chamber for a simulated condition representing the sprayer moving from a position where the map required no delivery from any part of the boom to an area requiring all of the boom to be delivering herbicide at full dose. A reduction in delivered concentration of almost 50% is observed over a period of approximately 0.3 s while the metering system responded to the step change in demand. Experiments are continuing to assess the extent to which this temporary dose rate reduction is transported to the nozzle systems, the effect at target level and the implications for the strategy when generating a treatment map. One possible method of minimising the observed effect would be to constrain the map generation such that the complete boom was not switched on together but the supply to different sections staggered.

The variation in delivered concentration after the complete boom was switched on may have resulted from a small quantity of air trapped in the metering cylinder and this is being further investigated.

DISCUSSION AND CONCLUSIONS

Results from the work to date has shown that the approach of using a treatment map to control a spatially variable sprayer has important advantages over direct control methods particularly when weed patch detection in established cereal crops is likely to use the results from more than one technique. Automatic detection of weed patch positions in cereal crops, although a long term goal, will not be achieved within the timescale needed for the first generation of commercially available patch sprayers. The detection of grass weed patches in cereal crops by the driver of a combine harvester equipped with a manual keypad and a field location system that may also be used for field mapping has been shown to be a practically useful approach.

A patch spraying system using only on/off control requires a high level of confidence in the method of weed patch detection and mapping if the full potential of the system is to be realised. Injection metering provides a practical method for enabling both the dose rate and mixture of chemicals to be varied in a patch spraying system but with disadvantages relating to relatively high costs and the need for the metering method to achieve high turn-down ratios. Systems based on twin-fluid nozzles, multiple nozzle lines or spinning discs would be able to adjust the applied dose rate by varying the volume rate at a given spray quality, but different mixtures of herbicides could then only be applied by using multiple tanks carrying dilute herbicide mixtures. This then requires a high level of management if the need to dispose of substantial volumes of dilute herbicide are to be avoided. A system applying a uniform base treatment across a field using conventional pressure control could use an injection metering system to add an additional herbicide component to the applied mixture in response to mapped weed patch positions.

A number of potential patch sprayer system configurations are therefore possible and results from research and development work currently in progress will aid the definition of the practical benefits of particular arrangements.

ACKNOWLEDGEMENTS

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The authors are grateful to colleagues at both research institutes who have contributed to the work and particularly to Mr G W Cussans who has led the collaborative project.

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COMMERCIAL PROGRESS IN SPOT SPRAYING WEEDS

W L FELTON
New South Wales Agriculture, The Tamworth Centre for Crop Improvement,
PMB 944 Tamworth, NSW 2340, Australia

ABSTRACT

Several recently released commercial weed detecting sprayers are reflectance based systems that automatically control the nozzles on a boomspray to apply herbicide only to green vegetation. Each nozzle is fitted with a solenoid valve that opens briefly to apply spray when the nozzle passes over green plants. Each nozzle has a sensor located ahead of it which has a "field of view" matching the spray pattern of that nozzle. Large reductions in the amount of herbicide required to control weeds have been achieved where the weeds are scattered and are of sufficient size to be reliably detected.

INTRODUCTION

Weeds cost billions of dollars annually in lost production and cost of control. Although herbicides have enhanced farmers' economic viability, and helped reduce the risk of soil erosion in minimum/no-tillage cropping systems, their use is seen by an increasing number of people in the community as a potential ecological hazard that cannot be ignored.

For viable crop production, weed control is often important both in the fallow or interval between crops, and in the crop, as even sparse weed populations can decrease the moisture and nutrients available and reduce productivity. Hand weeding was, and still is in countries where labour is cheap, a traditional method of controlling weeds. Herbicides have only been used for a relatively short period of time, but their introduction has revolutionised production methods. It is not surprising that new developments in technology continue to be directed at increasing the scope for using hebicides. Two current major areas of development are in spray application equipment, and in genetic manipulation to produce crop varieties that are tolerant to herbicides to which the crop was previously sensitive. In controlling scattered weeds, most of the herbicide sprayed from a standard spray boom will be deposited on the soil or litter (Thompson *et al.* 1991). The potential to reduce both herbicide costs and the possibility of environmental problems by selectively spraying only the weeds is therefore considerable.

EVOLUTION OF THE TECHNOLOGY

Devices designed to discriminate weeds from other ground covers by use of physical contact, such as the weed wiper, rope-wick applicator, herbicide impregnated wax bars, and the herbicide glove, rely on the weeds being in a different physical plane to the crop or stubble. In practice this rarely occurs because weeds, particularly those with a short or prostrate growth habit, may remain within the crop or stubble canopy. Furthermore, delaying control until the weeds grow sufficiently to be treated can still result in significant yield losses. Therefore, another method of discriminating green vegetation from other surfaces was required and optical methods were the most promising.

The contrasting optical properties of soil, dead plant material, and green vegetation provide a basis for discriminating between green plants from the others (Gates *et al.* 1965). Solar radiation incident on a surface is partially reflected from, transmitted through, or absorbed by the surface. Most incident solar energy is transmitted into green vegetation, being selectively absorbed in the blue and red wavebands by the chlorophylls while the near infrared (NIR) is strongly reflected (Swain and Davis 1978) particularly compared to both dead vegetation or soil (Fig. 1). These two wavebands are often used to achieve the best discrimination between green vegetation and other ground covers (Tucker 1980).

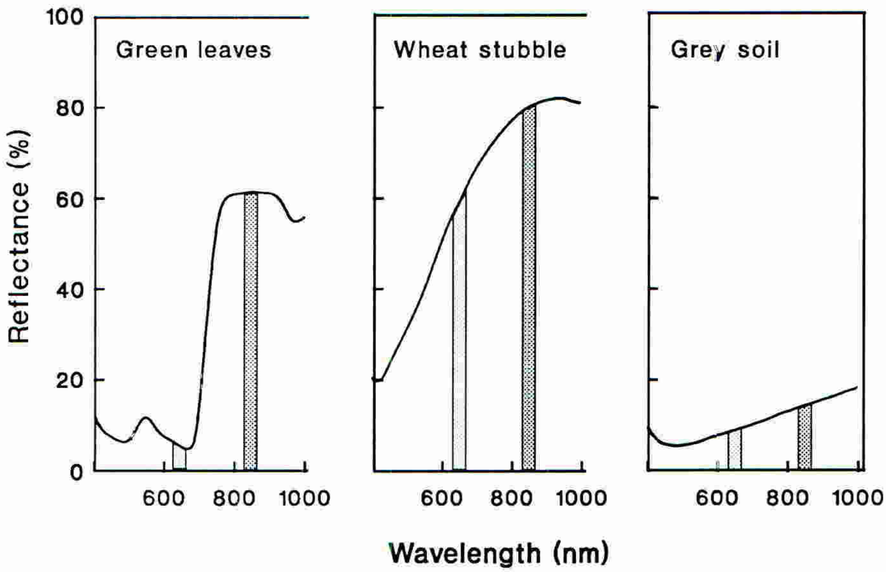

Fig. 1 A comparison of the spectral reflectance of green leaves, wheat stubble, and a grey soil, indicating the values at 650nm (red) and 850nm (near-IR)

Photoelectric sensors used in conjunction with an artificial light beam were used by Hooper *et al.* (1976) to distinguish plant and soil material. This approach also used the infrared to visible response ratios of radiance where the ratio of green vegetation is typically greater than that for soil or dead plant material. This technique experienced problems when used in direct sunlight and required rubber skirts to be fitted to shade the ground. The technology was applied to a selective chemical thinning machine which performed satisfactorily in sugar beet and cabbage. Haggar *et al.* (1983) used the radiance ratio R + IR/IR to develop the first patch sprayer. The problem is that the background conditions and irradiance are not constant. The density of radiance depends upon that of irradiance and the reflective properties of the surface. The density of irradiance depends on latitude, season, time of day, atmospheric attenuation, cloudiness and shadow, and the portion of the spectrum being considered. Measurements of radiance for a particular surface may therefore vary considerably. To obtain consistency in these measurements, the simultaneous level of irradiance must be considered. If the radiance in a waveband is expressed as a percentage of its irradiance, a property known as reflectance, which is consistent under changing conditions, may be derived. The ratio of near-IR reflectance to red reflectance will similarly be consistent for a given surface under varying conditions. The type of background contributes to the variation in the red and near infrared radiance so changes in soil type and stubble cover which can be quite variable have a significant influence. Other factors which influence radiance and reflectance that are of practical importance to weed detection are that leaves from dicotyledonous species reflect greater amounts of radiation than leaves from grasses, and physiological changes that effect chlorophyll content (for example water or nutrient stress) influence leaf reflectance (Grant 1987). The presence of dew on plants decreases the NIR/R ratio (Pinter and Jackson 1981) and reflectance is less from wet than dry soil. The geometry of the vegetation changes when plants wilt and the leaves droop but it is the change in orientation rather than a change in the reflectance of the leaf that is important (McCloy 1983).

Description of the New South Wales Agriculture prototype

In a research project with Dr Keith McCloy, formerly Principal Agronomist (Remote Sensing), New South Wales Agriculture, a reflectance based device that could automatically activate each nozzle of a boom so as to spray only green vegetation was developed. This work was the first to simultaneously measure radiance and irradiance to determine reflectance rather than radiance to discriminate weeds for spot spraying. The "weed detector" had to sense a field of view (FOV) consistent with the spray width of each herbicide nozzle, function under a wide range of environmental conditions, and discriminate green vegetation from other surfaces, which may be extremely variable in terms of soil types and conditions, in an automatic and consistently accurate manner (Felton 1990). The red and near-IR wavebands providing optimal discrimination (630-670 nm and 830-870 nm respectively) were selected after extensive high resolution spectral analyses of green and dead vegetation, soil, and litter, using a Collins IRIS spectroradiometer. Some types of litter were found to have responses in the red and near-IR bands that result in the near-IR/red reflectance ratio being similar to that of green vegetation and consideration was given to modifying the simple ratio discriminant function which was used in the prototype and subsequently detectspray. It was found only to be a problem on dark soils at low levels of irradiance. The prototype shown schematically in Fig. 2 (Felton *et al.* 1991) had an optical fibre which carried reflected energy to the detectors via the red and near-IR bandpass filters. The diffusing plates integrate hemispherical irradiance for transmission through corresponding filters to light detecting diodes. The diode signals were amplified before transmission to an analog-to-digital (A/D) converter, which transmitted digital data values to the central processing unit (CPU) for storage, analysis and display. The result of the analysis is a logical decision as to whether or not green vegetation has been sensed. The CPU then activates a solenoid operated nozzle if required. The first prototype was used to compare NIR/R radiance, NIR/R reflectance, and NIR - R/NIR + R (normalised) reflectance ratios as indices to separate green plants of various shapes and sizes, under a range of conditions. These data were used to design a 37 nozzle, 18 metre spray boom and fitted to a four-wheel-drive chassis (Felton 1990). One irradiance sensor pair was mounted above the vehicle cabin. Each independently operated nozzle had a radiance sensor pair and solenoid control valve. The radiance sensor pairs, which had a FOV matching the spray pattern, were located ahead of the nozzles and point downwards, negating the need for optical fibres. When the sensors detected a green plant, or an area of green plants, a microprocessor

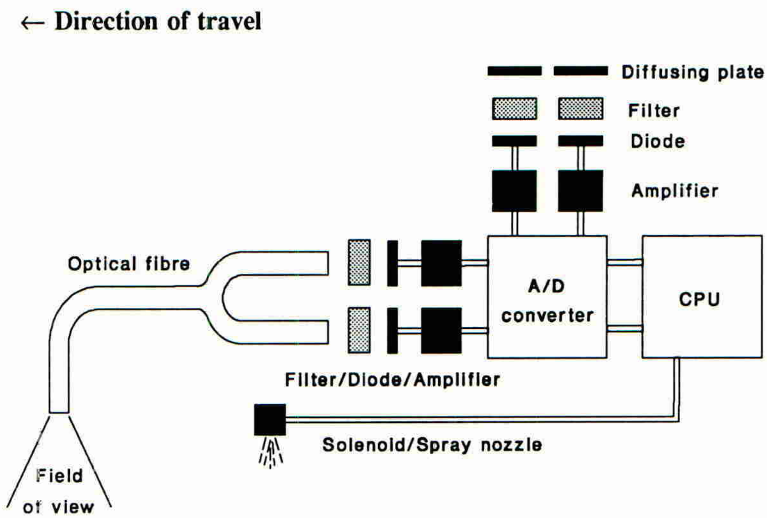

Fig. 2 Schematic diagram of the "weed detector" prototype

turned the nozzle on for a predetermined period. This time period was varied to test the spray pattern for different operating speeds. A central control microprocessor located in the spray vehicle communicated data to each detector and could be used to alter the sensitivity of the system by increasing or decreasing the slope of the decision line between "green" and "non-green". Both the irradiance and radiance detectors made 50 decisions/second in each wave band. Improved computing technology now allows faster decisions and increased speed of spot spraying without missing weeds. When the presence of green increases the near infra-red reflectance/red reflectance ratio above the value set for the particular soil/litter background, the solenoid valve was opened for a brief period (0.15 seconds). Each cycle involves:

Start ← ← ← ← ← ← ← ← ←
↓
Input irradiance and radiance values ↑
↓
Calculate red and near infra-red reflectance ↑
↓
Calculate near infra-red reflectance/red reflectance ratio ↑
↓
Is ratio > than threshold → No → → → ↑
↓
Yes → → → Spray → → → ↑

This sprayed an area 0.5 m (nozzle spacing) x 0.8 m at 20 kph. The size of the nozzle tip was also very important. For example, at the operating height of 60 cm the spray pattern took 50% longer to hit the target from a Spraying Systems 110015 nozzle than from a 11003 nozzle. Detection and activation were virtually simultaneous so that the period from detection to spraying the target was primarily determined by the mean spray velocity from the nozzle. The system also could be used as an overall boom spray by selecting a continuous spray option instead of the detection mode. Sensitivity of the system could be varied by increasing or decreasing a setting on the master controller. More green in the field of view was needed (a bigger weed) if a higher ratio value was selected. The system detected 3-5% green in the FOV depending on its shape. In a standard sprayboom with detectors 60 cm above the ground, the FOV was 60 cm x 20 cm which is equivalent to a weed 7 cm in diameter. Smaller weeds can be detected by decreasing the FOV by lowering the sensors closer to the ground but the sensor spacing must be reduced also.

Field evaluation of the prototype

In 1990 the prototype was evaluated in a wide range of conditions in northern New South Wales. It was operated at a ground speed of 12 kph and a spray line pressure of 250 kPa, as is common commercial practice. There was a diversity of annual and perennial weeds that exhibit a broad range of growth habits which included Johnson grass (*Sorghum halepense*), couch (*Cynodon dactylon*), Noogoora burr (*Xanthium occidentale*), Bathurst burr (*Xanthium spinosum*), mintweed (*Salvia reflexa*), camel melon (*Cucumis myriocarpus*), devil's claw (*Ibicella lutea*), thornapple (*Datura spp*), milk thistle (*Sonchus oleracae*), black thistle (*Circium vulgare*), rattlepod (*Crotalaria dissitiflora*), wild oats (*Avena spp*), volunteer sorghum (*Sorghum vulgare*), liverseed grass (*Urochloa panicoides*), barnyard grass (*Echinochloa spp*) and nutgrass (*Cyperus spp*). A total of 2681 hectares was treated on 33 farms. The mean saving in area sprayed, relative to an overall treatment, was 90%. On 20 of the farms, more than 95% of weeds were killed and on a further 5, more than 90%. In the 8 fields where control was less effective this was attributed to:

(a) Weeds too small to be reliably detected.
(b) An inadequate herbicide rate.
(c) Specific weeds not completely controlled by the herbicide mixture.
(d) Rough conditions causing spray boom instability.
(e) Rain after application reducing herbicide performance.

To control some of the perennial weed species which were present on 10 sites and are not effectively controlled with cultivation, for example *C. dactylon* and *S. halepense*, a high rate of herbicide (2-3 kg/ha of glyphosate) is required. Excellent control was achieved on 9 of these sites by selectively spot spraying with the recommended application rate and, because a minimal amount was wasted, the control was very cost effective (Table 1). On the 23 sites where annual weeds were the main problem, and lower herbicide concentrations could be used effectively, there were also considerable cost savings. Without selective spraying, farmers would have made the decision, based on cost, to cultivate 25 of the 33 fields. The cost of controlling larger weeds by spraying, and the risk of poor control, are two significant factors influencing farmers to cultivate rather than to spray. The most important considerations in spraying weeds are usually which herbicide(s) to use, the rate of application, and the method and timing of application. Herbicide selection with spot spraying is still as important as it is with overall spraying, but rates are less crucial. If only 5-10% of a paddock is to be sprayed, there is a negligible difference in cost, for example, between using 450 and 900 g/ha of glyphosate. Large weeds should no longer escape control because of insufficient herbicide. Mixtures should become more prominent, and products previously prohibitive in cost on an overall spraying basis, may now be considered. Adverse application conditions such as hot and windy weather, and drought stressed weeds, occurred at several paddocks. Control was better than expected because the application rates could be increased without becoming too expensive.

Table 1. A comparison of the average costs ($AU/ha) of controlling scattered fallow weeds on 33 paddocks in northern NSW in 1990.

	Perennial weeds	Annual weeds
Number of paddocks	10	23
Area treated (ha)	1004	1677
Average cost with spot spraying[A]	6	3
Average cost - overall spraying[A]	60	20
Average cost if cultivated	15	15

[A] Does not include cost of application

The first commercial spot sprayers

Following the success with this prototype the first commercial equipment was built, detectspray S45, which comprised: A single detector pointing upwards to monitor the incident solar energy (irradiance) in the red and near infra-red wavebands. A master control unit located in the cab of the spray vehicle which communicates the incident data and decision value to each radiance detector (3/second). The decision ratio controls the sensitivity of the system. A radiance detector pointing to the ground is located in front of each nozzle and scans the area sprayed by the corresponding nozzle. It measures reflected energy in the red and near infra-red wavebands in a narrow area (FOV) in front of each nozzle (300/second). Nozzles fitted with a solenoid valve which is opened briefly when a green plant, or area of green plants, is encountered in the field of view of the radiance detector. Each radiance detector contains a microprocessor which controls the corresponding solenoid/nozzle. The system scans at 300 cycles/second which means that a new assessment is made every 1.85 cm at 20 kph.

Several systems were sold in Australia in 1991 and in Canada and the United States. The potential of the concept was unanimously endorsed by these pioneer operators (Felton 1991, Schmuck 1992). Kelly Johnson, a custom applicator in Saskatchewan, Canada strongly endorsed the benefits of the system and claims detection of weeds smaller than reported by Felton *et al.* (1991) and claims that lateral drift is not a problem if wind deflectors are fitted to the boom (Pers. Comm.). After treating 10,000 ha in the first year he operated detectspray Johnson said "it gave him a new marketing tool" (Schmuck 1992).

Experiments by Hanson *et al.* (1994) and Blackshaw (1995) found that detectspray reduced the amount of herbicide used by up to 92% and 5-60%, respectively, but a dual boom system provided more reliable control. Detectspray was also found to be effective in combination with blade cultivation. Ahrens (1994) obtained a 47-88% reduction in herbicide required compared to overall spraying, but costs to the farmer for the full season were only reduced by 13%. Two factors were a problem, wind causing spray to miss the target, and the failure to control small weeds. This necessitated respraying. Blackshaw (1995) found that grass weeds were more difficult to detect than broadleaf weeds in a no-till fallow unless they have more than 5 leaves or are in patches. Performance early in the morning and late afternoon was reduced although these are often the best times to spray to avoid windy conditions. At some sites the detectspray treatments had to be sprayed more frequently because small weeds were missed. Variation in performance of the sensors was identified as a problem by Hanson *et al*. (1994).

A most important factor with spot spraying systems is sprayboom stability. Variation in the height of the detectors significantly influences the size of the FOV and hence the size of weeds detected. Boomsprays should have outrigger wheels to stabilise height. Vehicle mounted booms are less suitable for detectspray unless paddock conditions are favourable. Shadowing of the FOV from the vehicle or boom can increase the background ratio, but this false triggers the system rather than causing spray misses. This problem increases when the sun angle is low early in the morning or late afternoon. When the incident energy gets too small the system becomes less reliable because of the low signal values. The problem is obviously greater with inter-row spot spraying as the crop gets taller. Artificial lighting is a solution and was considered even for the original prototype.

It is imperative that the nozzle pattern is maintained, especially with side winds. Lateral pattern distortion will result in poor coverage and control of weeds at the edge of the spray pattern. Nozzles and pressures that produce a high percentage of small droplets are undesirable. Furthermore, droplet velocity is proportional to droplet size. Spraying Systems 11003 nozzles were much more reliable than 110015 nozzles. The radiance detectors have to be located further in front of the nozzles if fine nozzles are used, or the height the nozzles are located above the target is increased.

The important considerations in spraying weeds are usually which herbicide(s) to use, the rate of application, and the method and timing of application. Herbicide selection with spot spraying is as important as it is with overall spraying, but the rates are less crucial.

Dual booms

Several of the commercial boomsprays fitted with detectspray have dual application systems. The second sprayline can apply an overall treatment of a low rate of knockdown herbicide, or a residual herbicide, at the same time that detectspray is spotting out the bigger weeds with a higher rate of herbicide which even can be a different mixture if necessary. This considerably enhances flexibility, but more importantly improves reliability of control of small weeds without requiring 2 trips across the paddock. One commercial dual boom in Australia has 2 nozzles/solenoid valve 40 cm apart and closer to the ground. In tests with water sensitive paper this operator maintains that he has improved coverage with this system. Another alternative is to have just one sprayline with fine nozzles (11015) continuously delivering a low rate and have the spot spraying system fitted with higher volume nozzles (11004) to spray the larger weeds when detected.

Other systems

Since the Australian weed detector was developed several other reflectance based systems have been reported. Von-Bargen *et al*. (1993) used a pair of red and near infrared (NIR) sensitive photodetectors to measure the radiancy from the plant and soil and another which measure radiance from a highly-radiant reference surface to accommodate irradiance. The ratio of the target and reference radiancies (target reflectance) values were used in a normalized difference index to determine if a live plant is present within the FOV of the sensor. This system was also combined with a microcontroller for activating a solenoid controlled spray nozzle on a single unit prototype spot agricultural sprayer.

Applied Robotics, Saskatoon, Canada have developed Sprayvision. This is somewhat similar to detectspray, but calculates reflectance from a FOV using radiance in four wavebands, NIR, red, green and blue, and irradiance in the same wavebands, to determine the "weed signal" from the non green background. The SprayVision separates the background by the colour of the target rather than just green/non-green.

The Patchen system developed by J. Beck, Los Gatos, California, uses its own light source which is modulated to screen out the irradiance from sunlight. It therefore can operate in a wide range of conditions and at night. It is going to be especially suited to inter-row spraying where shading of the FOV reduces performance with detectspray.

Thompson *et al.* (1991) have been working on spatially variable herbicide application in cereals using a sprayer location system and a field map of weed location based on image analysis (tractor-mounted video cameras, aerial photographs and field observations). The basis of the spatially selective operation is the application of a low-dose rate spray to the whole field, with an enhanced dose rate or a different herbicide mixture being automatically applied to weed patches (as used in the dual booms). The system consists of weed patch detection, real-time sprayer location, field mapping and spray rate control.

Shielded sprayers

In Australia and the United States shielded sprayers are now widely used for inter-row weed control in row crops. Grass weeds in cotton are controlled with glyphosate and fusilade. The potential to combine this with spot spraying to reduce the cost of control for difficult to kill weeds such as *S. halepense* and *Cyperus spp.*, and to reduce the amount of herbicide that is being introduced into the environment, is considerable.

The Patchen system currently being trialled in the United States has been reported to detect weeds in the rows from the cotton stems enabling inter-row directed spot spraying (J. Beck Pers. Comm.). This is a most significant improvement in the technology which will certainly improve the control of weeds germinating after planting. It will also reduce the need for "high" rates of pre-plant and/or pre-emergence residual herbicides now used as the standard treatment.

In our own program in Australia, grain legumes are being trialled as row crops after no-till fallows to increase stubble retention of the previous cereal crop. An important problem with grain legumes, particularly chickpea, is the control of broad-leaved weeds. Currently simazine, and some cyanazine, are used but are unreliable with our erratic rainfall, and are sometimes too persistent on the alkaline clay soils. A combination of band spraying the residual herbicide over the crop row, and spot spraying the inter-rows, has the potential to improve weed control, reduce costs, and eliminate carryover of phytotoxic residues to a subsequently sown crop. The detectspray system, which uses sunlight to calculate reflectance, is less effective with inter-row spraying because of shadowing of the FOV of the radiance detectors by the crop. Radiance from the shaded area is independent to the irradiance values from the incident detector. The problem can be overcome by not using irradiance directly but in combination with artificial illumination of the FOV and correcting for natural irradiance. This is in fact what the Patchen system does.

FUTURE DEVELOPMENTS

Spectral difference between different plants is small compared to the variation that exists between the plants plus the background. Image analysis has the potential to discriminate different shapes of plants and different arrangements in a paddock. There will be advances in this area and breakthroughs in combining different techniques of separating targets using more sophisticated information about the targets. This then provides better opportunity to use neural networks in decision making. Maybe we will see the use of genetically introduced identifiable traits to crop varieties that allow these to be distinguished from weeds. Spot spraying as it is at this stage is still a "coarse" method for discriminating green from non-green. It took 7 years for Haggar *et al.* (1983) to build the first patch sprayer after Hooper *et al.* (1976) built their thinning device, and another 7 years for the release of the first commercial spot sprayer, detectspray. The Patchen equipment is the latest generation of commercial spot sprayer and no doubt there will be more now that the potential has been made so apparent.

CONCLUSIONS

Broadacre fallow spraying was the focus of the Australian work, but there are many other situations where spot spraying weeds is beneficial. In agriculture these include band spraying with shielded sprayers in row crops such as cotton, corn, soybean and sorghum, ornamental, vegetable and horticultural crops, and vineyards. Industrial uses include weed control on railway tracks, road verges, airports and along waterways. There is also potential to develop the technology for the application of nutrients and other pesticides.

Weed detecting systems will increase the adoption of minimum tillage practices by farmers. Benefits of this technology include the reduction in the volume of spray and consequently the cost of herbicide, time savings because of fewer stops to refill, lighter spray rigs and hence reduced soil compaction, better control of tolerant and difficult to kill weeds, and less non-target spraying which reduces potential environmental risks, and from more flexibility in timeliness of operations.

Prior to the availability of spot spraying technology the most difficult to kill weeds in a field determined the control strategy. Often this meant cultivation. Now, overall treatment rates can be reduced to the easy to kill targets and the escapes can be subsequently or simultaneously spot sprayed, with a dual boom system. Residual herbicide rates can be reduced, thus lessening the fear of carryover of phytotoxic residues. There is much more scope now for farmers to change their attitude to weed management. Spot spraying will open the door to more options that were previously unattractive for economic and environmental reasons. Spot spraying actually offers US farmers a means of developing environmental practice strategies which will conform to 1995 deadline requirements of the 1985 US Farm Bill.

"Black box technology" is still viewed with cynicism by many farmers, but there are an increasing number who have experienced the benefits of some of the innovations that have been introduced into agriculture in the last few years. Spot sprayers are just another such innovation that will be widely adopted once the products perform reliably and accepted as being very cost effective. These will be more important to farmers than the environmental concerns, although the latter are very important to the wider community.

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Session 9

Physics and Biology of Pesticide Application

Chairman	Mr T G Marks
Session Organiser	Mr T Robinson
Papers	9-1 to 9-5

EVALUATION OF DOWNWARDS AIR ASSISTED SPRAYS IN PEAS AND BEANS

C M KNOTT
Processors & Growers Research Organisation, The Research Station, Thornhaugh, Peterborough, Cambs., PE8 6HJ

ABSTRACT

Pesticide sprays applied to peas *(Pisum sativum)* and beans *(Vicia faba)* with downwards air assistance using a Hardi Twin-boom sprayer were compared with conventional sprays for biological performance. Applications were with flat fan nozzles using product label recommendations for dose rates and water volumes of 200 l/ha, or half doses and 100 l/ha water. Air assistance appeared to improve control of moderately susceptible weed species and broad-leaved or grass weeds sheltered by the crop, *Botrytis* in peas, probably because spray droplets were directed down to lower parts of the plant, and to some extent downy mildew *(Peronospora viciae)*, where sprays were circulated to the underside of broad bean leaves. There were indications that where the target, such as aphid *(Acyrthosiphon pisum)*, infested the growing point, air assisted sprays were less effective. In most cases water volumes of 100 l/ha were as effective as 200 l/ha irrespective of application method. With the exception of cycloxidim there may be little scope for reduction of dose rates as low as half.

INTRODUCTION

It is essential to spray pesticides at the recommended plant growth or infestation stage, particularly for vegetable crops where high quality and the correct harvest interval must be achieved. In practice this may be limited by high wind speeds and slow field work rates. Downwards air assisted sprayers were developed with the aim of: reduction of spray drift to allow more spray opportunities (Taylor *et al.*, 1989); using lower application volumes; improving spray deposit distribution pattern and possibly using lower pesticide dose rates. Boom sprayers with a centrally mounted fan and large inflatable ducts to distribute air along the boom were evaluated in cereal crops (Rutherford & Miller, 1993) and in sugar beet (May, 1991). Spray drift over a range of vegetable crops: Brussels sprouts, lettuce, leeks, peas and field beans was assessed and spray behaviour appeared dependent on crop growth habit and stage of maturity (Knott, 1993). The subject of this report is the study of the biological performance of pesticides with or without air assistance in pea *(Pisum sativum)* and broad bean *(Vicia faba)*, in 1992 and 1993. Both investigations were funded by the Horticultural Development Council.

METHOD & MATERIALS

The Hardi Twin-boom sprayer uses a fan to push air through a sleeve which runs the length of the spray boom and air is expelled through a slit situated above hydraulic (flat fan) nozzles. Details of the sprayer treatments are given in Table 1. Hardi flat fan nozzles 4110-12 (F110/0.73/3 BCPC) and 4110-14 (F110/0.91/3 BCPC) were used to give fine spray. The labels for herbicide products recommend applications using a fine spray quality, fungicides and the insecticide, medium spray quality, and a water volume of 200 - 220 l/ha. Nozzles were spaced 50 cm apart on the sprayer boom and used in vertical position without air, and at a 30° angle rearwards, with air stream vertically downwards. Nozzle height above the top of the crop was 50 cm. Full air of an average speed about 20 m/s was used for all air assisted treatments. Tractor speed was 7.2 km/h except for treatments 9 & 10 where it was 4 km/h.

Table 1. Sprayer treatments

Treatment No.	Air	Sprayer	Vol. (l/ha)	Nozzle BCPC code	Pressure (bar)	Pesticide dose rate
1992 & 1993						
1.	+	Hardi Twin-boom	100	F110/0.73/3	2	N
2.	-	Conventional	100	F110/0.73/3	2	N
3.	+	Hardi Twin-boom	100	F110/0.73/3	2	½N
4.	-	Conventional	100	F110/0.73/3	2	½N
1993 only						
5.	+	Hardi Twin-boom	200	F110/0.91/3	5	N
6.	-	Conventional	200	F110/0.91/3	5	N
7.	+	Hardi Twin-boom	200	F110/0.91/3	5	½N
8.	-	Conventional	200	F110/0.91.3	5	½N
1992 only						
9.	-	Conventional	200	F110/0.73/3	2	N
10.	-	Conventional	200	F110/0.73/3	2	½N

with (+) or without (-) air; N = normal dose rate recommended on the product label

The following materials were applied to peas: bentazone/MCPB + cyanazine (Pulsar + Fortrol) tank-mix for broad-leaved weeds; cycloxidim + adjuvant oil (Laser + Actipron oil) for *Elymus repens* control; deltamethrin/heptenophos (Decisquick) to control aphid *(Acyrthosiphon pisum)* and pea moth *(Cydia nigricana)* in tank-mix with vinclozolin (Ronilan) for *Botrytis* control. Bentazone (Basagran) for broad-leaved weeds and metalaxyl/chlorothalonil (Folio 575 SC) for downy mildew *(P. viciae)*, were applied to broad beans. Applications were at normal recommended timings, except for broad-leaved weeds in peas in 1992 which was late, to weeds at small plant stage.

Weed control was scored as 0 = no control; 7 = acceptable control; 10 = complete control and weeds for each species in 6 random 0.33 m^2 quadrats per plot were counted. Crops were also scored for herbicide damage (0 = complete crop kill; 7 = acceptable damage; 10 = no damage). Aphid were assessed by counting numbers on 25 main shoots per plot and pea moth damage at green (vining) stage, by examining peas from 15 plants per plot, *Botrytis*, as assessed for 15 plants per plot. At dry harvest stage the percentages by weight of peas with pea moth larvae damage, "chalky" or stained peas in 500 g samples were recorded.
The experiments were of randomised block design with four replications. Plot size was 6 m (to accomodate half a boom width) x 18 m. Data were statistically analysed using analysis of variance and angular transformations were carried out where appropriate.

RESULTS

Weed control in peas

All treatments gave statistically significant reductions in numbers of live *E. repens* shoots compared with the untreated (Table 2). Applications using 100 l/ha water volume were just as effective as with 200 l/ha volume for both air assisted and conventional sprays. The air assisted sprays at ½N dose rates were nearly as effective as the full N dose rate, but without air the ½N dose gave poorer control than the N dose and was at an unacceptable level. Foliar suppression was more variable in plots where conventional sprays were applied and where the crop at GS 201 had lodged, exposing the grass weed, sprays were more effective than where the crop sheltered the target. There were no crop effects from graminicide application with any sprayer treatment.

Table 2. Suppression of *E. repens* as a visual score and as percentage reduction in numbers of live shoots 50 DAT compared with untreated, 1993
Cycloxidim at N = 450 g a.i./ha plus Actipron at 0.8 l per 100 l water volume

	Sprayer treatment			Control of *E. repens* shoots	
	Air	Vol. l/ha	Dose	Visual score	% shoot reduction
1.	+	100	N	10.0	99.6
2.	-	100	N	9.7	95.2
3.	+	100	½N	9.2	90.1
4.	-	100	½N	6.8	74.7
5.	+	200	N	9.7	98.2
6.	-	200	N	9.8	97.5
7.	+	200	½N	7.3	85.6
8.	-	200	½N	6.6	67.9
0.	untreated			0	0
No. green shoots of *E. repens* on untreated 144/m^2					
Significance @ P = 0.05					SD
LSD @ P = 0.05					27.45
CV %					23.8

Table 3. Pea crop and weed control scores; numbers of weed species/m^2, 1993
Bentazone/MCPB + cyanazine at N = (800/800 + 200)g a.i./ha

	Sprayer treatment			Crop score	No. weed species/m^2					Weed score
	Air	Vol. l/ha	Dose		*G. aparine*	*F. officinalis*	*V. persica*	*A. cynapium*	Total	
0.	untreated		-	10.0	16	11	39	227	506	0
1.	+	100	N	8.1	1	1	1	0	10	8.6
2.	-	100	N	8.3	2	1	1	1	13	8.2
3.	+	100	½N	9.1	9	1	1	1	32	5.9
4.	-	100	½N	9.4	20	2	3	1	64	3.8
5.	+	200	N	8.5	2	0	0	0	11	8.2
6.	-	200	N	8.5	3	0	3	0	17	7.8
7.	+	200	½N	9.2	18	1	2	1	52	4.0
8.	-	200	½N	9.2	17	5	2	4	64	3.0
Significance @ P = 0.05					SD	SD	SD	SD	SD	SD
LSD @ P = 0.05					9.4	4.1	9.2	90.9	11.1	
CV %					66.0	128.0	116.0	250.0	67.4	

In 1993 (Table 3) bentazone/MCPB + cyanazine gave complete control of susceptible weed species *Chenopodium album, Fallopia convolvulus, Stellaria media, Sinapis arvensis, Aethusa cynapium* and no control of resistant *Papaver rhoeas* and *Poa annua* (data not presented). There were no differences between application rates and volumes with or without air assistance. Efficacy on moderately susceptible species was more dependent on dose rate, but there was little effect from volume. At half dose rate air assistance significantly improved control of *Galium aparine* at 3 whorl stage (for 100 l/ha) and of *Fumaria officinalis* (for 200 l/ha). Data is not presented here for 1992, when bentazone/MCPB + cyanazine was applied at a timing beyond the optimum target weed stage and half dose rates gave poor control of moderately susceptible species. Differences in weed numbers between treatments at normal dose rates were not statistically significant, although weed scores showed air assisted sprays overall performed marginally better than those without air, possibly because of better deposition on weeds sheltered by the crop. Crop effects for tolerant cultivar Baroness in 1992 were negligible (data not presented), but there was slightly more damage in the form of chlorosis and scorch for cv. Scout in 1993 (Table 3). Damage was increased slightly in both years at the lower volume and in 1993, where air assistance was used.

Table 4. Broad bean crop and weed control scores; weed species/m^2, 1992 and 1993 Bentazone at N = 1440 g a.i./ha

Sprayer treatment	Air	Vol. l/ha	Dose	Crop score	No. weed species/m^2					Weed score
					C. album	*F. convolvulus*	*V. persica*	*P. persicaria*	Total	
1992										
0. untreated					23	25	6	5	68	0
1.	+	100	N	8.0	2	2	0	0	4	8.0
2.	-	100	N	8.0	7	7	2	0	16	6.5
3.	+	100	½N	8.8	7	5	2	0	15	5.5
4.	-	100	½N	9.0	15	10	3	0	32	4.0
9.	-	200	N	7.5	11	5	1	0	17	6.5
10.	-	200	½N	8.8	14	11	4	0	30	4.0
Significance @ P = 0.05					SD	SD	SD	SD	SD	
LSD @ P = 0.05					7.6	12.0	3.2	0.8	14.1	
CV %					46.7	87.1	82.2	144.3	36.8	
					F. convolvulus	*P. persicaria*	*G. aparine*	*S. media*	Total	
1993										
0. untreated				10.0	1211	56	27	23	1470	0
1.	+	100	N	8.1	10	0	1	0	84	5.9
2.	-	100	N	8.5	51	1	2	0	121	4.0
3.	+	100	½N	9.5	87	0	17	0	176	3.1
4.	-	100	½N	9.5	113	1	22	0	212	3.0
5.	+	200	N	8.0	9	0	1	0	73	6.0
6.	-	200	N	8.4	31	0	4	0	113	5.2
7.	+	200	½N	9.5	86	0	9	0	193	2.5
8.	-	200	½N	9.5	127	1	33	0	254	2.2
Significance @ P = 0.05					SD	SD	SD	SD	SD	
LSD @ P = 0.05					157.3	43.5	24.2	4.4	13.4	
CV %					56.3	468.3	129.9	116.1	28.2	

Weed control in broad beans

Weed populations were low at the 1992 site and very high in 1993. All treatments gave excellent control (Table 4) of species *Polygonum persicaria* and *S. media* which are particularly susceptible to bentazone, and poor or no control of the more resistant *Polygonum aviculare, Galeopsis tetrahit, Viola arvensis* and *P. rhoeas* (data not presented). There were no statistically significant differences between treatments. In 1993, for moderately susceptible *G. aparine*, treatments with the normal dose rates of bentazone achieved good control irrespective of water volume or air assistance. At half normal rates, air assisted treatments performed slightly better than without air and at 200 l/ha, differences in weed numbers were statistically significant (Table 4). *F. convolvulus* predominated in both years and it was observed that plants which were sheltered by the crop were not controlled by conventional sprays and subsequently climbed up the bean stems. At both normal and half normal doses of bentazone air assistance appeared more effective, but differences were not significant. Sprays with air assistance also gave better control of *C. album* in 1992. Differences were significant for the half dose rates applied at 100 l/ha volume. Visual assessments for weed control in 1992 and 1993 showed superior results for air assistance.

Bentazone, which was applied at the limit of the label recommendation for maximum temperature in both years, caused some effects on the broad bean crop in the form of blackening of leaves. This damage was greater at normal compared with half normal doses. In 1993 air assistance resulted in a slight increase in crop damage compared with conventional sprays for normal dose rates (Table 4).

Pest and disease control in peas

Table 5. Control of aphid *(Acyrthosiphon pisum)* and damage from pea moth larvae
Deltamethrin/heptenophos at N = 7.5/120 g a.i./ha as one or two spray programmes

Sprayer treatment	Air	Vol. l/ha	Dose	Numbers of aphid/plant (transformed) 3 DAT 1992	1993	Pea moth larvae damage (%) 1993 spray x 1	spray x 2
0. untreated				1.029	0.752	2.30	4.02
1.	+	100	N	0.151	0.009	0.11	0.95
2.	-	100	N	0.065	0.000	0.07	0.84
3.	+	100	½N	0.184	0.175	0.14	1.30
4.	-	100	½N	0.091	0.013	0.08	1.19
5.	+	200	N	-	0.000	0.13	1.19
6.	-	200	N	-	0.000	0.11	0.76
7.	+	200	½N	-	0.004	0.20	1.22
8.	-	200	½N	-	0.013	0.28	1.19
9.	-	200	N	0.080	-	-	-
10.	-	200	½N	0.199	-	-	-
No. aphid/plant on untreated				17.0	4.8		
Significance @ P = 0.05				SD	SD	SD	SD
LSD @ P = 0.05				0.6597	0.0980	0.257	0.678
CV %				76.700	62.600	46.100	33.100

Aphid *(Acyrthosiphon pisum)* numbers on plots treated with insecticide were low in both years and significantly lower (at P = < 0.05) than the untreated for all treatments (Table 5).

The least effective treatment in 1993 was with air assistance at half dose rate and 100 l/ha water volume. There were no other statistically significant effects of water volume, dose rate or air assistance although trends suggested that air assistance gave no better and possibly poorer control of aphid which infested the growing point at the top of the pea plant. Damage to peas from the larvae of the pea moth *(Cydia nigricana)* was negligible in 1992. The percentage of damage on untreated peas at quick-freezing and dry harvest stages was low in 1993 but all treatments with the one spray and the two spray programme significantly reduced levels (Table 5). There were no significant effects of dose rates, water volumes or air assistance, although trends suggested that control may have been better without air.

Table 6. *Botrytis* control (one spray) and percentage by weight at harvest of chalky and stained peas (two spray programme)
Vinclozin at N = 500 g a.i./ha

Sprayer treatment				*Botrytis* infected pods (%) 28 DAT		Chalky peas (%)		Stained peas (%)	
	Air	Vol. l/ha	Dose	1992	1993	1992	1993	1992	1993
0.	untreated			38.8	7.2	3.28	4.2	7.06	22.3
1.	+	100	N	12.0	1.8	0.84	2.1	3.38	6.1
2.	-	100	N	20.8	4.1	0.54	1.7	2.91	7.6
3.	+	100	½N	15.2	3.1	0.99	2.1	1.99	8.4
4.	-	100	½N	22.7	5.2	1.08	3.2	4.58	14.2
5.	+	200	N	-	1.5	-	1.1	-	7.8
6.	-	200	N	-	3.4	-	1.9	-	8.7
7.	+	200	½N	-	3.8	-	2.5	-	11.4
8.	-	200	½N	-	4.7	-	3.6	-	12.0
9.	-	200	N	16.0	-	0.51	-	1.48	-
10.	-	200	½N	20.7	-	0.79	-	1.26	-
Significance @ P = 0.05				SD	SD	SD	SD	SD	SD
LSD @ P = 0.05				3.09	0.92	1.298	1.24	1.965	4.93
CV %				20.90	16.30	66.600	24.10	54.000	30.80

In 1992 fungicides applied a little later than optimum timing because of unsettled weather, were too late to prevent *Botrytis cinerea* infection on some of the first pods set. The percentage of infected pods on the rest of the plant was significantly lower than for untreated plots. The number of infected pods was significantly lower where air assistance was used (Table 6). For conventional applications, 200 l/ha performed better than 100 l/ha and control with half dose rates was significantly worse than normal dose rates. However, with air assistance the half dose at 100 l/ha gave better control than sprays without air assistance at 100 l/ha and similar to the normal dose at 200 l/ha. In 1993 the weather was also wet during flowering and pod set, and all sprays significantly reduced percentages of infected peas (Table 6). Irrespective of application method or volume, half dose rates performed significantly worse than normal dose rates. Volumes of 100 and 200 l/ha gave similar levels of control. Air assistance gave a significant reduction in percentage of *Botrytis* infected pods, which occurred at the lower nodes on the pea plant, compared with conventional applications. Chalky, and to some extent stained, peas are caused by *Botrytis* infection and with the exception of half dose rates applied without air in 1993, all treatments significantly reduced the percentages. In both years the least effective applications were without air with half doses. Water volume had little effect on levels of control in 1993 but in 1992 applications with 200 l/ha performed better than 100 l/ha.

Disease control in broad beans

In 1992, levels of infection in broad beans with downy mildew *(Peronospora viciae)* were low and although sprays with metalaxyl appeared to reduce the infected leaf area per plant, and on leaves at all nodes (data not presented), the difference in level compared with the untreated was only statistically significant at the 3rd node from the top of the plant. Here air assisted sprays at the normal dose rate gave significantly better control than other treatments. The ½N dose rates gave a lower level of control.

Table 7. Downy mildew assessed 19 DAT, 1993
Metalaxyl/chlorothalonil at N = 1000/150 g a.i./ha

Sprayer treatment				% leaf area infected downy mildew (mean 15 plants)								
	Air	Vol. l/ha	Dose	Top	node 1	2	3	4	5	6	7	mean of nodes/plant
0.	untreated			45.6	53.3	56.8	59.2	62.7	55.2	30.6	14.4	42.2
1.	+	100	N	0.0	0.5	2.0	3.2	11.4	23.1	8.1	0.8	5.5
2.	-	100	N	2.9	4.9	7.4	13.8	15.8	32.8	9.8	1.2	9.8
3.	+	100	½N	7.8	9.8	13.6	19.2	25.4	35.3	13.3	2.3	14.1
4.	-	100	½N	11.9	15.6	17.7	26.5	30.0	37.0	15.4	5.4	18.1
5.	+	200	N	0.3	0.7	2.2	3.5	10.3	23.6	8.8	1.5	5.7
6.	-	200	N	2.3	3.4	7.9	17.0	16.0	36.6	14.8	3.3	11.4
7.	+	200	½N	10.5	15.9	22.3	24.3	27.4	40.2	11.4	2.8	17.2
8.	-	200	½N	8.6	13.5	15.8	35.0	35.6	50.8	15.0	6.5	20.4
Significance @ P=0.05				SD	SD	SD	SD	SD	SD	SD	NSD	SD
LSD @ P = 0.05				12.29	12.06	11.35	15.45	15.38	16.75	10.57	-	8.63
CV %				84.40	63.20	47.00	40.40	51.20	30.90	51.20	171.6	36.90

In 1993, downy mildew infections occurred at a late stage and became severe in wet humid conditions. Reduction in leaf infections with fungicide application at N and ½N were statistically significant (at $P < 0.05$) compared with the untreated for all treatments except the ½N rates at 200 l/ha without air at node 5, the main site of infection when the spray was applied (Table 7). The action of the fungicide is preventative rather than curative. In many cases (upper nodes 2, 3 and 4) the ½N dose performed significantly worse than the full dose. At N dose rates application of fungicides with air assistance gave better mildew control than without air, particularly at node 3 and the differences were less marked for the 200 l/ha water volumes. However, none of the differences were statistically significant. Control of downy mildew using fine spray quality was not significantly worse with 100 l/ha than with 200 l/ha either with or without air.

CONCLUSIONS

Investigations with field sprayers necessitate the use of large trial areas so the incidence of weeds, pests and diseases is inherently more variable. Statistically significant differences between treatments were thus more difficult to achieve and in these experiments were usually detected only for the half dose rates. Therefore trends have been considered.

Applications of bentazone/MCPB + cyanazine in peas and bentazone alone in broad beans with or without air assistance gave excellent control of weed species which are known to be susceptible to these herbicides. Air assistance improved control of moderately susceptible weeds and those sheltered by the crop. Crop phytotoxicity increased from air assisted herbicides but was slight and transitory. An air assisted spray of cycloxidim and adjuvant oil at half normal dose achieved very good suppression of *E. repens*, better than without air and at an acceptable level in vining peas.

Air assisted sprays gave significantly better control of *Botrytis* in peas probably because spray droplets were directed down to the lower plants of the plant to protect developing pods. Trends also suggested better control of downy mildew *(P. viciae)* in broad beans where sprays circulated to the site of the mildew spores on the undersides of the leaves. Spray deposition studies (not reported here) in peas and broad beans showed that with air assistance, a higher percentage of droplets reached the lower parts of the plant. This appears to support the results for efficacy.

Where the target pest such as aphid infested the growing point of the plant there are indications that air assistance gave inferior control compared with conventional sprays. An observation study in green beans *(Phaseolus vulgaris)* (Knott, 1993) showed that early, air assisted applications of bentazone when there was little ground cover, were less effective than conventional sprays probably because spray bounced off the closed soil surface.

Volumes of 100 l/ha were as effective as 200 l/ha for both application methods and in the case of cycloxidim, 100 l/ha volume performed better. Lower volumes could increase sprayer work rate in the field. Although lower volumes than recommended on the labels for products in this study can legally be used, this is not the case for some other pesticides.

With the possible exception of cycloxidim for *E. repens* suppression in vining peas there seems little scope for reduction in spray doses as low as half rate and still to achieve adequate, consistent control but further work is needed.

Drift from air assisted sprays varies with growth stage and absorptive characteristics of the crop and is greater over closed surfaces i.e. bare ground. Where downwards air assistance reduces spray drift, pesticide applications can be made at the optimum timing. The experiments reported here also suggest better control of weeds and diseases can be achieved. However it is essential for the operator to consider the type of surface to which sprays are to be applied and the position of the target, before deciding whether to use downwards air assistance or not.

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OPERATOR EXPOSURE STUDY

T J TACK , T G MARKS
Ciba Agriculture, Hill Farm Road, Whittlesford, Cambridge, CB2 4QT

J R PURDY
Ciba-Geigy Canada Ltd, Agricultural Division, Mississauga, Ontario, Canada

MRS C SCHULZE
Ciba-Geigy Limited, CH-4002, Basle, Switzerland

ABSTRACT

Operator exposure studies are used to quantify the risk to an operator of a pesticide when applied according to Good Agricultural Practice (GAP). This paper reviews a study recently undertaken in the United Kingdom in support of an application for approval of clodinafop-propargyl (CGA 184927) by the Pesticide Safety Directorate (PSD) with particular reference to critical phases in the study which can affect interpretations of the study.

INTRODUCTION

The use of pesticides in modern agriculture has a degree of risk to the consumer, environment and not least the operator. To investigate the potential risk to a farm operator, clodinafop-propargyl formulated as Topik 240EC was applied to winter wheat through conventional farm machinery following the proposed label recommendation. Using the tiered approach (Carmichael 1993) an operator exposure study was undertaken in May 1994.

The study was designed to simulate the major use pattern of the formulation and to obtain the most relevant information for assessment of risk to workers using the product.

TRIAL DESIGN

The study was designed using proposed Organisation of Economic Co-operation and Development (OECD) guidelines (Chester 1993) as a passive dosimetry investigation using four replicates, to confirm the findings of an earlier study with a similar formulation of clodinafop-propargyl In Canada where 12 replicates were used.

Four experienced and qualified spray operators (National Proficiency Test Certificate PA2 holders) sprayed 50 ha of winter wheat each in one working day, using commercially available spray equipment comprising a tractor-drawn trailer sprayer with hydraulically folding 24 m booms and induction hoppers. This equipment was considered to be typical of that used on the majority of large UK cereal farms where the product was likely to be applied.

Personal Protective Equipment (PPE) was chosen according to label instructions i.e. coverall, separate hat, nitrile protective gloves. A whole-body method was used with workers wearing additionally cotton underwear (long-sleeved T-shirt and long pants) and inner cotton gloves, so that unprotected dermal exposure (deposit on PPE) and protected dermal exposure (deposit on inner clothing) could be measured. Inhalation exposure was measured using calibrated personal air samplers.

Mixing and loading the pesticide and application of the diluted spray solution were carried out by separate operators. This enabled measurement of exposure arising from each of these activities and hence clearly identified the operations with highest exposure.

Unprotected dermal exposure was assessed by analysis of the outer clothing which was sectioned as shown in Figure 1 immediately after removal. Each section was then individually wrapped before delivery to the analytical laboratory. (All samples were packed in solid carbon dioxide for transport to the analytical laboratory.) The inner clothing which was separated into T-shirt, pants and inner gloves before analysis, served as a surrogate skin. This enabled measurement of the amount of pesticide penetrating the outer coverall and nitrile gloves, thus giving a measure of the amount of pesticide penetrating the protective clothing and potentially able to penetrate the operator's skin.

A number of validation procedures and records were performed during the study.

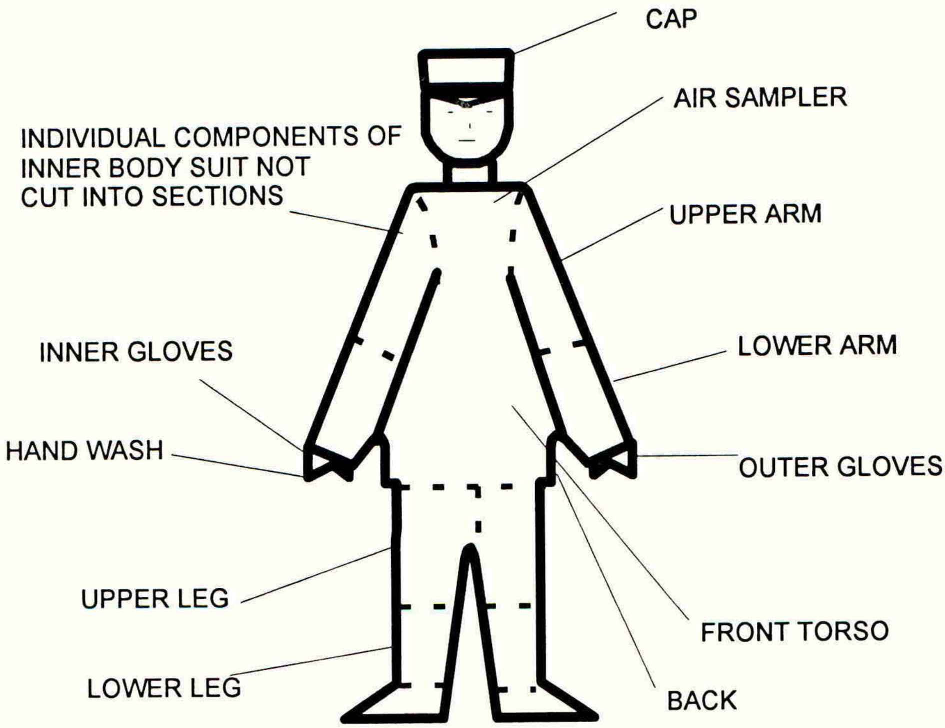
(i) Samples of spray tank liquor were taken from each spray load during spraying to confirm the correct target dose.

(ii) Field recovery 'spikes' were undertaken during both days for the duration of the study. This was done by adding known amounts of spray liquor by calibrated pipettes to sections of cotton coveralls attached to aluminium foil on a wooden board. The values chosen were representative of the total dermal exposure values detected from a previous study. The sections were placed at strategic locations away from the spraying and mixing areas so as to be exposed to the same climatic conditions as the spraying operation.

(iii) Every operation was observed and recorded by an independent observer who undertook no other part of the study. The observers were independent of Quality Assurance. One observer was assigned to each operator. The observers were placed at suitable locations so all aspects of the study could be clearly seen. The role of these observers was important as some unexpected findings could be attributed to the actions of the operators and not a general function of the study.

(iv) A video was taken of the study to assist in regulatory understanding of the study and to support independent observations.

Figure 1. Sectioning of PPE for analysis



The sequence of the study and samples taken is outlined in Figure 2. During spraying, operators did not wear protective gloves as they are not usually worn for this operation, but they were available in a closed box in the cab in case it was necessary for the sprayer operator to handle pesticide contaminated surfaces, e.g., clearing a blocked nozzle. This occurred on one occasion and the results were included in the final assessment.

All samples of PPE taken during and after the study were taken by a designated person wearing disposable gloves. Each sample was wrapped in aluminium foil and where appropriate the sample was turned inside out to avoid loss of chemical by abrasion

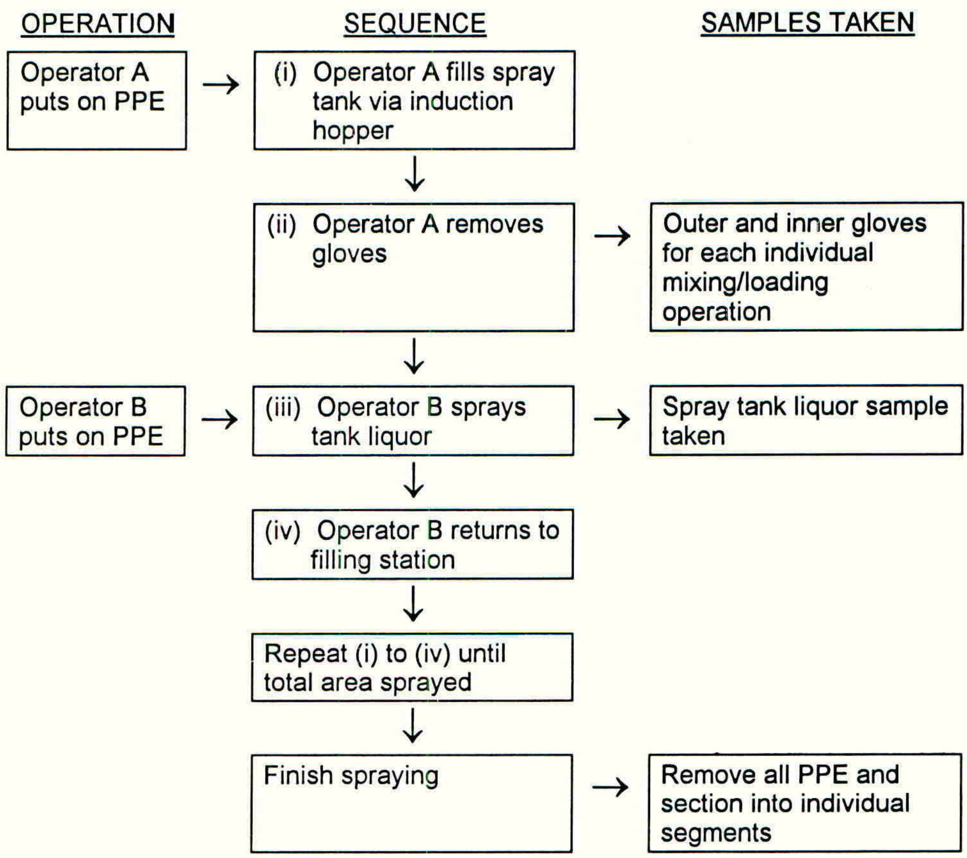
A large clean area away from the test site was dedicated for all PPE sampling to eliminate general contamination and give the operator adequate room to remove the PPE.

ANALYSIS

Samples of PPE including field spikes were analysed for chemical residue by extraction into acetone/pH7 buffer before quantification by electrospray LCMS-MS. Analysis was for CGA 184927 and associated metabolites and the results corrected to CGA 184927 equivalents.

Samples of spray tank liquor were analysed for CGA 184927 only by direct injection on reverse phase HPLC with UV detection.

Figure 2. Sequence of study and samples taken



RESULTS

The stability of the test substance was demonstrated by the analysis of field spike samples and summarised below.

Table 1. Summary of test substance stability

Location	Test Substance	Target Dose µg	% of Target Dose Recovered			
Buckland	CGA 184927	380.0	88.7,	84.4,	98.5,	103.4
		97.5	77.4,	85.2,	97.7,	95.1
		48.7	81.3,	97.1,	71.2,	69.0
Chatteris	CGA 184927	380.0	91.6,	95.1,	90.0,	88.9
		95.0	90.4,	83.8,	63.9,	105.7
		47.5	88.2,	84.0,	81.2,	70.7

Table 2. Summary of CGA 184927 operator exposure

Rep.	Operation	Operator/ Bodywt (kg)	Cotton U/wear (µg)	Inner Gloves (µg)	Hat (µg)	TDX (µg)	REX (µg)	TDX µg/kg bw	REX µg/kg bw	TUDX (µg)
	M+L x 3 +W/0 x 2	95	1.0	1.7	20.9	23.6	0	0.248	0	1466.7
	SPRAY	75	0	0	1.1	1.1	0	0.015	0	1.1
1	TOTAL		1.0	1.7	22.0	24.7	0	0.263	0	1467.8
	M+L x 3 +W/Ox 2	76	5.3	0	6.1	11.4	0	0.150	0	5070.5
	SPRAY	80	1.0	19.0	2.2	22.2	0	0.278	0	29.4
2	TOTAL		6.3	19.0	8.3	33.6	0	0.428	0	5099.9
	M+L x 3 +W/Ox 2	75	15.8	2.4	2.1	20.3	0	0.271	0	2293.9
	SPRAY	95	2.5	7.9	1.1	11.5	0	0.121	0	9.9
3	TOTAL		18.3	10.3	3.2	31.8	0	0.392	0	2303.8
	M+L x 3 +W/0 x 2	80	3.4	3.6	6.3	13.3	0.1	0.168	0.001	1229.8
	SPRAY	76	0	13.4	1.1	14.5	0	0.191	0	16.7
4	TOTAL		3.4	17.0	7.4	27.8	0.1	0.359	0.001	1246.5

Limit of determination 1.0 µg for coveralls and gloves, 0.1 µg for respiratory exposure

All Zero (0) figures are None Detected (ND) on analysis

M+L = Mix and Load
W/O = Wash Out of Spray Tank
TDX = Total Dermal Exposure - underwear + inner gloves + hat
REX = Respiratory Exposure
TX = Total Dermal + Respiratory Exposure
TRX = TX/Bodyweight
TUDX = Total Unprotected Dermal Exposure - outer coverall, nitrile gloves + hat

Systemic exposure was calculated taking account of the proportion absorbed from dermal (55%) and respiratory (100%) exposure as shown in Table 3 where the values of exposure are expressed in ascending order and the 75th percentile shown. (The values in rows do not correspond to each other and are the sum of individual operations/bodyweight calculations.)

Table 3. Total systemic exposure for sum of individual operations

TUDX (μg)	TDX (μg)	Percentage Transmitted Through PPE	TDX/ kg bw (μg)	REX (μg)	REX/ kg bw (μg)	Total Systemic Exposure μg/kg bw	
1246.5	24.7	0.6	0.263	0	0	0.145	
1467.8	27.8	1.4	0.359	0	0	0.197	
2303.8	31.8	1.9	0.392	0	0	0.216	75%tile
5099.9	33.6	2.0	0.428	0.1	0.001	0.236	

DISCUSSION

The results obtained in this study were generally lower than those found in the Canadian study as shown in Table 4. These differences are attributed to the use of a higher dose and lower spray volume and therefore higher concentration of diluted spray in Canada and the use of induction hoppers in the UK study. In both studies the systemic exposure was below any proposed Acceptable Operator Exposure Level (AOEL) derived from the results of toxicological studies, demonstrating that the risk to workers is minimal when using the recommended PPE. The value of using PPE to protect dermal penetration is shown by 1.9% of active ingredients only reaches the skin. This is less than the values used in the Predicitve Operator Exposure Model.

The highest exposure occurred during mixing and loading when the operator has exposure to the undiluted product as shown in Table 5. Each operator performed three mix and load operations during the study, adding a minimum of 39 containers to the spray tank. Most contamination occurred on the protective gloves, but the use of induction hoppers kept coverall contamination relatively low.

Table 4. Comparison of 75 %tile results from exposure studies in UK and Canada

	UK	Canada
Total unprotected dermal exposure (TUDX) - μg/operator	2303.8	8014.0
Dermal exposure (TDX) - μg/operator	31.8	283.0
Percentage transmitted through PPE	1.9	9.0
Respiratory exposure (REX) - μg/operator	0	9.44
Total systemic exposure μg/kg bw/day	0.216	2.36

Table 5. Total unprotected dermal exposure - mixing/loading

Replicate	TUDX Exposure (μg)			Comment
	Outer Gloves	Hat	Coverall	
1	923.1	20.9	522.7	Contamination of front torso and touched hat
2	4762.0	6.1	302.4	
3	2139.3	2.1	152.5	
4	846.2	6.3	367.3	All PPE change after first mix and load

During the study there were three separate mixing and loading incidents, verified by independent observers, which contaminated some parts of the outer clothing. These were:

(i) touching the hat subconsciously while mixing the formulation in the induction hopper

(ii) contamination of the lower legs with diluted formulation due to the incorrect placing of an empty container on the induction hopper mixing/washing system

(iii) incorrect setting of valves on the sprayer allowing some of the spray liquor to splash the operator. The seriousness of this could not be assessed at the time. As the spray tank was full, the operation was allowed to continue but the operator completely changed all PPE. Both the contaminated PPE and the fresh PPE were analysed and included in the results.

By comparison only one incident was recorded during spraying when maintenance had to be undertaken on the spray boom. Outer gloves worn for the maintenance were also analysed and included in the total unprotected dermal exposure (TUDX) calculation.

The incidents above show the value of using independent observers in these studies, enabling what may be atypical results to be satisfactorily explained if necessary.

ACKNOWLEDGEMENTS

The authors wish to thank all the participants from Ciba Agriculture for their time and effort in the conduct of this study.

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SPRAY APPLICATION FACTORS AFFECT DOSE:RESPONSE OF DAMINOZIDE

M. KNOCHE

DLO-Research Institute for Agrobiology and Soilfertility (AB-DLO), P.O. Box 14, 6700 AA Wageningen, The Netherlands

M.J. BUKOVAC

Department of Horticulture, Michigan State University, East Lansing, MI 48824, USA

ABSTRACT

Effects of droplet size and carrier volume on performance of daminozide were established using inhibition of bean (*Phaseolus vulgaris*) internode elongation as an index. At a constant dose (100 µg $leaf^{-1}$) decreasing drop size (10 to 1 µl) and increasing volume (10 to 200 µl $leaf^{-1}$) increased performance. Internode elongation was log linearly related to contact area between droplets and leaf surface. However, elongation was independent of contact area on addition of an equimolar quantity of $NaHCO_3$. Further, the $NaHCO_3$ effect was independent of dose at low (10 µl $leaf^{-1}$) and high (200 µl $leaf^{-1}$) volumes. In contrast to $NaHCO_3$, response to daminozide in presence of the surfactant Triton X-405 was greater at high than low volumes. Possible mechanisms of effects of application factors on performance are discussed.

INTRODUCTION

Spray application is an effective, but inefficient method for delivering pesticides to plants. Only a fraction of the active ingredient (AI) reaches the site of action on or within the plant. A major portion is lost during the spraying process and potentially pollutes the environment (Graham-Bryce, 1976). Hence, increasing efficacy of spray application is desirable from both an economic and ecological point of view. Spray application is a complex process consisting of a series of sequential steps, i.e., droplet transfer to the target, impaction, retention and, for systemic agrochemicals, uptake by and transport within the plant. Optimizing the spray application process therefore requires optimization of any or all of the individual events. Two important application factors affecting efficacy that can be readily controlled include droplet size and carrier volume, both of which affect droplet transfer to the target, impaction and retention. However, little is known about their effects on foliar uptake (Stevens & Bukovac, 1987a; for review see Knoche, 1994).

The objective of our study was to establish the effects of droplet size and carrier volume on biological performance of the plant growth regulator daminozide. We selected daminozide, because of its polar nature and its marked effect on inhibiting stem elongation. Inhibition of internode elongation in bean (*Phaseolus vulgaris*) is a sensitive index of plant response to daminozide and can be easily quantified (Crabtree & Bukovac, unpublished data). Daminozide was applied in the absence or presence of the buffer $NaHCO_3$ or the surfactant Triton X-405 (TX-405). These additives were selected, because (1) preliminary studies established that $NaHCO_3$ reduced daminozide phytotoxicity and (2) TX-405 is a nonionic, nonphytotoxic surfactant similar to those used in pesticide formulations (Lownds & Bukovac, 1988).

MATERIALS AND METHODS

Plant material

Beans (*P. vulgaris* cv. Nerina) were seeded in plastic pots (9-cm diameter, 3 seeds per pot) containing a commercial growing medium. Upon emergence plants were selected for uniformity and thinned to one plant per pot. Growing conditions in the growth cabinet were: 22/20°C day/night temperature, 425 µmol m^{-2} s^{-1} photosynthetic active radiation at plant level with a 14-h light period. Ten days after seeding, plants were transferred to the greenhouse for treatment and further culture.

Chemicals, application and sampling

Simulated spray solutions containing daminozide (purity 99%, technical grade; Uniroyal Chemical Corp.) were prepared with deionized water in the absence or presence of an equimolar quantity of $NaHCO_3$ one day prior to application. Solutions were applied to both primary leaves using a microliter syringe fitted with a mechanical dispenser (Hamilton Co.). Effects of droplet size (1 to 10 µl) and application volume (10 to 200 µl $leaf^{-1}$) were studied at constant daminozide dose (100 µg $leaf^{-1}$). Daminozide concentrations were 10, 5, 2, 1 and 0.5 g l^{-1} for application volumes of 10, 20, 50, 100 and 200 µl $leaf^{-1}$, respectively. Dose:response relationships were established at low (10 x 1 µl droplets $leaf^{-1}$) and high application volumes (200 x 1 µl droplets $leaf^{-1}$) in the presence or absence of $NaHCO_3$ or the surfactant Triton X-405 (Rohm and Haas Co.). TX-405 was added at constant mole ratios of daminozide:TX-405 (613, 61, 6.1 mole ratio daminozide:TX-405, equiv. to 0.1, 1 and 10% wt/V TX-405 at 50 g l^{-1} daminozide, respectively). Daminozide doses ranged from 10 to 500 µg $leaf^{-1}$.

Following treatment, plants were staked and watered and fertilized daily using a diluted nutrient solution. Two weeks after treatment length of first plus second internodes above primary leaves was determined. Preliminary experiments established that elongation of first plus second internodes was completed within two weeks after application (Nakagawa, Crabtree & Bukovac, unpublished data).

Statistics

Plants were grouped by length of first internodes at the time of treatment and internode length was used as a block factor. Initial internode length was always less than 7 mm. Experiments were carried out with 10 replications except for the study on the TX-405 effect where five replications were used. Where appropriate, data were subjected to analysis of variance. Mean comparisons were performed using Duncan's multiple range test ($P \leq 0.05$). Standard error bars were included in all graphs. Where not shown, error bars were smaller than data symbols. Regression analysis was carried out using individual replications. Within additives, slopes of dose-response relationships were compared using the t-test ($P \leq 0.05$). When not significantly different, parallel regression lines were calculated and Y-axis intercepts were subjected to a t-test ($P \leq 0.05$).

RESULTS

Daminozide inhibition of internode elongation was related to drop size and application volume. Decreasing drop size at constant application volume and increasing application volume at constant drop size increased response to daminozide (Table 1). There was no interaction between drop size and application volume. In some replications the leaf tissue underlying droplet residues developed phytotoxic symptoms at the lower application volumes (10 and 20 µl leaf^{-1}) and the larger droplet sizes (5 and 10 µl). Generally, no phytotoxicity was observed at higher application volumes or smaller droplet sizes.

TABLE 1. Effect of droplet size and application volume at constant daminozide dose (100 µg leaf^{-1}) on elongation of first plus second internodes of bean.

Droplet size (µl)	Internode length (cm)[a]					
	Volume (µl leaf^{-1})					
	10	20	50	100	200	Mean
1	7.4	8.5	7.3	8.5	7.6	7.8c
2	12.0	10.6	9.3	8.9	7.8	9.7b
5	14.1	11.6	11.5	10.3	8.2	11.1a
10	13.0	11.1	12.8	10.5	9.0	11.3a
Mean	11.6a	10.5b	10.2b	9.5b	8.1c	

[a] Mean internode length of nontreated plants was 16.7 cm. Means followed by the same letter were not significantly different (Duncan's multiple range test, $P \leq 0.05$).

In preliminary studies, bioassays were carried out at daminozide doses of 500 µg leaf^{-1}. Effects of application factors were similar to those at 100 µg leaf^{-1} (Table 1), but phytotoxicity was common at low volumes (and high concentrations). Since phytotoxicity may be related to the low pH of the daminozide solution (on average pH 3.6), $NaHCO_3$ was added to neutralize the acid function of daminozide (pH 6.5). After adding $NaHCO_3$ there was no consistent effect of drop size and/or carrier volume on internode length, but all treatments inhibited elongation compared to nontreated controls (Table 2). Further, no phytotoxicity was observed in presence of $NaHCO_3$.

TABLE 2. Effect of droplet size and application volume at constant daminozide dose (100 µg $leaf^{-1}$) on elongation of first plus second internodes of bean in the presence of $NaHCO_3$.

Droplet size (µl)	Internode length (cm)[a]					
	Volume (µl $leaf^{-1}$)					
	10	20	50	100	200	Mean
1	4.9a	5.8a	5.1a	7.0a	6.2a	5.8
2	5.6bc	6.1b	4.8c	4.8c	6.9a	5.7
5	6.6a	6.1a	5.4a	5.7a	6.0a	5.9
10	6.9a	6.5a	6.9a	5.1a	6.6a	6.4
Mean	6.0	6.1	5.6	5.7	6.4	

[a] Mean internode length of nontreated plants was 12.1 cm. Means within drop size followed by the same letter were not significantly different (Duncan's multiple range test, $P \leq 0.05$).

Calculating the contact area between spray solution and leaf surface and plotting internode length vs contact area revealed that droplet size and carrier volume effects were related to their effect on contact area (Fig. 1). Internode length decreased exponentially with increasing contact area in the absence of $NaHCO_3$, but was independent of contact area in the presence of $NaHCO_3$. Regression equations for the relationship between log contact area (mm^2) and internode length (cm) were: Length = 15.5 - 2.8 x (log Area), r^2=0.457** and Length = 6.1 - 0.06 x (log Area), r^2=0.002 in absence and presence of $NaHCO_3$, respectively (Fig. 1, Inset).

Internode elongation was log linearly related to daminozide dose in the absence or presence of $NaHCO_3$ or TX-405 regardless of application volume (Figs. 2 and 3, Table 3). Adding $NaHCO_3$ significantly decreased the slope of the dose:response curve at 10, but not at 200 µl $leaf^{-1}$. At high volume, $NaHCO_3$ decreased the Y-axis intercept and hence, increased overall response by about 1.0 cm (Fig. 2, Table 3). In contrast to $NaHCO_3$, TX-405 (mole ratio 6.1 daminozide:TX-405) did not alter slopes of dose:response curves, but increased overall response by about 2.4 and 1.9 cm at low and high volumes, respectively (Fig. 3, Table 3). Higher mole ratios had no consistent and significant effect on Y-axis intercepts (Knoche, unpublished data).

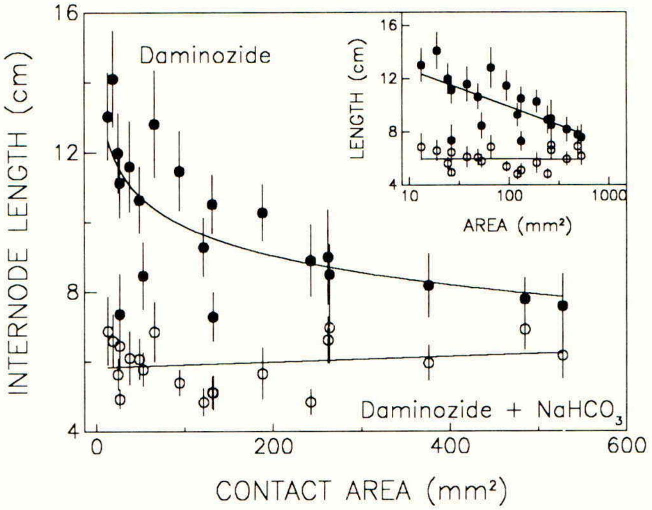

Figure 1. Relationship between the droplet:leaf contact area and daminozide inhibition of internode elongation in the absence or presence of $NaHCO_3$. Inset: Log Contact area vs Internode length.

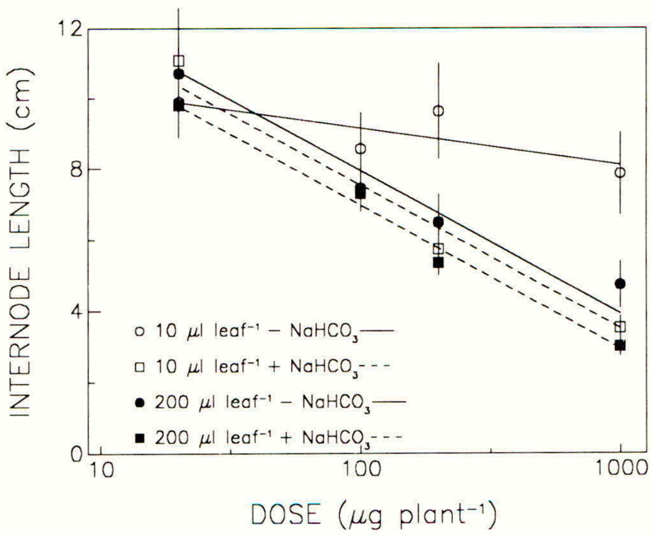

Figure 2. Dose:response of daminozide on internode elongation at low (10 µl leaf^{-1}) and high application volume (200 µl leaf^{-1}) in the absence or presence of $NaHCO_3$.

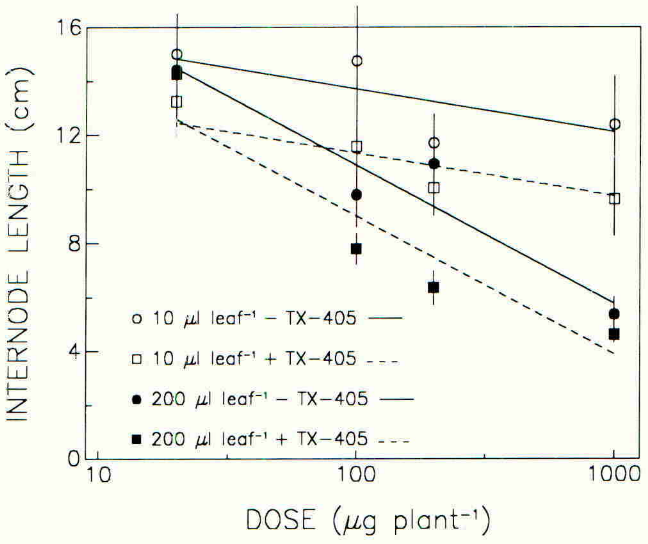

Figure 3. Dose:response of daminozide on internode elongation at low (10 µl leaf^{-1}) and high application volume (200 µl leaf^{-1}) in the absence or presence of TX-405. TX-405 was added at constant mole ratio of daminozide:TX-405.

TABLE 3. Regression equations for the effect of carrier volume on dose:response of bean to daminozide. Daminozide was applied at low (10 µl leaf^{-1}) or high volumes (200 µl leaf^{-1}) with or without $NaHCO_3$ or TX-405, respectively. The regression model was Length (cm) = a x [log Dose (µg plant^{-1})] + b.

Volume (µl leaf^{-1})	Additive	Parameters of regression equations		Coefficient of determination (r^2)
		a (SE)	b (SE)	
10	- $NaHCO_3$	-1.1 (0.9) a[a]	11.3 (2.0)	0.740
	+ $NaHCO_3$	-4.0 (0.2) b	16.0 (0.6) a	0.740
200	- $NaHCO_3$	-4.0 (0.2) b	15.6 (0.6) ab	0.740
	+ $NaHCO_3$	-4.0 (0.2) b	15.0 (0.6) b	0.740
10	- TX-405	-1.6 (0.5) a	16.9 (1.2) a	0.648
	+ TX-405	-1.6 (0.5) a	14.5 (1.2) b	0.648
200	- TX-405	-5.1 (0.4) b	21.1 (1.1) a	0.648
	+ TX-405	-5.1 (0.4) b	19.2 (1.0) b	0.648

[a] Parameter estimates within additives followed by the same letter are not significantly different (t-test at $P \leq 0.05$). For details, see statistics.

DISCUSSION

Our findings confirmed earlier observations indicating that performance of daminozide following spray application in field and greenhouse trials was positively related to carrier volume (Rogers & Krestensen, 1973; Lownds & Bukovac, unpublished data). However, in our system effects of application factors on performance were reduced to their effects on foliar uptake, since (1) simulated spray droplets were placed rather than sprayed on the leaf surface, thus delivering a finite dose to each leaf, (2) the ratios of $NaHCO_3$:daminozide and TX-405:daminozide were maintained constant when varying application volume, thereby avoiding confounding due to a simultaneously changing formulant:AI ratio, and (3) internode elongation was dose dependent (Figs. 2 and 3), hence ensuring that effects on uptake efficacy were readily detected.

The initial phase of foliar uptake is a diffusion process and, for a non-volatile AI such as daminozide, penetration is limited to the contact area between spray solution and leaf surface. Movement across this interface, i.e. penetration, is related to (1) the mobility of the AI in the cuticular membrane and (2) the physical chemical characteristics of the donor. Effects of application factors on daminozide mobility in the cuticle were unlikely. First, daminozide mobility in the cuticle was independent of daminozide concentration (Schönherr & Bukovac, 1978). Second, there was no evidence for $NaHCO_3$ altering AI mobility. As an ionic and highly polar compound it is unlikely to partition into the cuticle. Third, TX-405 was ineffective in increasing AI mobility in isolated cuticles (Knoche & Bukovac, 1993). Thus, application factors most likely affected the donor characteristics of the droplet residues with no effect on daminozide mobility in the cuticle. Time course studies revealed that most daminozide penetration occurred after droplet drying (Knoche, unpublished data). Therefore, the droplet residue represented the primary donor in our study.

Important donor characteristics with respect to penetration are (1) the concentration gradient between droplet residue and cuticle, (2) the partition coefficient (K) of the AI between droplet residue and cuticle and (3) the crossectional area of diffusion, i.e., the contact area between the AI in the droplet residue and the cuticle. Assuming complete removal of penetrated AI from the cell wall, the concentration gradient would correspond to the donor concentration, i.e., the amount of AI in the droplet residue divided by the volume of the residue solution. In an ideal system, where (1) the volume of the residual solution is independent of time, (2) the AI concentration of the droplet residue is independent of application factors, (3) AI mobility in the cuticle is constant, and (4) the AI is not accumulating in the receiver, initial rates of penetration would be expected to be positively related to the crossectional area of diffusion. However, the total amount penetrating at equilibrium may be independent of area provided that all of the AI in the residue was available for uptake. In such a system, performance would be affected by application factors, if performance was related to the initial penetration rates, but may be independent of area, if related to total uptake at equilibrium. Preliminary studies established that daminozide inhibition of internode elongation decreased as initial internode length at the time of application increased. This observation suggested that responsiveness of plants changed with time and developmental stage. Provided that the responsive phase of the plant ended before penetration equilibrium was reached, performance would be expected to be affected by application factors. In contrast, if the responsive phase extended beyond the time to reach penetration equilibrium, performance may be independent of application factors. Unfortunately, no information is available on the donor characteristics in our system and we do not know how $NaHCO_3$ or TX-405 altered the driving forces. However, based on the arguments presented above the following hypothesis may be proposed.

Daminozide

In the absence of $NaHCO_3$ or TX-405, daminozide formed white, powdery, macroscopically dry droplet residues indicating that daminozide crystallized on the leaf surface. However, since penetration occurred from the residues, these deposits must have been partially hydrated. In the absence of solvents or hygroscopic substances, deposit hydration was likely limited to a thin layer of the deposit in intimate contact with the leaf surface. Daminozide mobility in the residue was probably restricted to this hydrated portion of the residue, while crystallized daminozide in the nonhydrated portion was not available for penetration. In a deposit of such characteristics, the amount of mobile AI in the residue would be expected to be positively related to contact area as would be the initial rates of penetration and total amounts taken up. This hypothesis would account for a positive relationship between contact area and response.

Daminozide plus TX-405

The surfactant rich residues of daminozide plus TX-405 appeared to be "wet" throughout the experimental period. This was expected, since TX-405 is (1) hygroscopic (Stevens & Bukovac, 1987b) and (2) a large (MW 1966) and polar molecule with limited cuticular penetration. Therefore, the surfactant effect most likely was limited to effects on deposit characteristics. At present we do not know the solubility of daminozide in TX-405 and the *K* of daminozide between TX-405 and the cuticle. However, driving forces were independent of application factors in our study, since mole ratios of daminozide:TX-405 were maintained constant. Consequently, the composition of the deposit and the microenvironment of the AI in the deposit most likely were independent of application factors. Hence, the carrier volume effect observed in the presence of TX-405 may be attributed to increased penetration rates at the high volume.

Daminozide plus $NaHCO_3$

The absence of effects of application factors in the presence of $NaHCO_3$ suggested that uptake during the responsive phase of the plant was independent of contact area. This hypothesis is difficult to explain based on the arguments presented above, since rates of penetration were also expected to be positively related to area. Similar to TX-405, $NaHCO_3$ was added at a constant mole ratio. Consequently, the composition of the droplet residues and hence, pH and the *K* of daminozide between residue and cuticle were expected to be independent of application factors. However, differential rates of penetration do not necessarily imply differences in penetration at equilibrium. For example, in presence of $NaHCO_3$ droplet residues appeared "wet" and translucent indicating that daminozide crystallization on the leaf surface was reduced. Provided that resolubilization of the crystallized daminozide kept pace with penetration, the total amount penetrating at equilibrium may be independent of area. If penetration equilibrium was reached within the responsive phase of the plant, this argument would account for the absence of effects of application factors on performance. However, it has to be pointed out that these arguments are highly hypothetical. There was no evidence for $NaHCO_3$ increasing rates of daminozide penetration. First, $NaHCO_3$ increased pH of simulated spray solutions, thereby increasing daminozide dissociation. Since penetration of the dissociated species was limited (Schönherr & Bukovac, 1978), penetration rates were expected to decrease rather than increase upon addition of $NaHCO_3$. Second, $NaHCO_3$ is a polar and ionized molecule and only limited penetration would be expected. Therefore, $NaHCO_3$ will remain on the leaf surface and the volume of the residue solution would be unlikely to change with time. If the residue volume decreased for example due to removal of $NaHCO_3$ from the residue, the residual solution would maintain a high driving force for daminozide penetration accounting for increased rates of penetration even if cuticle permeability was not directly affected (Schönherr & Baur, 1994).

At present we do not know the mechanism of the $NaHCO_3$ effect and further studies are necessary. The characteristics of the droplet residue may be far more complex than the homogenous deposits assumed in the above discussion. In fact, some data suggest that deposits are heterogenous structures covering a significantly smaller contact area than the one covered by the droplet prior to drying (Bukovac et al., 1986; Bukovac & Petracek, 1993). Further complications may arise from a heterogenous AI distribution within such deposits resulting for example from sequential precipitation events. So far, little is known about such deposits, but interactions with effects of application factors may occur and are likely to alter subsequent penetration.

CONCLUSION

Our data demonstrate that application factors may alter daminozide performance in a formulation specific manner. Further, effects of droplet size and carrier volume were shown to be related to their effect on the contact area between spray solution and leaf surface. These findings have significant practical relevance. While increasing contact area by decreasing droplet size will improve performance, the efficacy of droplet transfer from the sprayer to the plant is likely to decrease. In contrast, coverage may be improved by increasing carrier volume at constant drop size without compromising efficacy of droplet transfer. Further, the formulation specific effects of application factors on performance indicated that special attention is required for development of pesticide formulations suitable for low volume applications. Mechanistically, effects of application factors on foliar uptake may be related to (1) effects on AI mobility in the cuticle provided that components of the spray solution alter AI mobility in a concentration dependent manner or (2) effects on donor characteristics of the droplet residues. The role of apparently dry droplet residues as a donor for foliar uptake has not received adequate attention even though an increasing number of studies (e.g. Baker & Chamel, 1990; Bukovac & Petracek, 1993) revealed that the droplet residue represented the primary donor in foliar uptake. A detailed understanding of the donor properties of droplet residues and how they are affected by application factors and formulation is a prerequisite to provide a sound basis for increasing efficacy of spray application by optimizing the application factors droplet size and carrier volume.

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THE CLASSIFICATION OF AGRICULTURAL SPRAYS BASED ON DROPLET SIZE DISTRIBUTIONS AND THE RESULTS FROM WIND TUNNEL TESTS

P C H MILLER; R W SMITH; C R TUCK; P J WALKLATE
Silsoe Research Institute, Wrest Park, Silsoe, Bedford, MK45 4HS

ABSTRACT

The results from measurements of droplet size distribution using a laser-based instrument and airborne spray volumes in wind tunnel tests estimated from horizontally mounted sampling collectors are reported and used to indicate how an existing classification of spray quality can be modified and extended. The existing classification scheme defines characteristic reference nozzles for fine, medium and coarse spray qualities based on the measurement of cumulative droplet size distributions and determines the spray quality boundaries by interpolation. It has been suggested that the scheme could be improved by using defined reference nozzle conditions to produce sprays that would then define the spray quality boundaries for any measurement system and the results presented in this paper show this to be a feasible approach.

The extension of the existing droplet size based classification system to include an element relating to the risk of drift when operating on a conventional boom sprayer has also been shown to be feasible and valuable. A difference in the airborne spray profiles downwind of flat fan nozzles operating singly or in multiple boom arrangements has been established for low wind speed conditions (circa 2 m/s). This result confirms a need to review the protocols for such wind tunnel tests and the ways in which the results from such tests are used in a spray classification system.

INTRODUCTION

The classification of agricultural sprays was introduced to give a relative indication of the droplet size distribution within a spray (Doble *et al.*, 1985). It has been recognised that the numerical results given by different instruments sampling sprays from the same nozzles and with the same operating conditions differ (Arnold, 1987), depending upon the operating principles of the instrument (Parkin, 1993) and the method of sampling the airborne spray (Frost and Lake, 1981). An approach based on characteristic reference flat fan nozzles was therefore proposed to define five spray categories of very coarse, coarse, medium, fine and very fine. This is now being used successfully as the British Crop Protection Council (BCPC) spray and nozzle classification to provide information on product labels and in codes of practice.

A spray classification based on droplet size provides important information relevant to the application of pesticide formulations that are sensitive to surface coverage and other droplet size distribution effects. There is also increasing concern relating to the risk of spray drift from different nozzle systems operating on a conventional boom sprayer. As a first approximation, the risk of spray drift has been related directly to the droplet size distribution (Anon, 1990). However, the risk of drift for a given droplet size distribution is a function of spray structure, droplet velocities and entrained air conditions (Miller *et al.*, 1993). The use of wind tunnel approaches has therefore been proposed as a method of adding an indication of the risk of spray drift to the existing classification method based on droplet size distributions.

A collaborative study was conducted in the UK aimed at developing test protocols for use in wind tunnels. Airborne spray profiles measured at a defined downwind distance of 2.0 m from the nozzle were compared for a range of different wind tunnel configurations using different sampling systems to quantify the volumes of airborne spray from a range of types of spray generator. The results from this work showed relatively good agreement between the values obtained for the different wind tunnels and sampling methods used in the study. This agreement was further improved when the results were normalised using data relating to the reference flat fan nozzles defined in the existing BCPC system. The results from the study were also used to make recommendations relating to test protocols for wind tunnel tests for spray nozzle classification purposes which included:

- the use of a single spray generation system with a defined orientation (when relevant) to the air flow;

- the use of wind tunnels having a minimum cross-sectional area of 1.5 m^2 with air speeds in the range 2.0 - 2.5 m/s and with relatively low levels of turbulence;

- airborne sampling techniques with a high collection efficiency; and

- interpretation of the results based on normalising measured airborne profiles using data for defined reference spraying systems.

It has also been envisaged that the use of wind tunnel approaches may provide a basis for the classification of sprays from systems that have been difficult to classify in the existing BCPC scheme. This is particularly relevant to the classification of sprays which have cumulative volume/droplet size characteristics that are very different from those of the reference flat fan nozzles (eg. spinning discs and some hollow cone nozzles) and in sprays which have "air inclusions" in some of the droplets (eg. twin-fluid and venturi nozzle designs).

At an international meeting held in Rotterdam in 1994 it was agreed that the existing BCPC spray classification scheme should be modified and extended by:

(a) defining nozzle conditions that would create sprays that could be used to define the boundaries between fine/medium, medium/coarse and coarse/very coarse spray qualities; and

(b) defining wind tunnel test protocols and methods of data interpretation that can be used to extend the existing scheme to include an element of drift risk assessment.

This paper describes some initial work that seeks at providing information relevant to the above objectives. Droplet size distribution data for defining the fine/medium, medium/coarse and coarse/very coarse spray quality boundaries is presented together with the results from wind tunnel tests with single and multiple boom arrangements of flat fan nozzles. The wind tunnel data is relevant to the definition of test protocols for nozzle classification purposes and has formed part of a collaborative project involving the Federal Biological Research Centre (BBA) in

Braunschweig, Germany and Silsoe Research Institute in the UK (Miller *et al.*, 1995).

MATERIALS AND METHODS

Measurement of droplet size distributions

Droplet size distributions were measured using a single component phase-Doppler analyser (Dantec Ltd) operating with a 400 mW Argon ion laser. The instrument was fitted with 600 mm focal length lenses on both the transmitting optics and the receiving optics with the analysis software configured to measure droplets in the range 0 to 825 μm. The instrument was arranged such that the sampling volume was 350 mm below the nozzle orifice and droplet velocities were measured in the vertical plane. To enable the whole of the spray fan to be sampled, the nozzle was mounted on an x-y transporter which was programmed to give up to 56 scans through the short axis of the flat fan sprays with each scan being 300 mm long and a distance of 20 mm between scans. The speed of the nozzle movement was 40 mm/s.

All measurements were made spraying water and 0.1% of a non-ionic surfactant. The liquid supply to the nozzles was from pressurized containers with the liquid pressure monitored immediately up-stream of the nozzle and controlled to the set value by adjusting the input air pressure to the feed canister. Data was analysed using purpose-written software at Silsoe Research Institute.

Measurements were made with the reference flat fan nozzles used in the existing BCPC classification system. Additional measurements were also made with plastic F110/1.2/3.0, F110/1.95/2.0 and F80/2.92/2.5 nozzles to define the fine/medium, medium/coarse and coarse/very coarse spray qualities respectively. These nozzle conditions were selected based on proposals made by Heestermans (1994) and presented at the international meeting in Rotterdam.

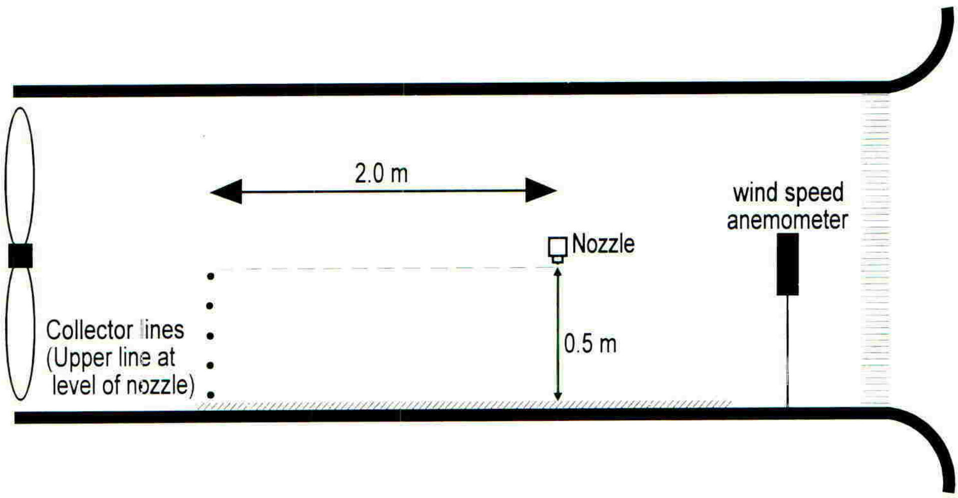
Wind tunnel measurements

Two series of wind tunnel tests were conducted at Silsoe Research Institute: the first examined the effects of using multiple and single nozzles in the air flow and the second measured the drift with the F110/0.49/4.5, F110/1.2/3.0 and F110/1.95/2.0 nozzles used to define the boundaries between fine/medium and medium/coarse spray qualities.

For the single and multiple nozzle experiments, a small boom was constructed supporting three flat fan nozzles spaced 0.5 m apart. The feed to the nozzles was arranged such that the centre nozzle was supplied with a tracer dye solution (0.05% of Green S, Warner Jenkinson) while the supply to the two outer nozzles was of water only. The spray liquid to all nozzles also contained 0.1% of a surfactant (Tween 80, ICI America). Both supplies were from pressurized canisters with the spraying pressure monitored close to the nozzles and adjusted by varying the input air pressure to the canisters. The supply to each of the nozzles was controlled by solenoid valves such that the spraying times of 5, 10 and 12 s could be controlled by an electronic timer. All measurements were made in a mean wind speed of 2.0 m/s which as measured with a three dimensional sonic anemometer (Gill instruments) mounted at the nozzle height in the inlet section of the tunnel.

The airborne spray was collected on a matrix of 1.98 mm diameter polythene tubing which consisted of five lines supported horizontally across the tunnel at a vertical spacing of 100 mm. After spraying for the pre-set time and allowing the deposits on the sampling lines to dry, each line was sectioned into 100 mm lengths and the volume of airborne spray was quantified using spectrophotometric techniques. A diagram of the experimental arrangement is shown in Figure 1. Measurements were made with two sizes of nozzle, F110/0.6/3.0 and F110/1.6/2.5 which produced sprays typical of the fine and medium spray qualities in the existing system respectively. Spraying periods of 10 and 12 s were used for the fine and medium spray quality nozzles respectively.

Figure 1 : Diagram of wind tunnel arrangement



In the second series of experiments, single nozzles were used in a mean wind speed of 3.0 m/s. The experimental techniques were similar to those above but the deposits on the sampling lines were determined for the full line only with no sectioning. A spray time of 5 s was used for all nozzle sizes defining the very fine/fine, fine/medium and medium/coarse spray quality boundaries.

For all the experiments, the floor of the tunnel was covered with a plastic grass material to minimise spray bounce. All measurements were replicated at least twice.

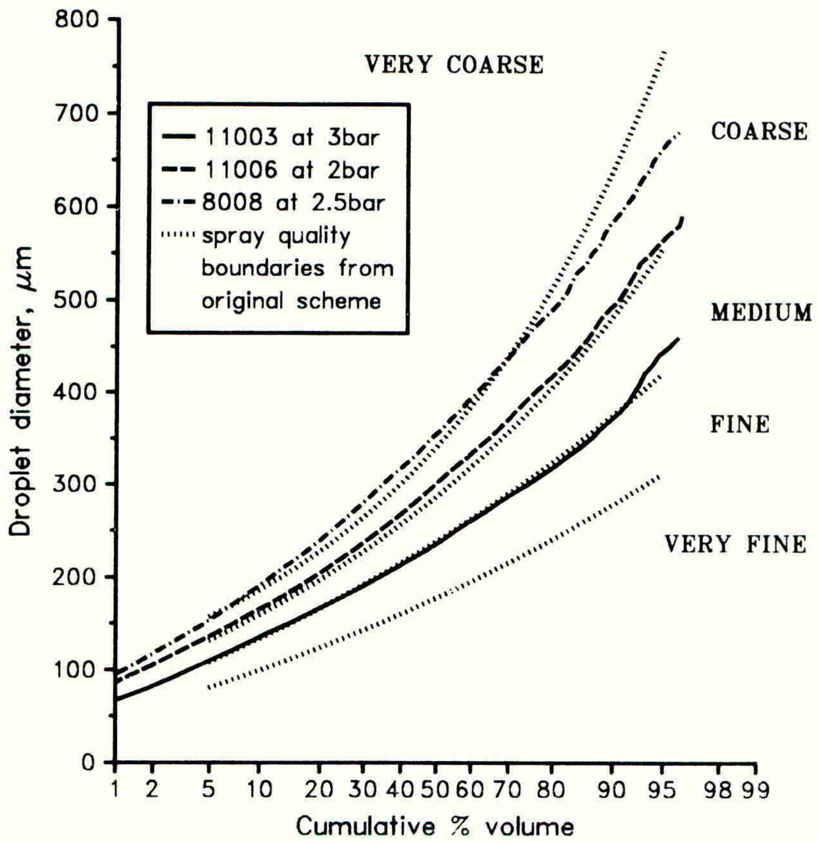
RESULTS AND DISCUSSION

Droplet size distribution

Results from the droplet size measurements made with the nozzle conditions selected to be comparable with the existing spray quality boundaries are plotted in Figure 1 together with those boundaries determined according to the existing protocols and reference nozzles. The agreement between the fine/medium spray quality boundary determined from the F110/1.2/3.0 nozzle and by the existing interpolative methods is very good. Reasonable agreement was also found for the medium/coarse and coarse/very coarse spray quality boundaries determined by the two methods although there was some evidence that the spray from the F110/1.95/2.0 nozzle gave a spray that was slightly coarser than the boundary determined by the interpolating routines and that the F80/2.92/2.5 nozzle gave a different shaped cumulative volume/droplet size characteristic.

The results plotted in Figure 2 are the mean values from three replicated measurements and plastic nozzle tips were used in each case. It is likely that the nozzle tips to be used in a revised definition of the classification protocols will be of stainless steel and hence further work is now required to:

Figure 2 : Comparison of spray quality boundaries determined with existing protocols and reference nozzles and with alternative reference nozzle conditions



(a) verify that equivalent results can be obtained with designs of stainless steel nozzle tip selected probably from different manufacturers; and

(b) that similar relative results are obtained with the above nozzles and existing protocols when using a range of different measurement systems in different laboratory situations.

When data from the above investigation is available, then it will be necessary to review the level of agreement between spray qualities obtained with existing and new proposed protocols and to adjust the reference spraying conditions in the new protocols if appropriate. Preliminary results with a Particle Measuring Systems instrument indicate that some adjustments to the new nozzle reference conditions may be required.

Wind tunnel tests with single and multiple nozzle arrangements

The results of the total airborne spray deposits measured on each sampling line are summarised in Table 1.

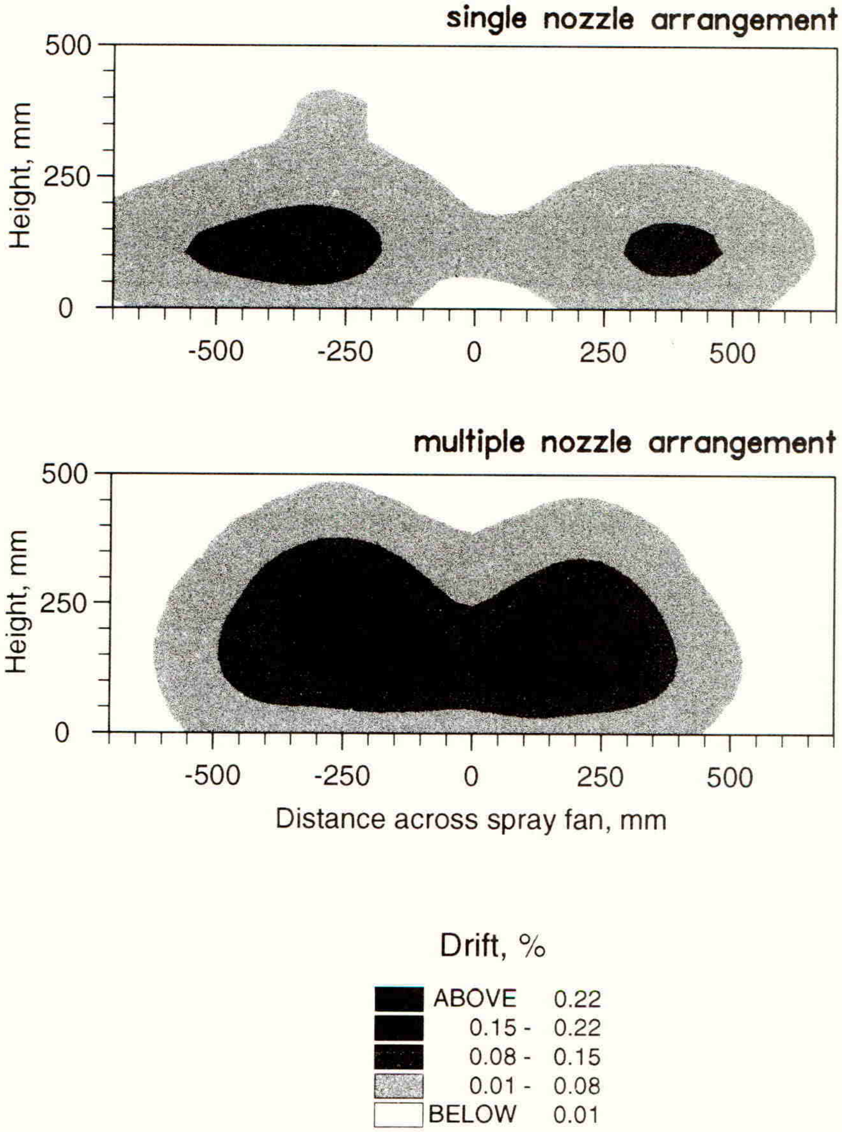
Table 1. Sampling line deposits for single and multiple nozzles in the wind tunnel test at a wind speed of 2.0 m/s

Height of sampling line below the nozzle, mm	Estimated airborne spray for each 100 mm height increment expressed as a percentage of nozzle output			
	F110/0.6/3.0 nozzle		F110/1.8/2.5 nozzle	
	single	multiple	single	multiple
400	4.84	3.78	1.42	1.47
300	4.79	4.21	0.54	1.41
200	1.77	4.41	0.09	0.86
100	0.23	1.48	0.01	0.22
0	0.03	0.03	0.00	0.02
Total airborne spray, % of nozzle output	12.27	14.49	2.25	4.18
Standard error, % of nozzle output	0.29	0.06	0.01	0.25

As expected, the levels of airborne spray measured 2.0 m downwind of the nozzle and expressed as a percentage of nozzle output were much higher for the nozzle creating a fine quality spray (F110/0.6/3.0) than for the medium quality spray (F110/1.8.2.5). The ratio of the measured airborne spray volumes is in reasonable agreement with other published data from wind tunnel (Miller *et al.*, 1993) and field experiments (Gilbert and Bell, 1988). There were significant differences between the multiple and single nozzle cases for both sizes of nozzle with higher airborne spray volumes measured in the case of the multiple nozzle configuration. For the larger nozzle size, the total quantity of airborne spray measured in the multiple nozzle case was 85.8% greater than with the single nozzle whereas for the smaller nozzle the increase was 18.1%. There are also differences in the measured airborne spray profiles for the two configurations with larger volumes found at the higher levels with the multiple nozzle configuration.

The difference in airborne spray profiles can also be seen in Figure 3 which plots the measured deposits on the sectioned lines as vertical contours again as percentages of nozzle output. As well as having a larger total volume of airborne spray and at greater heights, the airborne spray from the multiple nozzle configuration is also narrower.

Figure 3 : Measured airborne spray profiles for the F110/1.8/2.5 nozzle 2.0 m downwind in a wind speed of 2.0 m/s



The observed patterns are consistent with the hypothesis that in low air speed conditions, the spray acts as a bluff body with the air flow going around the spray. In the case of multiple nozzles, the air flow is therefore accelerated through the regions between the adjacent nozzles on the boom. Studies at Braunschweig in Germany (Miller *et al.*, 1995) have shown that at higher wind speeds (circa 6.0 m/s), the air flow will penetrate the spray structure and hence the difference between multiple and single nozzle configuration is eliminated. However, air speeds of 6.0 m/s and greater at nozzle height are not typical of the conditions on most boom sprayers arising from a combination of the forward speed of the sprayer and the natural wind. The difference in the behaviour with the two nozzle sizes is also consistent with expectation. Previous studies (Ghosh and Hunt, in press) have shown that the penetration of an air flow into a spray fan is a function of the ratio between the cross air flow velocity and the entrained air velocity. The larger nozzle size will have a higher entrained air velocity, a more dense spray cloud and will therefore provide a greater resistance to the air flow. This then gives a greater difference in airborne spray profiles between single and multiple nozzle configurations.

Protocols for nozzle classification based on wind tunnel experiments therefore have to account for the observed differences between the results found with multiple and single nozzle arrangements particularly if single nozzles are to be used in the wind tunnel tests and related directly to sprayer performance in field conditions. Existing recommendations concerning wind speed conditions for wind tunnel testing of between 2.0 and 2.5 m/s at the nozzle are in a range where there are likely to be effects due to the effective porosity of the spray to the air flow. Such effects are also likely to differ between different nozzle types and sizes.

Further work to define wind tunnel protocols and to relate wind tunnel results to those from field measurements is continuing.

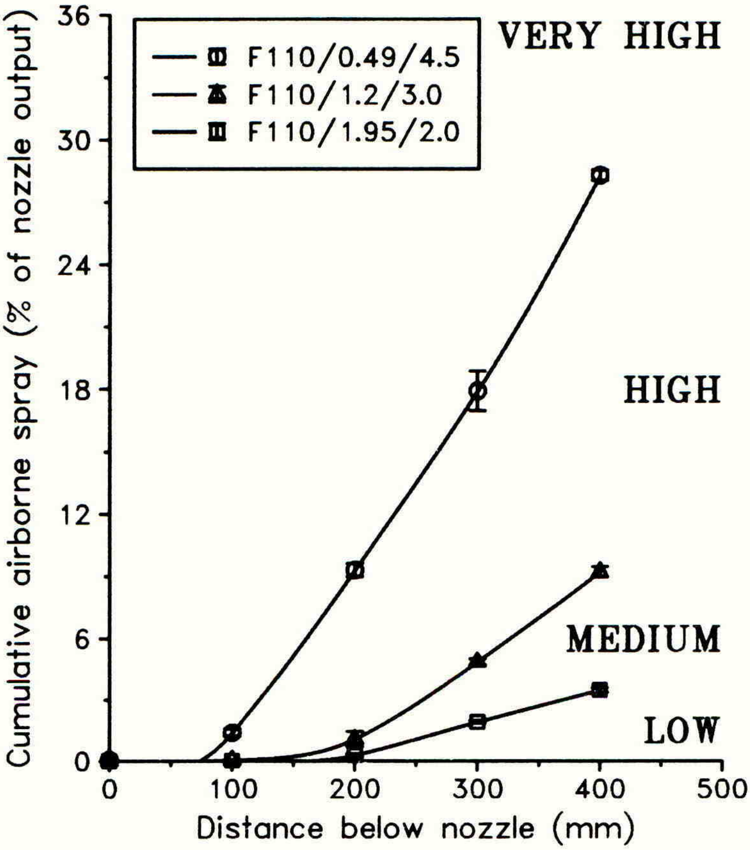
Wind tunnel tests with the nozzles defining the spray quality boundaries

The measured airborne spray profiles for the three nozzle conditions used to define the boundaries between very fine/fine, fine/medium and medium/coarse spray qualities are plotted cumulatively on Figure 3. It can be seen that if these nozzles are also assumed to define the boundaries between low/medium, medium/high and high/very high drift risk, then a similar approach to that taken for spray classification in terms of droplet size distribution (Doble *et al.*, 1985) can also be used for the drift risk classification. Such an approach may also account for the conditions where total airborne spray volumes from two nozzle systems are similar but with one system giving the airborne spray at a greater height which, under field conditions, would then be more susceptible to drift (Castell, 1993). Such nozzles would produce a characteristic having a different gradient on a plot such as that in Figure 4 and the drift risk could be equated to the highest value through which the curve passed.

CONCLUSIONS

The proposed nozzle conditions for defining the spray quality boundaries between fine/medium, medium/coarse and coarse/very coarse give reasonable agreement with those boundaries defined in the existing system based on interpolative approaches. Further work is in progress to confirm new reference nozzles which will be made in stainless steel and to verify that comparable results are obtained with a range of different measurement systems.

Figure 4 : Measured airborne profiles in wind tunnel tests for the nozzles used to define spray quality boundaries



Wind tunnel approaches will provide a basis for extending the existing classification system to give a measure or drift risk and to aid the classification of spray systems that have been difficult to classify in the existing system. The definition of wind tunnel protocols will need to account for likely nozzle interactions on a boom sprayer.

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DEPOSIT MEASUREMENTS AND BIOLOGICAL EFFICACY, THE EFFECTS OF VOLUME RATES AND AIR ASSISTANCE ON WEED CONTROL

J C VAN DE ZANDE
IMAG-DLO Institute of Agricultural and Environmental Engineering, Mansholtlaan 10-12 PO Box 43, 6700 AA Waginen, The Netherlands.

ABSTRACT

Three years of experiments were done on the deposition of spray liquid and the biological effects on weed control in a winter wheat crop. The sprayers used were equipped with different nozzle types. Two types of hydraulic nozzles (XR11003 and XR11002) and one twin-fluid nozzle (Air-jet) were used to spray 100 l/ha or 200 l/ha.

The amount of deposition of spray liquid was established by washing paper strips suspended in the crop using Brilliant Sulfo Flavine (BSF).

In addition to absolute deposition (quantity of chemical), the coverage and droplet spectrum on the target area were determined by video recordings of the spray deposition on water sensitive paper that was suspended in the crop. The video recordings were analysed by means of vision technology. Biological effects of the sprayings were investigated by quantifying the number of weed plants before and after the application of Starane/CMPP combination. Spray concentrations ranged from 0% to 100% of the dose recommended. The use of the different application techniques resulted in differences in efficacy on weed control. Differences were found between volume rates. Within the 100 l/ha volume rate also differences occurred between the nozzle types and air-assistance.

INTRODUCTION

Because of environmental contamination, a general reduction in the use of pesticides is required. The aim of the Netherlands is to reduce the use of pesticides by 50% by the year 2000. Drift of spray to surface water next to cultivated land should be reduced by more than 90% (Tweed Kamer der Staten Generaal, 1991). In accordance with the Multi Year Crop Protection Plan, research has been set up to develop improved application techniques for pesticides. Improvements in spraying application techniques can contribute to these goals by better deposition on the leaves and reduction of drift to soil, surface water and air (Tijink, 1993).

If the essential aspects of dose-effect relations of the chemicals are not well understood, this is often compensated for by an over dose of the active ingredient. Reducing the use of chemicals now having top priority, more attention needs to be paid to achieving better leaf coverage with less chemical. Furthermore, emission of crop protection chemicals is a major problem in crop protection. New spray application techniques might improve the deposition and reduce drift. In a series of experiments spray deposition and biological effect were determined in a winter wheat crop using a sprayer equipped with twin-fluid nozzles and an air assisted system. Water volumes, the dose of active ingredient, and the use of air-assistance was compared.

MATERIALS AND METHODS

During three growing seasons (1991-1993) field trials were established in a crop of winter wheat (cv. Obelisk) at De Kandelaar Research Station. Plots measuring 10m wide by 21m long, were marked out in a randomised block design incorporating three replicates. Sprayers used were a Douven twin fluid (air-jet) and a Douven sleeve boom sprayer. For air assistance the sprayer was operated at it's maximum air flow with nozzles and air assistance kept vertical. Because of it's ability to operate without air assistance the Douven sleeve boom sprayer was used to apply the standard conventional non air-assisted spray treatments. The air sleeves on the machine were folded. The following treatments (Table 1) were used.

Table 1 Settings Sprayers used for treatments

Volume Rate (l/ha)	Nozzle Type	Pressure Water	Air	Spray Quality (BCPC)
200	XR11003	2.5	-	Medium
100	XR11002	1.5	-	Fine
100	XR11002	1.5	Full	Fine
100	Airjet Tk-vs10-35	2.1	0.7	Medium

For all treatments tractor speed was 6.5 kph, boom heights were 0.5m above the crop canopy.

Spray deposition

The trial areas for the deposition measurements were in a strip alongside the field trial. At the time of herbicide application, deposition measurements were carried out by adding the fluorescent dye Brilliant Sulfo Flavine (BSF) to the spray agent (0.5g/l water). The detergent Agral N was added in a concentration of 1ml/l water to simulate a pesticide formulation. After spraying the dye was extracted from the collectors. The collectors used were chromatography paper strips 20cm long and 2cm wide, folded around bamboo sticks, and 100 x 8 cm filter tissues on the soil surface, simulating a broad leaved weed. Collectors were placed systematically at three positions under the sprayer boom. A single spray pass was made across each target. The rate was measured by fluorimetry and expressed per surface area of the collector. The measured deposits were expressed as a percentage of the application rate of the sprayer (dose). In addition to the absolute deposition (quantity of chemical), the results included the coverage and droplet spectrum on the target area. For this part of research, video recordings were analysed by means of vision technology. Results are not reported.

Biological effect

Biological effects of the sprayings were investigated in randomised field trials during three consecutive growing seasons (1991-1993). In each growing season the level of weed control was measured by means of counting weed populations. Countings were done before and after spraying in three defined places, and in three randomised places covering a total area of $1.5m^2$ per plot. The level of weed control in the crop were recorded at time of application and at fortnightly intervals until no effect of desiccation was registered.

A single herbicide treatment (a mixture of Starane + CMPP both at 1 l/ha) was applied at an early growth stage of the winter wheat in April. Doses varied from 100%, 75%, to 50%. An untreated control was also included. The whole field received normal farm inputs of fertiliser, pest and disease control, and growth regulation.

RESULTS

Spray deposition

Deposit measurements in 1992 indicated that soil surface deposition with the 200 l/ha twin-fluid nozzle was lower than that of the conventional 200 l/ha flat fan nozzle. No differences could be found between the 100 l/ha application techniques using the flat fan nozzles (XR11002) with and without air. However in 1993 deposition using the 100 l/ha with air is higher than both other 100 l/ha techniques and conventional 200 l/ha. On average 100 l/ha with air results in the same level of deposit as conventional 200 l/ha but produces a greater soil deposit than the twin fluid nozzle at 100 l/ha.

Table 2. Mean deposition on soil surface as % of sprayed volume

Volume (l/ha)	Rate	Air Assistance	Ground Deposit 1992	1993	Average
200		none	99	61	80
100		none	90	61	75
100		full	86	83	84
100		Twin-fluid	80	50	65

From the deposit measurements on the artificial targets (Table 2) it becomes apparent that the average deposition on the upright collectors is lower for the twin-fluid nozzle than the conventional flat fan 200 l/ha and 100 l/ha.

Table 3. Upper, lower and mean deposition on artificial targets, as % of sprayed volume

Volume rate (l/ha)	Air Assistance	Target Deposition (%)								
		1992			1993			Average		
		Upper	lower	Mean	Upper	lower	Mean	Upper	lower	Mean
200	none	34	20	54	59	6	65	47	13	60
100	none	40	22	62	53	8	62	47	15	62
100	full	37	22	59	47	8	55	42	15	57
100	Twin-fluid	32	8	40	56	6	62	44	7	51

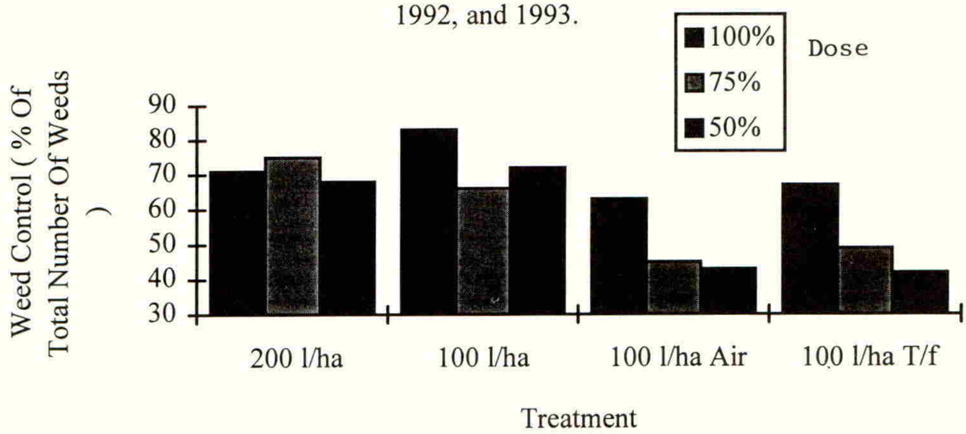
Biological effect

During the individual growing seasons the weed development was reasonable, but not homogeneously distributed. Weed density before treatment varied from 10-200 plants per m2. Most common weed species were *Galium aparine* and *stellaria media.* Weed control data presented (Table 4) are for total number of weeds. From Table 4 it becomes clear that a dose effect is apparent for all spraying techniques. This effect is least for conventional flat fan 200 l/ha and most for 100l/ha with air and 100 l/ha twin-fluid nozzle. The effect of spraying technique (apart from dose) on weed control is obvious. Conventional flat fan sprays at 100 l/ha and 200 l/ha controlled the weeds best. The use of air assistance at 100 l/ha reduced efficacy. The 100 l/ha twin fluid nozzle results show an equally reduced efficacy. However effects on weed control in individual years can vary much for the application rates used.

Table 4. Weed control (%number of total weeds) with different spray dosage.

Volume rate (l/ha)	Air Assistance	1991			1992			1993			Average		
		100	75	50	100	75	50	100	75	50	100	75	50
200	none	70	72	70	52	70	52	91	82	82	71	75	68
100	none	85	49	76	78	59	60	86	91	81	83	66	72
100	full	58	28	25	62	34	30	68	73	73	63	67	43
10	twin fluid	76	20	0	55	62	64	71	64	61	67	49	42

Figure 1. Bar Chart Illustrating Average Weed Control For 1991, 1992, and 1993.



DISCUSSION

There was little dose effect for conventional applications at 200 l/ha. Conventional applications at 100 l/ha performed on average marginally better than at 200 l/ha, although the results were slightly more variable. The full dose Twin-fluid and air assist treatments at 100 l/ha performed no better than the 75% and 50% doses of the conventional flat fan sprays.
When spraying a volume of 100 l/ha with air assistance soil surface deposition is as high as conventional 200 l/ha. The use of a coarser spray quality, with a lower spray volume as was done with the twin-fluid nozzle decreases spray deposition on artificial targets. Remarkably this resulted in lower soil surface deposition. Similar effects of drop size, air assistance and target area on deposition were found by Nordbo et al (1991), and Nordbo (1992). Combined effects resulted in a lower efficacy of weed control for the twin-fluid nozzle compared to conventional nozzles. Air assistance also resulted in lower efficacy in weed control. Probably due to the settings of air speed (full) and angling of the air sleeve (vertical). This is in contrast with the findings of Ayres et al (1985) who found considerable differences in soil deposition but no differences in efficacy between nozzle types (spray qualities) and volume rates.

The series of trials demonstrates that while it may be possible to improve the performance of a fluroxypyr/CMPP mix through air assisted and Twin-fluid spraying, more work is needed to optimise the setting of the equipment. A higher degree of operator training and knowledge will be necessary to obtain the best results from the equipment.

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