SESSION 5C

ADVANCES IN SENSING AND CONTROL FOR PRECISION MANAGEMENT OF INPUTS

Chairman:	Mr R Cook, *Ministry of Agriculture Fisheries & Food, London, UK*
Session Organiser:	Professor W Day *Silsoe Research Institute, Bedford, UK*
Papers:	5C-1 to 5C-4

Site specific control of pest and diseases - a challenge and an opportunity

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ABSTRACT

Different technologies for variable rate applications are discussed. Although no complete decision support system has been developed for site specific application of pesticides, it is claimed that simple application maps can be used to explore the technology. Such maps can be based on available yield or canopy density maps, simple field observations and the manager's experience. The density of the crop is an important factor having impact on foliar concentration of active ingredients and the competition between crop and weeds. Examples of field application maps are given. Farmers have been satisfied with solutions for site specific applications based on a commercial spray controller with some saving up to 13 percent of chemical inputs. A proper infrastructure serving precision farming is needed in order to facilitate data exchange between farmers, advisory services and other services.

INTRODUCTION

Site specific farming is gaining increasing interest worldwide. It is one of the means to improve the management in agriculture and may rationalise the use of inputs and decrease the negative impact they can impose on the environment. Site specific application of farmland inputs can be seen as a natural development in decision making, moving the resolution in management from a field level to a more detailed part-field level, but yet based on the same agronomic factors. The more resource-demanding data processing and monitoring in precision farming can conflict with the need for fast and efficient treatments in today's agriculture but are facilitated by the technologies and management systems associated with precision farming. From a historical point of view, precision farming can be seen as a return to the practices of earlier times, as the management units centuries ago were much smaller and allowed cultivation to be adapted to local variations.

Most research and development in precision farming have been focused on monitoring field variation of yield and soil characteristics with a view to variable application of nutrients. But to achieve the full benefit of precision farming, it will be imperative to include site specific crop protection in field management. These inputs often represent a major cost and they can have great impact on the economical output. Some research has indicated the large potential of site specific crop protection (Secher 1997, Christensen *et al.* 1999). The difficult and time-consuming monitoring of field variations in the occurrence of disease, pest or weed species is one of the barriers to implementing site specific applications of pesticides. Another obstacle is the limited knowledge on the interactions between crop physiology, target organism population dynamics/epidemiology and pesticide mode of action. Research is carried out to try overcome these problems (Bjerre *et al.* 1998, Bjerre, 1999, Christensen *et al.* 1997, Heisel *et al.* 1999) but no practical solutions have yet been commercialized.

However simple and pragmatic decision rules can be applied, in order to get started before complete decision support systems are available. Such decision rules will be based on basic factors indicating the field variations, such as yield maps, topography and soil analysis and the manager's detailed knowledge about the land. These factors can all contribute to a prediction of gradients of infestation.

INPUTS FOR PEST AND DISEASE APPLICATION MAPS

Pest and disease maps

Modern crop protection strategies are founded on need-based applications with appropriate dose rates adjusted to a reduced but sufficient efficacy. The most important factors in the calculation of appropriate dose rates are related to the target organisms (weeds species, insects or diseases), the incidence of these and the status of the crop (physiological stage, resistance level etc.). The mechanisms of these factors are implemented in decision support systems, which are widely used (Secher & Murali 1998). The same factors are important when deciding on site specific applications. Of those, the incidence of target organisms can show large variations within fields. This variation is difficult to monitor since disease and pest assessments are labour-intensive and field areas can be large. However, variation might be predicted by indirect factors as described by Bjerre (1999). It is well known that shelterbelts may influence intra-field variation of Powdery mildew (*Erysiphe graminis)* as seen in Figure 1.

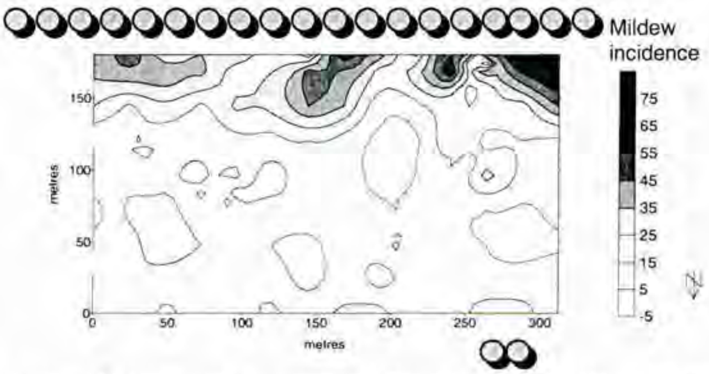

Figure 1. Frequency of plants with symptoms of Powdery Mildew (*Erysiphe graminis*) on the upper 3 leaves in a winter wheat field at Giesegaard in Denmark, 1997 (GS 53). Filled grey and black circles outside the map denote shelterbelts or other vegetation with similar lee effects (from Bjerre et al, 1998).

In addition, intra-field disease variation may be influenced by crop density variation (Bjerre 1999). Since no explanatory models are yet developed the field variation of pests and diseases are hard to implement in decision rules. In many cases, the manager's experience can be the best input and an important source when estimating field variation.

Canopy density maps

An important factor is the density of the canopy, and this is currently being taken account of in practice. A substantial intra-field variation in crop density have been found in commercial wheat fields (Bjerre *et al* 1998) and may be as big as variation in yield. The density of the crop has a direct effect on the deposition of pesticides on leafs. In Figure 2, the leaf surface concentration of a tracer is shown as a function of penetrated Leaf Area Index (LAI). Results from Secher (1998).

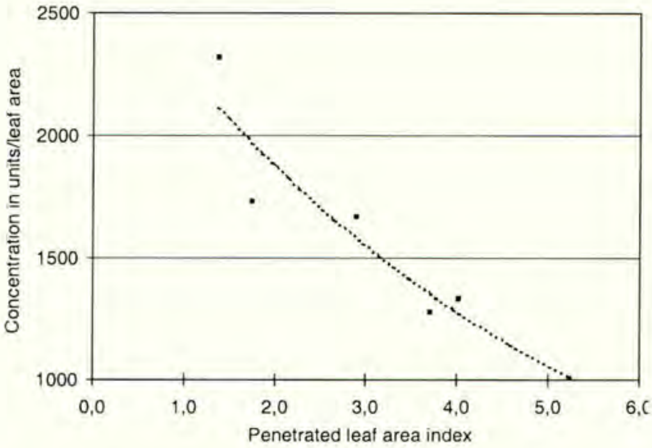

Figure 2. Concentration of tracer on winter wheat leaves shown as a function of the penetrated leaf area index. Treatment with 140 l/ha, HARDI 4110-14 nozzle and 2.5 bar in winter wheat at GS 69 (from Secher 1998).

Since the LAI can have great variation across a field, an appropriate dosing therefore must be related to the canopy density in order to achieve a uniform treatment in the target compartment of the canopy (e.g. leaf 2 or leaf 3). In order to evaluate the dynamics and impacts of application rates adjusted to the canopy density a function for canopy interception of spray deposit will be used for further simulations.

Assuming Lambert-Beer's law is valid for pesticide deposition in canopies (Gyldenkærne *et al.* 2000, Akkerhuis *et al.* 1999), the following equation can be used:

$$C_l = C_0 \cdot e^{(-k \cdot \Sigma LAI)} \qquad (1)$$

C_l = Concentration on leaf surface, C_0 = Concentration above canopy, k = Extinction coefficient and ΣLAI = The accumulated LAI above leaf surface.

From the data presented in Figure 2, the extinction coefficient, k, is estimated to 0.21. The concentration of spray deposit can then be estimated at different heights in the canopy when combining (1) with a canopy architecture as described by Akkerhuis *et al.* (1999) and assuming the relative distribution of LAI in height is independent of the total canopy LAI.

In Figure 3 the coefficient of variation (CV) for leaf surface concentration at different canopy LAI's is presented as a function of the canopy height for a conventional and a site specific application adjusted according to canopy density.

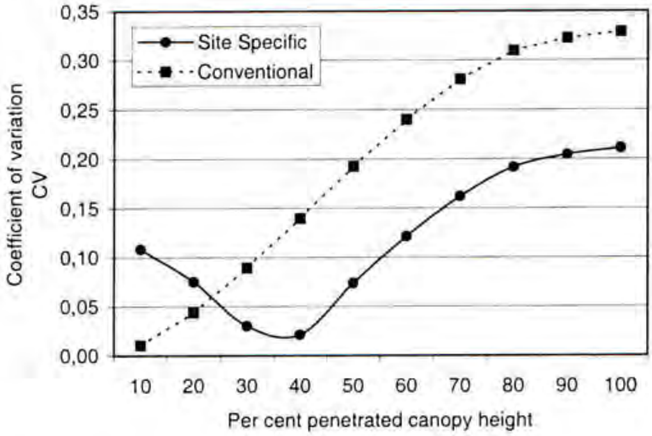

Figure 3. Estimated coefficient of variation (CV) of leaf surface concentration in discrete canopy height stratums for a cereal crop. The variation is achieved by calculating the concentration when total canopy LAI varies from 5 to 9, each contributing with equal weights. Conventional = uniform application rate at all LAI's. Site Specific = adjusting the application rate from 85 per cent (LAI = 5) to 115 per cent (LAI = 9).

Figure 3 indicates that a site specific application can be a means to achieve higher uniformity of leaf surface concentrations in lower canopy levels. This is achieved at the cost of more variation in the upper canopy due to the variations in application rates. The higher application rates in dense crops corresponds positively with data presented by Paveley *et al.* (1996) indicating a higher return for pesticide inputs in higher yielding areas. In addition the site-specific application will result in a lower deposition on the soil.

The canopy density map can be generated by different means ranging from ground-based measurements (Christensen *et al.* 1997), and the use of satellite images (Gabriel & Haveresch 1999) to estimates based on the use of historical field records combined with seasonal weather data (Figure 4). Yet no methodology is fully operational and commonly accessible. It will be a pre-requisite for further development of the technology that such maps can be readily generated.

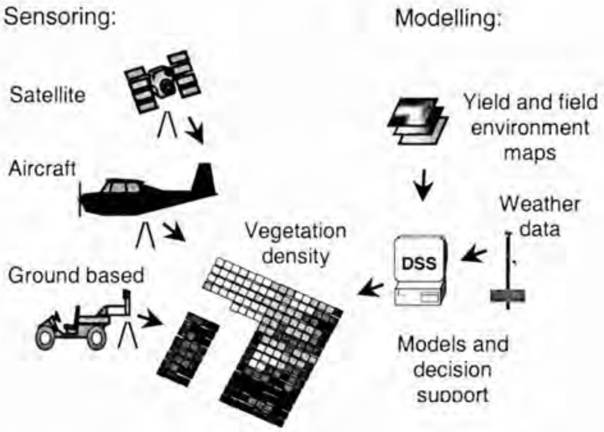

Figure 4. Different methodologies to achieve canopy density maps. A density estimate could be calculated on the basis of historical field and weather records, combined with weather data from the actual season.

Field environment maps

As discussed by Bjerre (1999) and Secher (1997), other field characteristics than pest, disease or canopy density maps can be important for proper decision making. Field topography, slope and aspect can influence the microclimate with an impact on pest and disease development. In a similar way, surrounding vegetation can influence pest and disease development. Soil types can have impact on both crop and target organisms. Finally the history of the field can be useful, in order to make use of known earlier variations in cultivation practices and to estimate in-field variations common from year to year.

TECHNICAL SOLUTIONS FOR APPLICATION

Management systems

Although many farmers practice site specific applications as they vary driving speed or pressure while applying pesticides, a true precision farming system can only be operated with the assistance of a management system. This management system must be able to handle geo-referenced data and facilitate the exchange of data between farm implements, management system and decision support. No management system or decision systems have yet been reported that can calculate application maps for pest and disease control. Systems for weed control are further advanced with some systems currently under development and testing (Christensen *et al.* 1999). In most existing packages for precision farming, as in the CLAAS Agrocom or AGCO Fieldstar systems, application maps can be drawn manually or converted from geo-referenced maps.

Sprayer technology

Variable rates achieved by changing pressure while spraying are based on simple and well known technology. Most spray controllers are using the same principle when automatically adjusting the application volume to changes in driving speed. An advantage is the immediate change in nozzle flow when pressure is changed, resulting in a short response time while spraying. The disadvantage is the negative impact of a variable pressure on droplet sizes. In order to keep the droplet sizes in the spray cloud within an acceptable range, the application volume must be kept within average +/- 25 per cent when using a conventional hydraulic sprayer. Most systems based on variable rates by change of pressure simply hook up a spray controller to a precision farming terminal such as the HARDI precision farming system conceptually illustrated in Figure 5.

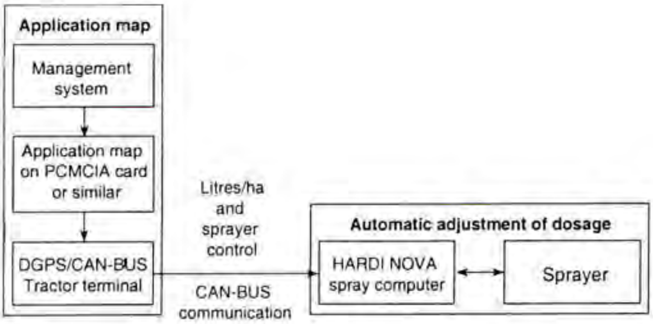

Figure 5. Elements in the HARDI precision farming system. Based on the HARDI NOVA spray computer linked with a precision farming terminal and using standards for CAN-BUS communication.

Direct injection is basically a system in which the concentrated pesticide is injected directly into the liquid system of the sprayer. Usually the main tank only carries clean water and the injection point can be either on the pressure side or the suction side of the main sprayer pump. Most direct injection systems are based on a small pump for injection. An advantage is the unlimited range of pesticide application rate. The pesticide application rate can be varied from 0 to 100 per cent without having impact on the application technique. Another advantage is the possibility of independent mixing and alternation between different pesticides. Disadvantages are the relatively long response time creating specific demands for the sprayer liquid system and the difficulties cleaning the system and in handling dry formulated pesticides.

IMPLEMENTATION OF SITE SPECIFIC CROP PROTECTION IN PRACTICE

A simple application map can be generated following the steps shown in Table 1. The average application rate can be reduced according to the belief in increased efficacy due to the better targeted application.

Table 1. General steps in the construction of application maps based on simple inputs

Step	Description
1	Deciding the average application rate: Could be the rate applied with a conventional treatment reduced by 5-15 % because of the better targeted site specific application.
2	The average dosage is adjusted guided by an estimated variation in canopy density. Where the canopy density is high, herbicide applications are reduced because of improved competition and foliar applications are increased to compensate the dilution. The opposite adjustments are made in open areas of the field.
3	Finally, the map is corrected in the areas where the manager has experience of either high or low treatment need. For example areas with a high disease level or a large weed population.

The application map illustrated in Figure 6 is based on an aerial infrared photograph indicating field variation in canopy density. Different soil types and previous crops are the main cause of the variation.

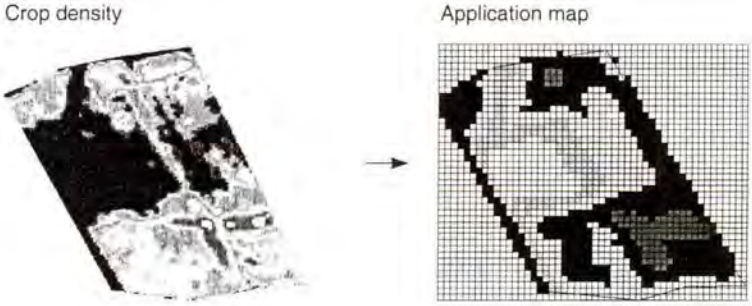

Figure 6. Application map derived from an aerial picture taken in the growing season. Application rates are increased in the dense areas of the field. Fungicide application in winter wheat 1998, Ballerstedt, Germany.

CONCLUSIONS

There are good biological reasons to expect benefits from site specific application of pesticides. The development of diseases depends strongly on crop density and the microclimate in the crop, and the weed species and their density are often distributed uneven in the fields. It is therefore likely that the further development - and simplification - of site specific application of pesticides can lead to a more rational use of the active materials and thus to a further reduction in usage and more profitable production for the individual farmer. Field experience from 1997 to 1999 has indicated that visual assessments in the field and farmers' experience can be used to create realistic application maps.

More research will be needed to prove the benefits of site specific application of fungicides. It is necessary to increase operational understanding of the use of yield maps, pesticide deposition and spatial variations in disease development. Most important are the development of simple registration methods and models for calculating disease variation within the field, based on constant factors that do not need to be determined every year.

A proper infrastructure serving precision farming is needed, in order to facilitate data exchange between farmers, advisory services and other services, and handle geographical referenced data

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On-the-go optical measurements to assess the crop nitrogen status

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ABSTRACT

The development of techniques to allow nitrogen application to be spatially varied on an intra-field scale should enable a logical advance from the current practice of uniform application according to soil nitrogen analyses or an assessment of field and crop factors. To this end, a measurement platform was developed to assess the crop nitrogen status. The optical measurements were conducted at canopy level, in particular the reflectance properties in the visible and near infrared were investigated in order to identify and evaluate optical indicators - reliable under field conditions - for the crop nitrogen status. Different optical sensors were mounted together with a DGPS-system to record the geographical position of all measurement spots. The platform was moved through a test field containing plots that received 5 different nitrogen application rates. Calibration samples were taken after measurement and analysed for Kjeldalh-N, chlorophyll a + b and biomass. A preliminary data analysis showed a strong, growth stage dependent, linear relation between plant nitrogen and chlorophyll content. This resulted in the development of three Partial Least Squares (PLS) models predicting plant nitrogen content with an Root Mean Squared Prediction Error (RMSEP) of respectively 880, 1270 and 1750 mg Kjeldahl-N/m².

INTRODUCTION

The application of fertiliser nitrogen (N) to field crops is of critical importance to maximise the crop yield and product quality. Cereal yields can be trebled through the use of optimum N rates compared to nil use and product quality – i.e. reflected by wheat grain protein content - can be substantially increased (Pearson, 1984). However concern over nitrogen leaching to watercourses and groundwater is encouraging approaches that restrict nitrogen application to an optimum rate maximising product quantity and quality whilst minimising environmental impact. At present more than 50% of all nitrogen depositions in water bodies in Belgium originate from agricultural farmland, limiting the use of ground and surface water as drinking water (Verstraete, 1995). The spatial variability of nitrate nitrogen in, for example, potato fields (Meirvenne & Hofmann, 1989) and the spatial variation of soil features affecting nutrient utilisation by the crop, create a bottleneck for lowering diffuse N losses at field level. Information is needed about the variability of plant-available nitrogen to allow for variable rate N application. This information could be acquired by assessing the crop nitrogen status. Soil and plant tissue sampling for nitrogen availability are well documented. However, these methods require considerable effort for sample collection and processing which makes repeated sampling throughout the growing season very laborious and time consuming. In addition, a time delay exists from sampling until laboratory results are obtained. A faster method is the use of the chlorophyll meter (Piekielek & Fox, 1992). This technology provides instantaneous results but data obtained from the chlorophyll meter is a point measurement on a single leaf from a single plant. Consequently, many plants must be measured to obtain a representative average for the particular sampling date and to adequately assess the spatial variability. Remote sensing of canopy reflectance has the capability of sampling a plant community rather than a single plant or a small number of plants. Consequently it could provide a quick way to assess the spatial variability within a field. However the necessary images are expensive and measurements are dependent on weather conditions (Makepeace, 1996). The objective of this study was to investigate the use of ground-based canopy reflectance measured with different sensors to determine and map the spatial variability of the *in situ* plant nitrogen status throughout the growing season.

METHODS AND MATERIALS

On-the-go optical measurements were carried out on wheat canopies during the crop-growing season, from the beginning of February till the end of June (from Zadok scale 20 till 70). A test field was created by the Belgian Soil Service consisting of sixty 16 m x 12 m plots. The field was located in Leefdaal (lat. 50°50'N, long 4°04'E, alt. 60 m) on a loamy soil (16% clay, 78% loam and 6% sand) and with the following chemical properties: pH-KCl: 6.7, C: 1.1%, P: 14 mg/100g, K: 16 mg/100g, Mg 12 mg/100g, Ca 250 mg/100g, Na: 2.2 mg/100g. Three seeding densities and 5 nitrogen application rates were applied, each treatment with 4 replications. Seeding densities were 249, 321 and 413 grains/m^2 and the received nitrogen application rates were 0, 95, 160, 195 and 230 kg N/ha applied as three dressings on March 12, April 20 and May 15, 2000.

Above ground biomass was determined on April 10, May 5 and May 24, 2000 (Julian day 101, 126 and 145). One square meter of plants were collected on each plot, fresh biomass was weighed before drying of two representative subsamples at 70°C. Dry matter and Kjeldahl-N content was determined on one subsample while the other subsample was analysed for chlorophyll a + b.

Optical measurements were performed with a custom built-platform. A small (12 meter) sprayer boom was converted to a measurement platform so that all the optical sensors, measuring the same spot, could be mounted on one end of the adjustable boom. Consequently the distance from the sensors to the centre of the tramlines was between 3.5 and 4 meter depending on the sensor, providing a measurement spot 1.5 to 2.5 meters away from the plot borders. The measurement platform was connected to the three-point suspension of the tractor. The following sensors were mounted:

Cropscan MSR5 radiometer, a photodiode-based multispectral radiometer measuring canopy radiance and incoming irradiance simultaneously in five bands with centre wavelengths 480, 550, 660, 830 and 1650 nm respectively. With a field of view of 28 degrees and the sensor mounted 2 meter above canopy at nadir (downward-looking) the resulting measuring spot was circular with 1 meter diameter.

Ocean Optics S2000 spectrophotometer working in the 300 to 1100 nm wavelength range. The captured light at the end of the boom was guided through an optical fibre to the centrally-placed spectrophotometer. With the sensor placed at nadir and with the fibre optic's field of view of 20°, the resulting measuring spot had a diameter of 70 cm.

An Imspector V9 spectrograph (Specim) connected to a digital CCD camera was installed in a downward-looking position. The spectral range of the spectrograph was between 445 and 921 nm. The recorded images had 480 x 640 pixels of which the longer axis corresponded to the spectral axis of the spectrograph while the shorter axis corresponded to the spatial axis. Hence, the spectrograph measured a line of view of which the dimensions are determined by the height of the camera above canopy and field of view of the optic used. In this case the spectropgraph was mounted together with the other sensors at 2 meter above the canopy and using a 3.6 mm focal length lens, the resulting line of view was ±2 meter in length and 3 to 4 cm wide.

Analogue CCTV camera JVC TK-C1380 (480 x 640 pixels) was mounted to take colour images as references for the measuring spots. These images were also used to calculate the soil coverage.

Position (latitude and longitude) of each data point was determined with a Trimble AgGPS132 differential global positioning (DGPS) system. The antenna was mounted at the end of the boom together with the other sensors, a sub meter accuracy was obtained. Data was logged with a laptop and docking station. The acquisition software was programmed in Labview and enabled to adjust sample frequency of each sensor independently. The millivolt signals from the Cropscan photodiodes were processed and corrected for the cosine diffuser properties and the photodiodes' temperature dependencies. The calibration and correction equations supplied by Cropscan were programmed in the acquisition program. Consequently a data file was produced with the Cropscan reflectance values and the geographic positioning information. In a similar way all the other data is recorded together with the DGPS data.

The measurements were taken before fertiliser application, 1 to 2 weeks after fertiliser application and when plant samples were taken. In total, measurements were made on 12 separate days during the growing season.

RESULTS AND DISCUSSION

A preliminary data analysis has been performed on the Cropscan reflectance data and the chemical analyses results. Assessing the crop nitrogen status through the use of optical measurements is based on two important features: chlorophyll content was found to be the most important independent factor affecting leaf reflectance (Thomas and Gausman, 1977) and there was a strong relationship between chlorophyll and nitrogen content (Kleman and Fagerlund, 1987). Laboratory studies have already shown effects of nutrient and water deficiencies on the spectral reflectance and transmittance of single leaves. Leaf reflectance has been used to estimate the nitrogen and chlorophyl contents in bufflegrass (Everitt et al., 1985) and barley (Kleman and Fagerlund, 1987). Figure 1 shows the Kjeldahl-N content plotted against the chlorophyll a+b content, for each sampling date and for each plot. By multiplying the analysis values by the above-ground biomass the contents can be expressed as mg N per square meter, thus allowing for biomass density differences induced by different seeding densities.

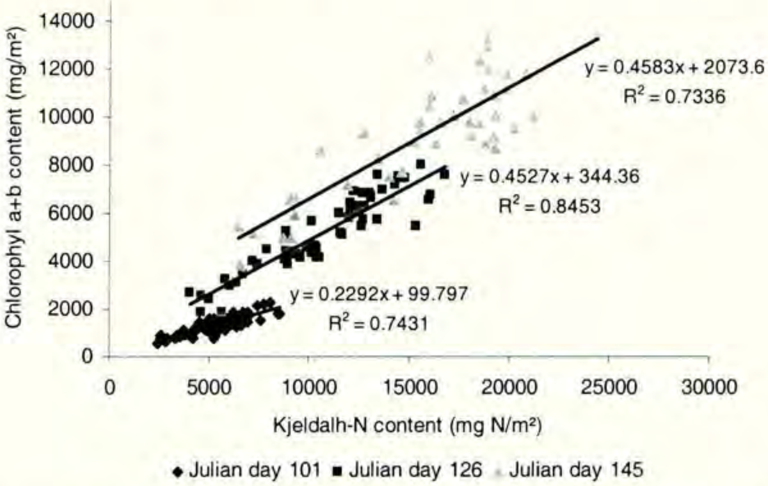

Figure 1 . Relation between Chlorophyl a+b and Kjelhdahl-N content for three sampling dates

Figure 1 demonstrates a strong relation between the chlorophyll and nitrogen content. However it is dependent on the growth stage. The coefficient of determination is largest (R²=0.8453) for second sampling day (Julian day 126); a possible explanation could be the fast crop growth in this stage and the consequently high chlorophyll synthesis, taking up the biggest part of the N-supply to the plant. Al-Abbas et al. (1974) found that not only plant nutrient deficiencies, but also physiological age of leaves influenced reflectance in the visible but not in the NIR wavelengths.

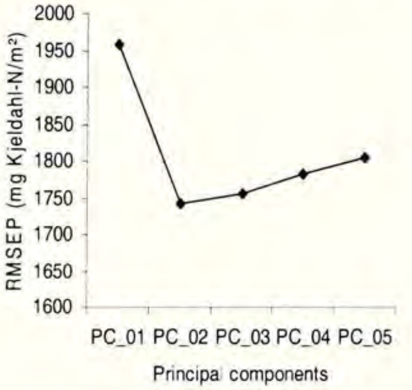

Figure 2. Relation between RMSEP and the number of PC used in the PLS model

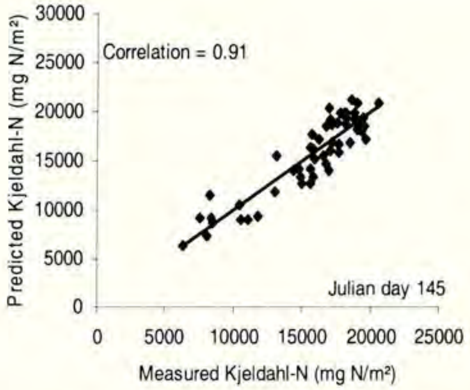

Figure 3. Measured and predicted N content values for the third sampling day (Julian day 145)

This also explains why a partial least squares (PLS) model developed on the three sampling dates together was a poor predictor of the N content compared to PLS models developed for each sampling date independently. The predicting capability of regression models was evaluated with a full cross-validation strategy, obtaining a root mean square error of prediction, RMSEP. Figure 2 and Figure 3 shows the resulting PLS model using 2 principal components (PC) for the third sampling date, after outlier removal and data centering. A minimum RMSEP is reached by using the first 2 principal components. Analogue results were obtained for the PLS models developed for the first and second sampling day (Julian day 101 and 126) as is shown in table 1.

Table 1. PLS model performance for the three sampling dates

Sampling day	Correlation	RMSEP (mg N/m²)	Number of PC used	Mean (mg N/m²)	RMSEP/Mean
101	0.85	880	2	5265	0.16
126	0.90	1270	2	10835	0.12
145	0.91	1750	2	15532	0.11

The RMSEP/Mean ratio is an indicator of how well the model performs, and in our case a prediction error of approximately 10% of the mean is a satisfactory result. The models can be used to predict the N content using the Cropscan data acquired for the whole test-field, however the data must be acquired in the same time period and under the same conditions to achieve the best results. In this way N content maps can be created as is illustrated by figure 3.

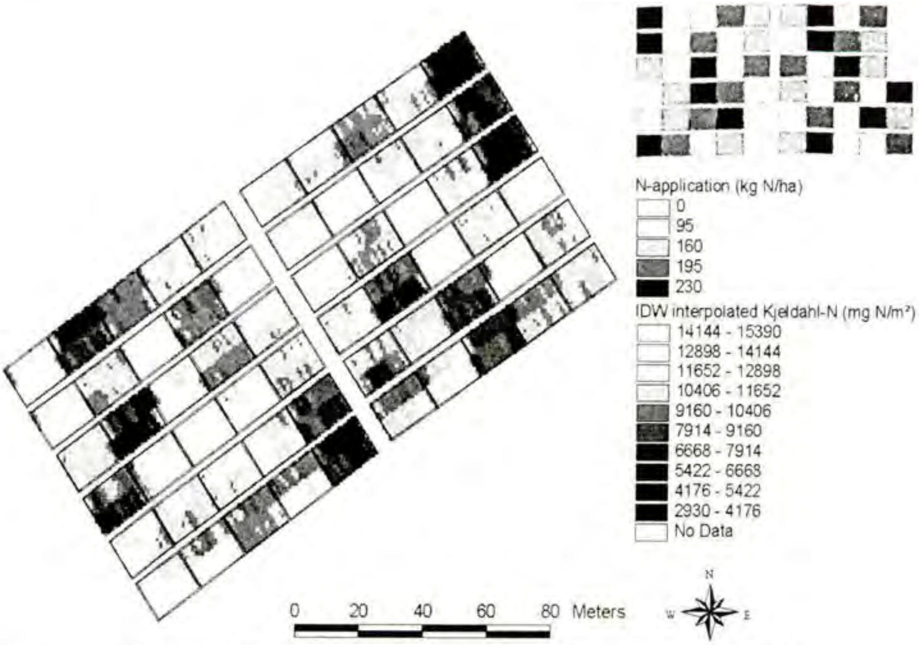

Figure 3. Layout of the test-field with predicted N content using the PLS model of Julian day 126 applied to data acquired on Julian day 121

CONCLUSIONS

Already in this first approach the Cropscan sensor has delivered a relatively good estimate of the crop N-status. However these experiments were conducted on one test field with only one variety of wheat. The influence of these factors needs investigation. A general model is required that takes taking into account the effects of growth stage, wheat variety and soil type to produce N application maps starting from N content maps. The introduction into these PLS models of new variables, delivered by the other sensors, will offer strategies to improve N content prediction. This will be particularly important early in the growing season when changes in surface moisture content affect soil colour and its reflectance (Bausch, 1993), thus introducing variability not associated with actual plant conditions.

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Is precision management of nematicide inputs an option for the control of potato cyst nematodes?

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ABSTRACT

The most important constraint to potato production in the UK is the damage caused by the potato cyst nematodes (PCN) *Globodera pallida* and *G. rostochiensis*. Management systems for PCN depend heavily on the use of nematicides which, at *c.* £360 per ha for granular and *c.* £550 per ha for fumigant nematicides, are costly. Of all the inputs in UK agriculture, nematicides offer the largest potential savings if safe and reliable spatial application procedures can be developed. These savings would be accompanied by the environmental benefits of local reductions in the burden of toxic nematicides applied to land. We have mapped the PCN infestations in three fields due for ware potato production and have monitored the changes in PCN population density and distribution that have occurred when a susceptible potato crop is grown. The inverse relationship between pre-planting population density and multiplication rate of PCN make it difficult to devise safe spatial application procedures, especially when the pre-planting population density is just below the detection threshold. Also, the fine scale of spatial dependence found suggests that the coarse sampling grids that are used commercially may produce maps showing distribution patterns that are misleading.

INTRODUCTION

A recent survey of potato production in England and Wales revealed that 64% of the fields surveyed were infested with potato cyst nematodes (PCN) and that, of the infested fields, 67% were essentially pure *Globodera pallida* (Minnis *et al.*, 2000). Only 8% appeared to be pure *G. rostochiensis*, and the remaining 25% contained mixtures of the two species. Yield losses occur at population densities as small as 5 eggs/g soil (Trudgill, 1986), which means that nematicides are essential for PCN control if acceptable yields are to be maintained. Barker *et al.* (1998) have shown how nematicides influence the yields and gross margins associated with potato crops grown on PCN-infested land, and that it is not unusual for potato production in such circumstances to be more profitable if two different types of nematicide – a fumigant and a granular nematicide – are used in combination.

Fumigants such as 1,3-dichloropropene (1,3-D) appear to kill the two species of PCN non-selectively and have the additional benefit of releasing soil nutrients through the mineralisation of nitrogen. Granular nematicides are usually more effective than fumigants at killing PCN but act differentially on the two species – they are somewhat less effective against *G. pallida* than against *G. rostochiensis*. This means that each use of these nematicides selects for *G. pallida*, a fact that is all the more serious because other components of PCN management programmes also act selectively in favour of *G. pallida*. When non-host crops are grown, *G. pallida* populations decline more slowly than those of *G. rostochiensis*, and resistant cultivars are much less effective against *G. pallida* than they are against *G. rostochiensis*. Operation over the last 30 years of PCN management systems that rely on rotation, resistance and granular nematicides has been responsible for the switch to *G. pallida* from a situation in the 1960s where *G. rostochiensis* was the dominant species (Brown, 1970). The current predominance of *G. pallida* is what has led to the increasing likelihood that growers will use 1,3-D for PCN control, a usage that is in conflict with mounting pressure from environmentalists to reduce nematicide usage.

Concern to protect the environment, combined with narrow gross margins for potato production recently, have promoted the investigation of variable rate application for nematicides on potatoes. Of the current inputs on whole fields for potato production, variable application of pre-emergence herbicides or prophylactic blight fungicides would be inappropriate. Of the rest, by far the most expensive, and therefore the ones that offer the greatest potential savings, are the nematicides. Granular nematicides cost *c*. £360/ha and fumigants *c*. £550/ha (Table 1).

Table 1. Inputs for potato production and their potential for spatial application.

Input	Variable?	Cost (£/ha)	Potential saving (£/ha)
N, P, K fertiliser	Yes	220	33 (15%)
Lime	Yes	30	6 (20%)
Herbicides (i) pre-emergence	No	60	-
(ii) post-emergence	Yes	60	60 (100%)
Fungicides	No	144	-
Insecticides	Yes	26	26 (100%)
Nematicides (i) Granular	Yes	360	360 (100%)
(ii) Fumigant	Yes	550	550 (100%)

Evans *et al*. (1998, 1999) have already considered the possibility of using maps of PCN distribution within fields for spatially variable application of nematicide, and we report here the changes in within-field distribution of *G. pallida* in three very different fields. The characteristics of the infestations were determined by geostatistical analysis, and the consequences of use of nematicides at large and small population densities are described.

MATERIALS AND METHODS

The three fields, at Ram Farm, Lincolnshire, and Lane Farm and Sacrewell, both in Cambridgeshire, all infested with *G. pallida*, were mapped (in 1997, 1998 and 1999, respectively) on 20 m x 20 m grids that were set out using GPS guidance. Samples were taken with a trowel to a depth of 15 cm at each sampling station. Post-harvest samples were taken at the same stations (re-located by GPS) from one of the fields. In the other two fields, the sampling stations were re-located just before harvest, and point yields were estimated by weighing the tubers produced by four plants. Soil samples were then collected from the harvested area by taking 25 cores with a soil corer (20 cm x 2.5 cm). PCN counts were made by standard methodology (Southey, 1986).

Variograms were computed from the data and models fitted to determine the correlation ranges (if they exist) and to provide models for interpolation by ordinary kriging. Maps of both PCN infestations and yield were made in this way when models could be fitted.

To examine more closely the influence of PCN population density on field multiplication rates, the field at Ram Farm was divided into 1-ha blocks. The average initial population density (P_i), final population density (P_f) and multiplication rate (P_f/P_i) were computed for each of the resulting 10 blocks or part blocks. From the curve obtained by plotting P_f/P_i against P_i, the specific values in Table 2 were read off.

Table 2. Initial population densities (P_i) and multiplication rates (P_f/P_i) from hectare blocks at Ram Farm.

P_i	0.2	1.0	4.4	20
P_f/P_i	100	60	20	3.5

To examine the effects of treating larger and smaller PCN population densities with nematicide, an infested area of Horsepool field at Woburn Experimental Farm, Bedfordshire, was divided into 64 plots (6 m x 3 m). From each of these, soil samples were taken (40 cores of 20 cm x 2.5 cm) to determine PCN densities. Twenty-four of the plots were selected for study, eight in each of the three classes:

> 12.0 eggs/g soil	moderate count
5.0 to 12.0 eggs/g soil	low count
0.1 to 5.0 eggs/g soil	very low count

Four plots in each category were treated with Vydate at 4.5 kg a.i./ha. The field was then planted with potato cv Estima, which is fully susceptible to both species of PCN. At harvest, soil samples were again taken from each plot to estimate final population densities. Potato yields were also recorded from each plot.

RESULTS

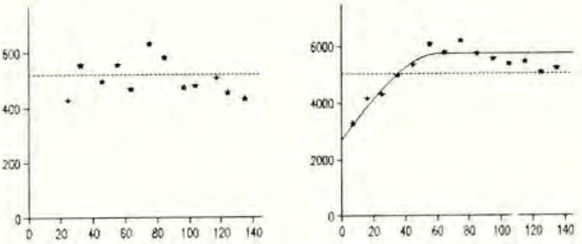
The summary statistics for the PCN counts before and after cropping the three fields are in Table 3, and they show three very distinct types of infestation. Sacrewell had a sparse population, Ram Farm had a heavier infestation but, whilst Lane Farm had the heaviest initial infestation of all, the population did not increase. We ascribe this to the presence of biological control agents for PCN, the most important of which appeared to be *Verticillium chlamydosporium*.

The variograms for the pre- and post-cropping data sets are in Figure 1. The pre-cropping data for Ram Farm produce a scatter of semi-variances about a horizontal line, approximately the variance of the data, and show no evidence of spatial correlation, whereas after cropping the semi-variance increases with increasing lag distance. Where models could be fitted, the variograms for data from two of the three farms indicated that spatial independency occurred around 40 to 60 m, a distance that corresponds to the medium-scale of distribution identified by Been and Schomaker (2000). Absence of independency post-cropping at Lane Farm may have been because this field was almost uniformly infested and had the complication of biocontrol agents at work.

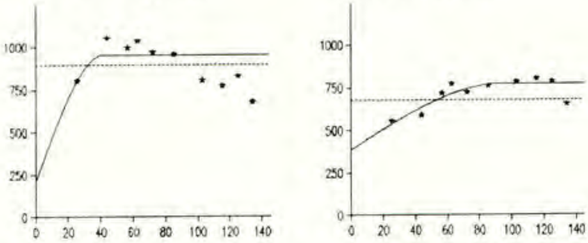
Table 3. Summary statistics for the pre- and post-crop samplings at the three farms.

	Ram Farm		Sacrewell		Lane Farm	
	Pre-crop	Post-crop	Pre-crop	Post-crop	Pre-crop	Post-crop
Number of samples	175	354	100	97	100	99
Minimum	0	0	0	0	0	1
Maximum	160	496	6.5	675	131	169
Mean	8.4	65.6	0.3	9.7	29	28.6
Standard deviation	22.8	71.0	0.7	69	30	26.1

Ram Farm – Before cropping After cropping



Lane Farm - Before cropping After cropping



Sacrewell – Before cropping After cropping

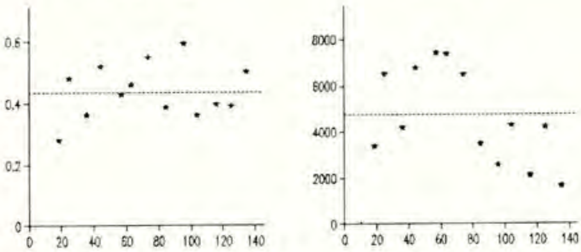


Figure 1. Variograms (lag in m against variance) of nematode density in three fields with models fitted as appropriate. The dashed horizontal lines show sample variances.

The distributions of PCN at Ram Farm before and after cropping are shown in Figure 2. Similar maps, plus a yield map, for Lane Farm is in Figure 2. Because no models could be fitted to the variograms for Sacrewell, the PCN distributions and yield for this field are represented by bubble maps (data are natural logarithm transformed for PCN) in Figure 4.

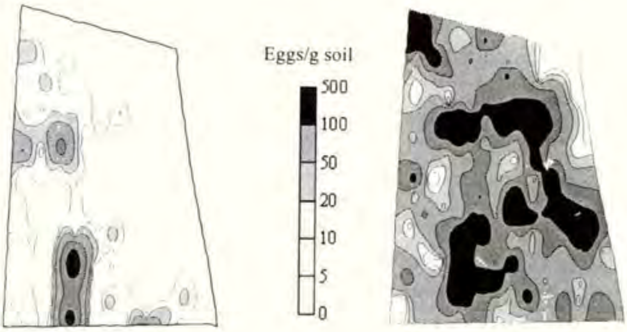


Figure 2. Pre-crop (left) and post-harvest (right) distributions of *G. pallida* at Ram Farm.

Fig. 3. Pre-cropping PCN (left), post-harvest PCN (centre) and yield maps at Lane Farm.

Figure 4. Pre-cropping PCN (left), post-harvest PCN (centre) and yield maps at Sacrewell.

By taking the observed initial population densities and the resultant multiplication rates for *G. pallida* found at Ram Farm (Table 2), and by assuming a mortality independent kill from nematicide of 80%, we could compute the effects on nematode multiplication rate of treating smaller and larger infestation levels with nematicide. The P_i values chosen were 1 and 22 eggs/g of soil because it would normally be a clear-cut choice for a grower not to treat the former with nematicide but to treat the latter. The results are in Table 4 and show that, whereas the potential P_f values with no nematicide are 60 and 77 eggs/g soil, the effective P_i values with a nematicide are 0.2 and 4.4 eggs/g soil, and these would give P_f values of 20 and 88 eggs/g soil. The relative efffectiveness of nematicide for population control is given by dividing P_f with nematicide by P_f value with no nematicide in each case. Treating a small P_i (1 egg/g soil) with nematicide gives a ratio of 0.33, whereas treating a larger P_i (22 eggs/g soil) gives a ratio of 1.14. The degree of population control is much greater at the small P_i.

Table 4. Effects on final population densities (P_f) of nematicide treatment at different initial nematode population densities (P_i).

	Population density at time of treatment	
	1 egg/g soil	22 eggs/g soil
Potential multiplication rate	60	3.5
Potential P_f (eggs/g soil), *B*	60	77
Effective P_i with nematicide (80% kill)	0.2	4.4
Multiplication rate with nematicide	100	20
P_f with nematicide, *A*	20	88
A/*B*	0.33	1.14

The experiment in Horsepool field at Woburn was done to confirm (or otherwise) the theoretical argument in favour of treating small population densities of PCN with nematicide for optimum control. The P_f/P_i ratios in untreated plots ranged from 55 in the very low class through 16.5 in the low to 11 in the moderate class (Table 5), clearly demonstrating the density dependence of the reproductive rate. With Vydate treatment, the ratios were 0.74, 1.88 and 2.06 in the very low, low and moderate categories, respectively, demonstrating the greater efficacy of nematicide treatment at low densities. There were no differences of yield between plots treated with Vydate in the three infestation classes and there was no yield penalty of not applying Vydate to plots in the very low infestation class, but the deleterious effect of PCN on potato yield on this sandy soil is seen in the untreated plots of the low and moderate infestation classes. For long-term nematode control it may thus be wise to use a nematicide even at very low population densities of PCN, even though there will not necessarily be yield benefit in the current crop. This is the first practical demonstration of this fact.

Table 5. Initial and final population densities, P_f/P_i ratios, and yields of plots treated or untreated with Vydate.

P_i Range (eggs/g soil)	Treatment	Mean P_i (eggs/g soil)	Mean P_f (eggs/g soil)	Mean P_f/P_i	Mean Yield (kg)
0.1 to 5.0	Vydate treated	2.3	1.9	0.74	21.9
0.1 to 5.0	Untreated	1.7	101	55.0	21.3
5.0 to 12.0	Vydate treated	7.9	16.6	1.88	23.8
5.0 to 12.0	Untreated	7.4	132	16.5	19.2
> 12.0	Vydate treated	29.5	61.9	2.06	22.8
> 12.0	Untreated	31.6	274	11.0	14.3

DISCUSSION

The three fields surveyed behaved very differently in terms of PCN population density changes when potatoes were grown. The Ram Farm field went from 8 to 66 eggs/g soil, whereas the Sacrewell field went from 0.3 to 9.7 and the Lane Farm field from 29 to 29 eggs/g soil (Table 3). The first had many zero counts (48 out of 175) before cropping, but the infestation was latent, and the whole field was heavily infested after cropping. The latency is due to the practical detection threshold of 1 egg/g soil. The Sacrewell field had a very small P_i and many zero counts (*c*. 80 out of 100) but the low P_f of 9.7 eggs/g hid 'hot spots' that were revealed by the mapping in Figure 4. The largest count of 675 eggs/g was more even than the largest value from Ram Farm. The field at Lane Farm had the largest P_i but the P_f was unchanged from this value. The yield maps in Figures 3 and 4 reflect PCN distribution in these latter two fields, but only loosely.

Lane Farm would not have been a candidate for spatial nematicide application because the P_i exceeded the economic damage threshold in all parts of the field. Although the large number of zero counts and the large proportion of Ram Farm field apparently free of PCN would perhaps have tempted the grower to vary the application rate of nematicide, this distribution also should not be considered for such treatment.

On the other hand, the field at Sacrewell had a much sparser P_i with many zeroes. Computation of the area within the field that exceeded a P_i of 1 egg/g soil revealed that almost 90% of the field would have been untreated if 1 egg/g were taken as the threshold for nematicide application. This would represent a huge cost saving and would have been acceptable policy if the only aim was to prevent loss of yield. However, it would have left untreated a large PCN patch on the eastern edge of the field only revealed in the P_f map in Figure 4. If long term PCN management is the objective (the 'strategic' management of Parker, 1998), it would be difficult to advocate variable application of nematicide in any field where PCN has been detected. The long-term benefits of treating non-damaging densities of PCN with nematicide are underlined by the information in Tables 4 and 5. As it happened, we noted during visual inspection of the crop at Sacrewell an area of heavy PCN damage that fell between sample stations. The counts from surrounding sample positions gave no indication of a potential PCN 'hot spot'. This occurred despite the sampling at 20 m, which is intense compared with some commercial sampling at 100 m spacing. However, such small 'hot spots' are probably characteristic of newly infested fields. An older infestation would probably have larger patches that would be picked up in the sampling procedures that are currently in routine use. The interpretation of distribution maps for varying nematicide application safely will depend on development of analytical procedures that interpret distributions in terms of likely infestation age – and the consequent likelihood that zero counts in the field represent a true absence of PCN.

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Matching the application of fungicides to crop canopy characteristics

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ABSTRACT

Field experiments were conducted to determine the interactions between spray application variables and crop canopy structure so as to explore the potential for improving the performance of fungicides applied to cereal crops. Crop canopy characteristics of winter and spring wheat crops were assessed using reflectance radiometry at an early stage of growth. Field areas were then defined as having high or low crop canopy densities and plot trials conducted in each of the areas at two stages of growth examining the effects on spray deposition patterns of application volume rate, spray quality and trajectory angle.

Results showed large differences in mean deposit levels at two growth stages with deposits at growth stage 39 43% less than those at growth stage 32. At a given growth stage, there was some variation in deposit levels and distribution between the areas of high and low crop canopy density but these were not statistically significant. Total deposit levels in the winter wheat at both growth stages were increased by an average of 13% by angling nozzles at 45E to the vertical and by 38% by using a volume rate of 100 l/ha compared with 200 l/ha applications, with the largest differences measured at the earlier growth stage. Higher deposits were consistently measured when applying a fine spray. The results therefore indicate some potential to optimise fungicide use by adjusting the delivered spray volume rate to match crop canopy characteristics as assessed by radiometry.

INTRODUCTION

Relatively cheap and physically robust sensing systems for monitoring aspects of crop canopy structure have been developed. As a result, there is now the possibility to match the delivery of plant protection products to measurements of crop structure, if appropriate relationships linking descriptors of the canopy and the application method can be defined. One such potential application relates to the use of fungicides in cereal crops where the basic mode of action, whether protectant or eradicant, is based on activity at the leaf surface of the crop. A simple hypothesis in such circumstances might therefore be that the volume rate of a fixed concentration of tank mixed formulations should be directly related to the leaf area index (LAI) of the crop canopy. Experimental work by Secher (1997) has indicated that there may be the potential to improve the use of fungicides when dose rates applied to a winter wheat crop were varied in accordance with crop characteristics assessed using boom-mounted radiometers. Yield results from areas treated with the spatially variable fungicide input were statistically higher than the uniformly treated crop. This was not supported by results reported by Bjerre (1999) where no increases in yield were recorded from spatially variable treatments applied on the basis of a vegetation index assessed using radiometers. Bjerre's work used the simple hypothesis outlined above and aimed at delivering a given amount of fungicide per unit area of crop leaf surface. In support of the approach, some preliminary results from experiments by Secher were quoted in which spray deposits at different levels in a wheat crop canopy treated conventionally were found to vary depending on the density of the canopy with less penetration into the canopy being recorded in areas of higher canopy density.

The establishment and spread of a fungal disease within a crop canopy is also likely to be influenced by crop canopy density. Paveley *et al* (1996) considered the scope for the spatially variable application of fungicide and noted that variations in the structure of the crop canopy may have the opposite effect on the distribution of disease to that relating to fungicide application. They also concluded that the spatially variable application of fungicides in response to directly sensed disease parameters would require very sensitive, complex and automated field monitoring techniques.

In the work reported in this paper, we have sought to establish how spray application parameters can be adjusted to change deposition patterns in areas of different crop canopy density. Bonciarelli and Covarelli (1995) have shown that there is a robust relationship between the proportion of spray intercepted by a crop and the leaf area index, and that the nature of this relationship is influenced by the volume application rate. Results reported by Bryant and Courshee (1985) showed that deposits at different levels in a cereal crop were almost constant over a range of volume rates between 50 and 200 l/ha at a given crop growth stage but with higher levels of deposit being recorded in a smaller canopy as expected. Work by Combellack and Richardson (1985) using a static boom and plants on a moving track showed increases in deposit in the order of 60% by angling the spray at 45° to the direction of travel and similar results have been obtained in field trials (Robinson - personal communication with data). An important feature of the nozzle-angling experiments conducted under field trials was the ability to manipulate the site of deposition within the crop canopy by adjusting the delivery angle. The work of Combellack and Richardson suggests that while total capture may be increased by changing nozzle angles on the boom, there may be a performance penalty in relation to the uniformity of deposits at target level.

The work reported in this paper examined the effects of spray application volume rate, spray quality (Doble *et al.*, 1985) and nozzle angle on the deposition patterns in cereal crop canopies of different canopy density. The results obtained from the first year of a two year study have been interpreted against a background aiming at improving the use of fungicide materials using application techniques that are matched to physical features of the crop canopy.

MATERIALS AND METHODS

Selection of systems for monitoring crop canopy characteristics

Two possible systems were considered in detail, namely:

X the use of a laser-based range-finding instrument that would measure the distance from a position equivalent to a nozzle mounted on a spray boom to the first point of interception with the crop canopy for a range of trajectory angles corresponding to different spray fan angles (Miller and Walklate, 2000);

X a system for measuring the integrated reflectance characteristics from the complete crop canopy in a configuration for determining a normalised vegetation index (Paice *et al.*, 1999) derived from reflectance measurements in the wavebands 640-660 nm (red) and 790-810 nm (near infra-red). Previous work (e.g. Curran 1983) has shown a good correlation between vegetation indices determined from spectral reflectance measurements and leaf area index in cereal crops for leaf area indices up to approximately 3.

It was recognised that both of the possible crop canopy sensing methods would not give good resolution of differences in canopy structure when leaf area indices were greater than approximately 3. However, it was considered that if information relating to crop canopy structure was to be used as a basis for making decisions, then measurements would need to be made at relatively early stages of growth when the potential systems would give some discrimination of differences in canopy structure. The spectral reflectance method of monitoring the crop canopy was selected since this had been developed to a practical stage where it could be used in field conditions in a reasonably reliable and practical manner.

Measurements of crop characteristics and field plot layouts

Radiometers (Skye Instruments type SKR 1800) were mounted vertically downwards on the boom of a 24 m wide mounted sprayer at a spacing of approximately 4 m. A single radiometer was mounted vertically upwards on the sprayer boom to provide a correction for incident radiation levels. The sprayer was then driven along tramlines in the crop at a speed of approximately 10 km/h and with a boom height of 1.5 above the crop such that radiometer measurements were obtained for circular sampling areas approximately 0.6 m in diameter at a sampling interval of about 0.3 m. Radiometer measurements were recorded simultaneously with field location determined from a Global Positioning System (Racal Ltd.) operating in differential mode. This enabled field maps to be plotted showing the distribution of a calculated normalised vegetation index based on a Kriging interpolation model (Paice *et al.*, 1999). The field area was divided into two approximately equal areas by determining a threshold vegetation index that then defined areas of relatively high and relatively low crop canopy density. Sixteen treatment plots, two replicates of eight application treatments, each 10 x 20 m, were then allocated to the areas of high and low crop canopy density.

Measurements were made in two field conditions at Silsoe Research Institute in winter and spring wheat crops. Radiometry measurements were made at early stages of growth such that spray application treatment could be made at growth stages 32 and 39. In addition to the radiometry measurements, direct measurements of tiller numbers per square metre were also made for both the high and low crop density areas.

Spray application and determination of deposit distribution

The spray application variables investigated were volume application rates of 100 and 200 l/ha applied as fine or medium spray qualities with conventional flat fan nozzles operating either vertically downwards or at an angle of 45E forwards. All experiments sprayed a tracer dye with 0.1% of a non-ionic surfactant from a 24 m mounted sprayer treating plots positioned to one side of the tramlines. Treatments were achieved using the nozzle conditions specified in Table 1.

Extended range flat fan nozzles were used that were rated at operating pressures of between 1.0 and 4.0 bar. It was recognised that the selection of a pressure of 1.0 bar to achieve a medium quality spray at a volume rate of 100 l/ha was on the edge of the operating envelope for the nozzles chosen but was selected to keep the range of forward speeds for the different treatments as small as possible.

Table 1. Nozzle conditions used in the application treatments

Spray quality	Volume application rate l/ha	Nozzle orientation	Nozzle descriptor	Pressure, bar	Forward speed, km/h
Fine	100	Vertical	FF110/0.6/3.0	3.0	7.0
Fine	100	45E angle	FF110/0.6/3.0	3.0	7.0
Medium	100	Vertical	FF110/1.2/3.0	1.0	8.3
Medium	100	45E angle	FF110/1.2/3.0	1.0	8.3
Fine	200	Vertical	FF110/1.2/3.0	4.0	8.2
Fine	200	45E angle	FF110/1.2/3.0	4.0	8.2
Medium	200	Vertical	FF110/1.6/3.0	2.0	7.8
Medium	200	45E angle	FF110/1.6/3.0	2.0	7.8

From each treated plot, two sets of ten crop tillers were sampled at random from the centre of the plot and were sectioned into three components by cutting stems between the main leaves at growth stage 32 and at comparable positions for growth stage 39. Cut plant sections were placed in a pre-tared plastic bag, weighed and the dye on the plant sections recovered by adding a measured volume (50 mls) of de-ionized water and agitating vigorously for approximately 15 seconds. The wash solution was then transferred to tubes and taken to a laboratory for spectrophotometric analysis calibrated against samples of the original sprayed liquid taken from the nozzles.

Two glass slides were mounted horizontally in the centre of each plot prior to application and the dye deposits from the surface recovered and quantified to provide a first order check on the application rate applied to the plot. Because each field was treated twice with plots in the same positions at the two different growth stages, different dyes were used for the two spray occasions to minimise the risk of any carry over of deposit from the first application.

RESULTS

Radiometry measurements and plot layout

Figure 1 shows an example of the distribution of normalised vegetative index as measured and divided at a defined threshold to give regions of approximately equal area of high and low crop canopy density. For this field with a winter wheat crop, the areas of highest canopy occurred in the centre of the field area and treatment plots were distributed at random in the areas of high and low crop canopy density. A different crop canopy density distribution was recorded for the field established with the spring wheat crop.

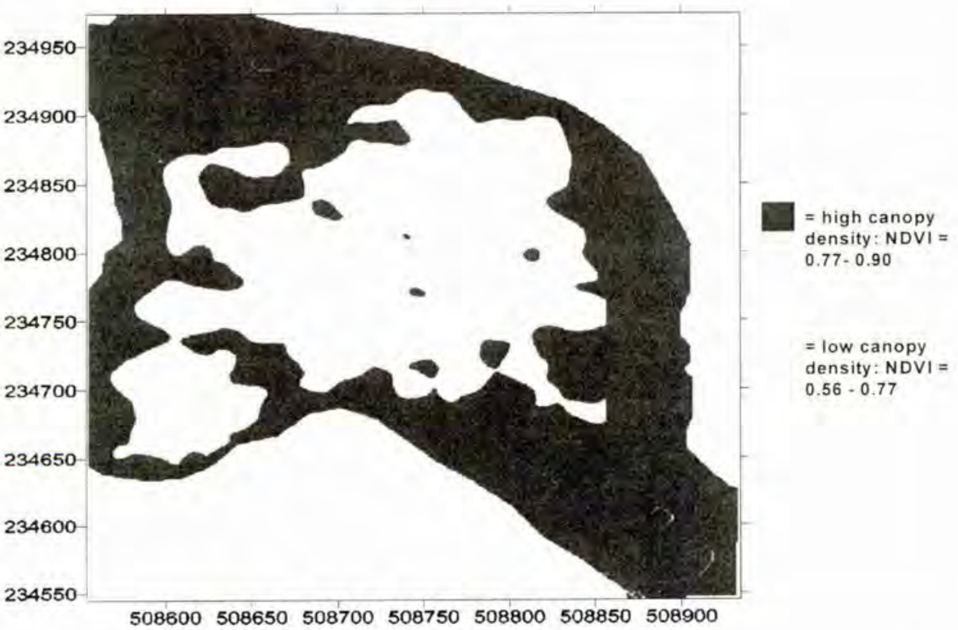

Figure 1. **Map showing NDVI measured in the winter wheat field and divided into areas of high and low crop density**

Spray deposit distribution measurements

Table 2 shows the mean spray deposits expressed as Φl/g of leaf weight measured at the three levels in the crop canopy for the winter wheat crop treated at growth stage 32. These results show some of the expected trends particularly in relation to the levels of deposit at two stages of growth. Deposit levels measured at growth stage 39 were 43% less than those at growth stage 32 and this directly reflects the increase in plant size and weight. At the early growth stage, mean deposit levels were higher in the low crop canopy density areas but not significantly so. At the later stage higher deposit levels were found in the higher canopy density areas and this was not consistent with the original simple hypothesis.

The relationship between deposit levels and application variables showed that:

- applications with a fine quality spray tended to give higher levels of deposit with the largest differences in mean deposit of 15.7% measured at the earlier growth stage compared with 7.6% at growth stage 39;
- angling the nozzles increased the total deposit by 22% at growth stage 32 and 4% at 39 with some evidence that angling increased deposits at the higher levels in the canopy as expected;
- operation at 100 l/ha gave higher deposits than at 200 l/ha by 63 and 14% at growth stages 32 and 39 respectively; while this trend is consistent with previously published data (e.g. Bryant and Courshee, 1985; Cawood *et al*., 1995), the magnitude of the difference at the earlier growth stage is much larger than expected.

Table 2. Measured spray deposits, Φl/g leaf weight, at growth stages 32 and 39 in the winter wheat crop normalised to represent expected levels per 100 l/ha of applied spray at both volume rates.

TREATMENTS				**SPRAY DEPOSIT, GS32**			**SPRAY DEPOSIT GS39**		
				Section of Tiller			**Section of Tiller**		
Crop Density	**Spray Quality**	**Volume l/ha**	**Nozzle Angle**	**Top**	**Middle**	**Base**	**Top**	**Middle**	**Base**
High	Fine	100	Angled	23.3	16.6	7.0	16.8	2.5	0.5
			Straight	15.0	11.7	7.0	21.2	2.2	0.5
		200	Angled	12.2	10.0	3.6	16.8	2.3	0.3
			Straight	8.5	7.7	2.9	13.7	1.8	0.4
	Medium	100	Angled	14.4	12.8	6.7	17.8	3.5	0.9
			Straight	17.2	13.4	5.7	15.6	2.6	0.5
		200	Angled	10.0	8.5	3.0	13.1	1.9	0.3
			Straight	9.0	9.6	4.0	12.2	3.0	0.8
Low	Fine	100	Angled	26.2	13.6	7.0	18.0	2.0	0.5
			Straight	16.0	13.0	6.9	11.3	1.5	0.4
		200	Angled	13.2	12.0	5.0	11.9	2.2	0.4
			Straight	11.7	9.3	3.8	14.8	2.3	0.3
	Medium	100	Angled	18.1	17.3	7.8	11.5	2.6	0.6
			Straight	10.6	10.9	6.2	13.1	2.3	0.4
		200	Angled	8.5	9.2	3.4	13.0	2.3	0.5
			Straight	8.2	9.2	3.8	13.4	2.0	0.4
	Standard Error of Mean				1.80			1.31	

The distribution of deposit was very different at the two growth stages examined. At growth stage 32, deposit levels at top and middle sections were generally comparable whereas at growth stage 39 more than 80% of the total deposit was in the top section of the canopy. This reflects changes in the canopy structure as well as the mean size of the overall crop canopy. There was some evidence of increased penetration into the canopy when using coarser sprays, higher volume rates and nozzles directed downwards but the effects were small and not statistically significant.

DISCUSSION

The lack of significant differences in deposit distribution between the areas of high and low crop canopy structure may relate to the field conditions used for the work. Although there were differences in canopy structure, the indication is that these were not sufficiently large to influence the spray deposition patterns obtained. However, the differences between the applications at the two growth stages suggest that there is scope to improve the match between spray application parameters and crop canopy structure even if this is not on spatially variable basis within a field as a first step. Such an approach requires an effective method of sensing crop canopy structure and it may be that existing approaches, while effective at early growth stages, give inadequate resolution in a well-established crop canopy.

The approach based on a single measurement of crop canopy structure at an early growth stage was explored as one that could be practically implemented with existing sensing systems and little disruption to existing farming practices. However, there is then the scope for the spatial variability in crop canopy structure to change substantially from the time when the sensing measurements are made to when the spray application treatments applied particularly at the later stages of growth. Making measurements of crop canopy structure immediately prior to application would improve the potential to match fungicide applications to canopy structure but this would then involve:

- sensor measurements of the crop canopy either shortly or immediately prior to an application – if a mapping approach is to be adopted then a separate operation in the field would be required;
- the use of a sensor system that is able to resolve differences in crop canopy structure when working with relatively well established crops having a leaf area of more than 3.0.

The large difference in total deposit levels measured between applications at 100 and 200 l/ha may relate to the nozzle conditions selected particularly the use of a pressure of 1.0 bar. There was some evidence from the microscope slides in each plot that the 200 l/ha treatment was under-applied or had a higher than expected non uniformity across the plot, and this may have related to the spray formation with this nozzle at a relatively low operating pressure.

The effects of spray application volume rate and the effect of angling nozzles has implications beyond the application of fungicides to all plant protection products. The increase in deposit levels when operating at low volume application rates and with angled nozzles could enable improved spraying performance to be achieved particularly when combined with the improved timeliness effects that can be associated with operation at reduced volume rates (Rutherford and Miller, 1993).

Future research aimed at exploring the potential for improving agrochemical use with a mode of action based on leaf area needs to examine methods of sensing crop canopy characteristics, to relate such measurements to conventional descriptions of the canopy such as growth stage and then to relate the canopy to application parameters particularly volume application rate. An initial step would be to use crops at different stages of development prior to examining variations at a given growth stage and the potential for spatially variable treatments.

ACKNOWLEDGEMENTS

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Thanks are also due to colleagues who helped with the work particularly M E R Paice (Silsoe Research Institute), staff of the Analytical Laboratory at Silsoe Research Institute, Mr T H Robinson (Novartis Crop Protection Ltd.) and Mr B Freer (Morley Research Centre).

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SESSION 6A

ECONOMICS OF PEST AND DISEASE MANAGEMENT IN CEREALS

Chairman	Dr P Gladders *ADAS Boxworth, Cambridge, UK*
Session Organiser	Dr T Locke *ADAS Rosemaund, Hereford, UK*
Papers:	6A-1 to 6A-4

Economics of Cereal Disease Control - a European Perspective

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ABSTRACT

As European cereal prices are now at world levels, the production costs for cereals are being closely questioned, the natural reaction often being to reduce inputs, especially those such as fungicides. Cereal diseases have been shown to give significant yield penalties across Europe and trials show that the use of fungicides to control these diseases results in economic benefit, even at low grain prices. Along with agronomic measures to ensure high quality, yield remains a key driver for economic cereal growing, with comprehensive fungicide programmes resulting in good returns which are on average higher than those of lower input programmes.

INTRODUCTION

The European Union's cereal production in 1998 was estimated to be 211 million tonnes (EU 15), of which some 94 million tonnes was common wheat and 52 million tonnes was barley. According to official statistics of the EU (European Commission, 2000), total production of all cereals has increased over the period of 1994 to 1998 (Table 1). During this period, the trend has been for average yields of common wheat, durum wheat and barley to increase, the changes being +11.8%, +4.4% and +14.5% respectively. These yields have been subject to fluctuation from year to year, caused partially by climatic conditions and differences in planted varieties, but nevertheless the trend remains towards an increased productivity per hectare of the major small-grained cereals in Europe.

Since 1996/97 there has been a sharp fall in the revenue for the cereals sector in Europe. The main cause of the reduction in profitability has been the fall in grain price by almost 30 per cent since 1997/98. Subsidies were transferred to area payments from direct support for grain price and area payments now account for around 40% of European farmers' incomes with many cereal farmers making losses. At these times the natural tendency is for growers to reduce expenditure on inputs by reducing variable costs, such as fungicides, herbicides and insecticides. This paper discusses the role of fungicides in the European cereal market today and in the future in supporting the continued profitability of growers.

THE EUROPEAN FUNGICIDE MARKET

The evolution of the cereal fungicide market can be closely related to the development of cereal production in the EU. At the end of the 1960's tridemorph and ethirimol were introduced to combat mildew on cereals. They were the first foliar fungicides to be targeted specifically at cereal diseases and they were also the first of the systemic fungicides.

Their use catalysed a growing awareness of the benefits to be gained from cereal disease control. With the political incentive of a high price for the output as the EEC regime guaranteed, inputs to cereals generally increased in the early 1970's. The high value market created by the Common Agricultural Policy promoted efforts into new fungicide research and development. The first triazoles were introduced into the market at the end of the 1970's and rapidly displaced older chemistries due to their superior level of control of diseases, their broad spectrum of activity and flexibility in usage (curative and systemic properties). At this time much innovative development work was done resulting in improved knowledge about when and how to use the products (timing and dose) to maximise disease control, yields and return on investment. Fungicide programmes based on triazoles often resulted in improved green leaf retention with a concomitant yield benefit, sometimes over and above that which was believed to be due to disease control.

The triazoles became an essential part of cereal farming during this period, together with the morpholines (mainly for powdery mildew control) and prochloraz (mainly for eyespot control once resistance to benzimidazoles became widespread). Cyprodinil was introduced to the French market in 1991 and brought a new standard of eyespot control, together with a broad spectrum of control of foliar diseases, including powdery mildew and *Rhynchosporium secalis*.

In 1997, a major new class of fungicides, the strobilurins, was introduced to the cereal sector. Based on beta methoxyacrylate, the class offered control of a wide range of diseases at low rates of application and since the introduction of the first two members of the group (kresoxim-methyl and azoxystrobin) these fungicides have become an integral part of European cereal production. As the understanding of how to use this chemistry continues to develop, the improved disease control, green leaf retention and outstanding yields first observed with the triazoles some 15 to 20 years earlier have been repeated and surpassed.

Since 1994, the cereal fungicides market in Europe has grown considerably to the present day. However, in 1999 the market declined, due mainly to continuing low grain prices and a return to 10% set-aside in the EU. The value of this market is now around €1127 million (Figure 1).

Oerke (1994), estimates that production losses in Europe for wheat and barley were around 6% in 1988-90 despite the use of fungicides (Table 2). In the absence of fungicides, losses would have been much higher, in the range of 17-22% for wheat and 17-20% for barley with the overall figures for Europe of 21 and 20% respectively, the damage being attributed mostly to rusts, Septoria, powdery mildew and stem-base and root diseases. Such estimates are limited in their accuracy but give an indication of the value attributable to the use of fungicides. The high disease pressure in Western Europe in recent seasons suggests that these figures would be reasonably representative of the situation today.

With a current wheat price of €94/tonne, the value of the fungicide market in Europe is equivalent to 12 million tonnes or around 8% of the European wheat, barley and rye harvest in 1998. The estimated losses of 20% without fungicide protection show that on a European level the cost benefit of fungicide use is clearly positive.

Table 1. Cultivated area, yield and total yield of cereals in the European Union (EU-15), 1994 - 1998 (source: European Commission)

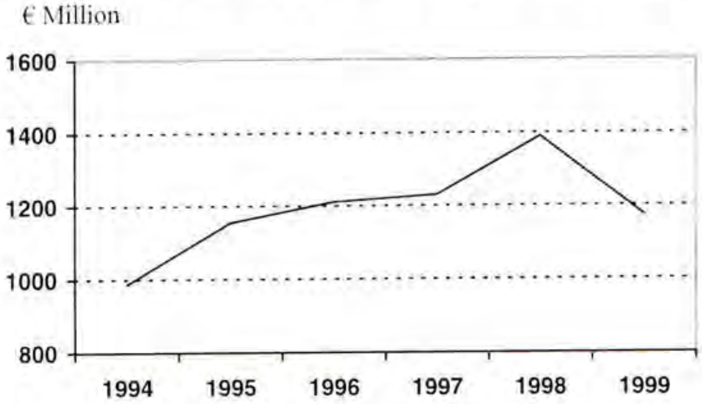
	Area 1000 ha					Area Yield 100 kg/ha					Total Production 1000 t				
	1994	1995	1996	1997	1998	1994	1995	1996	1997	1998	1994	1995	1996	1997	1998
Total Cereals (*)	34 842	35 576	36 938	38 110	37 367	50.1	49.9	55.8	53.9	56.5	174 291	177 696	206 141	205 881	211 104
Common wheat	12 826	13 412	13 758	14 067	13 979	60.4	60.1	66.2	62.4	67.5	77 424	80 628	91 186	87 565	94 423
Durum wheat	3 046	3 147	3 210	3 228	3 244	26.8	22.5	27.4	22.6	28.0	8 274	7 086	8 737	7 375	9 071
Barley	10 943	11 008	11 443	11 677	11 342	39.9	39.6	46.2	44.1	45.7	43 649	43 505	52 739	52 572	51 790
Rye	1 275	1 450	1 358	1 361	1 448	39.7	43.5	43.0	45.1	44.5	5 083	6 215	5 813	6 161	6 443

(*) = without rice, including maize, triticale etc.

Table 2. Estimated annual losses in production (%) due to disease in wheat and barley 1988-90 (from Oerke *et al.*, 1994).

Country	Wheat		Barley	
	Actual	Potential	Actual	Potential
Austria	8	18	7	18
Benelux	7	22	5	21
Denmark	7	20	5	21
Finland, Norway, Sweden	7	17	7	17
France	6	21	7	20
Germany	7	20	5	20
Ireland	6	21	7	19
Switzerland	7	20	5	18
United Kingdom	7	22	7	18
Overall	6	21	6	20

Figure 1: Value of the European Cereal Fungicides Market 1994-99



EFFECTS OF FUNGICIDES ON YIELDS AND PROFITABILITY

Yield responses in wheat and barley due to the control of foliar and stem-base diseases are well known and have been the basis for their widespread use over the past thirty years. The economic response to two important diseases of wheat, eyespot and Septoria, will be used to demonstrate how the improving fungicide technology brings greater benefits to the grower.

Common eyespot (*Pseudocercosporella herpotrichoides*) reduces yield through stem-base lesions restricting translocation and in severe cases causing lodging. In England and Wales alone the losses due to eyespot in wheat and barley have been estimated at €37 million (Hardwick *et al*., 1998). An experiment with 14 replicated field trials (non-foliar disease situations) was carried out in France in 1999 to evaluate the effect of eyespot on yield and the economic benefit of fungicides applied at BBCH 31-32. The data from these trials, assuming a grain price of €94/t, show that the average margin over input cost (MOIC) was €29.61/ha using prochloraz, and €57.14 using a cyprodinil based formulation (Table 3). As expected, if the trials are separated into those where lodging occurred and those where the crop remained standing, the effect on yield and therefore the MOIC, was lower in the absence of lodging (€21.81 and €28.38/ha for prochloraz and cyprodinil respectively, Table 4). Where lodging occurred, whilst both treatments reduced the lodging compared to untreated the MOIC figures show €40.61/ha for prochloraz and €94.18/ha for cyprodinil (Table 5). The additional activity against eyespot of cyprodinil, together with its ability to control a wider range of diseases (Leadbeater *et al*., 1994) provided more effective protection of the yield potential and a greater return on investment.

To demonstrate the cost effectiveness of strobilurin fungicide programmes on wheat, a series of trials was carried out during 1999 comparing a non-strobilurin based fungicide programme with strobilurin-based programmes. The predominant disease in these trials was *Septoria tritici*, and various two-spray programmes were applied, at BBCH 31-32 followed by BBCH 37-39. A comparison of the yields of fungicide programmes with different

Table 3. Margin over input cost from control of eyespot. Mean data from 14 trials in France 1999. (1 tonne wheat = €94)

Treatment	Rate g ai/ha	Eyespot infection %	Yield t/ha	Yield increase t/ha	Gross value of yield increase €/ha	Cost of fungicide €/ha	MOIC €/ha
Untreated		49.3	8.19	-	-		
Prochloraz	450	33.3	8.68	0.493	46.34	16.73	29.61
Cyprodinil + cyproconazole	600 + 80	23.9	9.35	1.166	109.60	52.46	57.14

Table 4. Margin over input cost from control of eyespot in non-lodging situations. Mean data from 8 trials in France 1999.

Treatment	Rate g ai/ha	Eyespot infection %	Yield t/ha	Yield increase t/ha	Gross value of yield increase €/ha	Cost of fungicide €/ha	MOIC €/ha
Untreated		45.7	8.02				
Prochloraz	450	25.4	8.43	0.41	38.54	16.73	21.81
Cyprodinil + cyproconazole	600 + 80	22.0	8.88	0.86	80.84	52.46	28.38

Table 5. Margin over input cost from control of eyespot in lodging situations. Mean data from 6 trials in France 1999.

Treatment	Rate g ai/ha	Eyespot infection %	Lodging %	Yield t/ha	Yield increase t/ha	Gross value of yield increase €/ha	Cost of fungicide €/ha	MOIC €/ha
Untreated		54.3	82.7	8.18				
Prochloraz	450	42.4	64.6	9.01	0.61	57.34	16.73	40.61
Cyprodinil + cyproconazole	600 + 80	28.4	27.2	9.96	1.56	146.64	52.46	94.18

intensity of strobilurin use was made at two sites on six cultivars, and the mean results are presented in Table 6. All fungicide treatments increased yield compared to untreated. A programme of fenpropidin + cyproconazole followed by chlorothalonil + epoxiconazole gave a mean increase in yield of 18.2 dt/ha compared to untreated. The substitution at the second application timing of trifloxystrobin + epoxiconazole increased this to 21.4 dt/ha. A programme of trifloxystrobin + cyproconazole followed by trifloxystrobin + epoxiconazole gave a mean increase in yield of 24.9 dt/ha.

In these trials the yield response to strobilurin treatments was remarkably consistent and the highest yields in all trials were obtained with greatest intensity of strobilurin use. The fungicide programme with two applications of strobilurin in each trial gave a higher yield than a programme containing only one application. This in turn, was higher yielding than a programme using only conventional chemistry.

When the analysis of financial returns is made there was a mean positive benefit from all fungicide programmes and there was no difference in economic return for programmes with just one and no strobilurin use. Despite the additional cost, the programme containing a strobilurin at both timings provided on average the largest margin over input cost. This additional benefit occurred in 8 of the 12 individual trials (data not shown).

Table 6 Yields (dt/ha) and margin over input costs of strobilurin and non-strobilurin based fungicide programmes in wheat - 12 trials in Europe 1999

Spray at BBCH 31-32 (g ai/ha)	Spray at BBCH 37-39 (g ai/ha)	Mean yield (dt/ha)	Value of extra yield @ € 9.40/dt	Margin over input costs (€/ha)
untreated	untreated	98.5	-	-
fenpropidin + cyprodinil (300+48)	chlorothalonil + epoxiconazole (500+63)	123.4	233.90	113.08
fenpropidin + cyprodinil (300+48)	trifloxystrobin + epoxiconazole (150+63)	119.9	20.77	114.27
trifloxystrobin + cyproconazole (113+48)	trifloxystrobin + epoxiconazole (150+63)	116.7	171.24	135.42

DISCUSSION

Key drivers for profitable cereal production in Europe include quality (for example price premiums obtained for bread making wheat and malting barley) and yield. As European cereal growers now have to compete at world market prices with the extensive producers of North America and Australia, reducing the unit cost of production is the key to profitability. Many farms have already reduced their fixed costs and there is little scope for much further improvement although further farm consolidation can be expected across Europe with average farm sizes increasing. To further reduce unit cost of production, fixed costs need to be spread over a greater number of tonnes of grain and output per hectare needs to increase to do this. So it is likely that yield will remain a key driver for the profitability of cereal farming in the future and in order to obtain premiums for specific markets this must be yield of the required quality. The continued profitability resulting from the use of cereal fungicides in Europe has been demonstrated in this paper using eyespot and Septoria as examples (although rather simple calculations have been used, not taking into account labour and fuel costs of application) and when used in integrated crop programmes can be expected to continue to contribute to sustainable farm incomes. The use of modern fungicides, such as cyprodinil and the strobilurins, has contributed to the trend of increasing yields in cereals in Europe, which can be expected to continue. The strobilurins have brought a new level of yield response through control of plant diseases and data in this paper show that increasing strobilurin inputs generally results in not only increased yields, but increased margins over input costs. The contribution of fungicides to increasing cereal quality is well known, resulting for example in increased specific weights and reductions in grain contaminated with the mycotoxin-causing *Fusarium* spp. and these can also be expected to continue to be important factors in world cereal markets.

For the future, new advances can be expected from the crop protection industry to further increase the yield potential of cereals, as new solutions are found to give more effective control of such diseases as take all (*Gaumannomyces graminis*) and Fusarium ear blight. More effective control of these diseases will bring benefits in terms of both yield and quality of cereal grain, resulting in increased profitability and therefore contributing to the sustainability of cereal production in Europe.

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METHODS AND MATERIALS

The methods used in the annual surveys were as described by King (1977), Polley & Thomas (1991) and Polley *et al.* (1993). Farm selection was made on a regional basis. The distribution of addresses between regions was proportional to the regional area of winter wheat or barley grown, except for Wales where additional addresses were requested in order to obtain meaningful figures for the area. The addresses were selected at random from the returns of the previous years June MAFF Agricultural and Horticultural Census (Anonymous, 1969-98). From 300-400 crops were sampled each year in each survey.

The surveys were carried out in June and July. Winter barley crops were sampled at the watery-ripe to early-milk growth stages (GS 71-73) and winter wheat sampling was carried out at the early to medium-milk growth stage (GS 73-75; Zadoks *et al.*, 1974). On each farm, a field was selected at random and a sample of 50 fertile tillers was collected, taken at random from a diagonal traverse of the field. The sampling was done by ADAS and the samples were packed in polyethylene bags and dispatched to the Central Science Laboratory (CSL) for assessment, accompanied by a completed questionnaire giving agronomic details such as cultivar, sowing date and previous cropping, as well as details of all pesticide applications. Randomly selected sub-samples of 25 tillers were assessed on arrival at CSL. Foliar diseases were recorded as the percentage area of the flag and second leaves affected, using standard area keys (Anonymous, 1976) and stem base diseases on a four point severity scale (Scott & Hollins, 1974). Green leaf area and insect damage were also recorded. Data were stored in an INFORMIX relational database. Yield losses were calculated using the formulae cited by Cook *et al.* (1991).

RESULTS

The number of crops treated with a fungicide increased dramatically following their introduction to winter wheat crops in 1973 and reached a plateau of in excess of 95% crops treated after only 12 years (Figure 1). In 1999, 99% of crops were treated, with a mean number of applications of 2.5 per crop. Prior to 1985, the dominant foliar disease was *Stagonospora nodorum* (teleomorph: *Phaeosphaeria nodorum*) which reached a peak of 27% area leaf 2 affected in 1973. However, *S. nodorum* was only present at a level of 0.1% in 1999. The dominant disease is now *Septoria tritici* (teleomorph: *Mycosphaerella graminicola*), which was at its peak in 1985 at 15.5% area leaf 2 from when it fell to a mean of 2.1% from 1986-1997. However, in 1998 and 1999 levels reached 7% (Figure 5).

Eyespot (*Pseudocercosporella herpotrichoides*) has always been a major disease of winter wheat and in the last three years the percentage of stems affected by moderate plus severe lesions (the level at which significant yield loss occurs) has exceeded 13% (Figure 6). Data on stem base diseases were collected from 1975 and combined moderate and severe categories of both eyespot and sharp eyespot have increased (Figure 1).

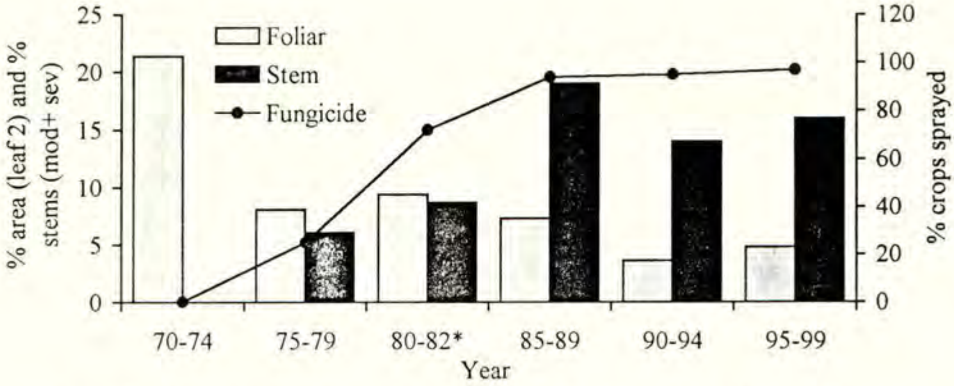

Figure 1. Winter wheat: five-year means of foliar and stem-base diseases (* mean of three year only).

Data for winter barley have only been collected from 1981 (Figure 2). Indications were that prior to that date the percentage of crops being treated was higher than for winter wheat. In 1999, 95% of crops were sprayed with a mean number of 1.6 applications. The main diseases of winter barley have been leaf blotch (*Rhynchosporium secalis*), net blotch (*Pyrenophora teres*) and brown rust (*Puccinia hordei*) at 2.6, 2.5 and 1.4% area of leaf 2, respectively, for the period 1995-1999. Mildew levels have been generally below 1% area leaf 2. Eyespot and sharp eyespot have affected 7.3 and 1.5% of stems with moderate and severe lesions for the same period.

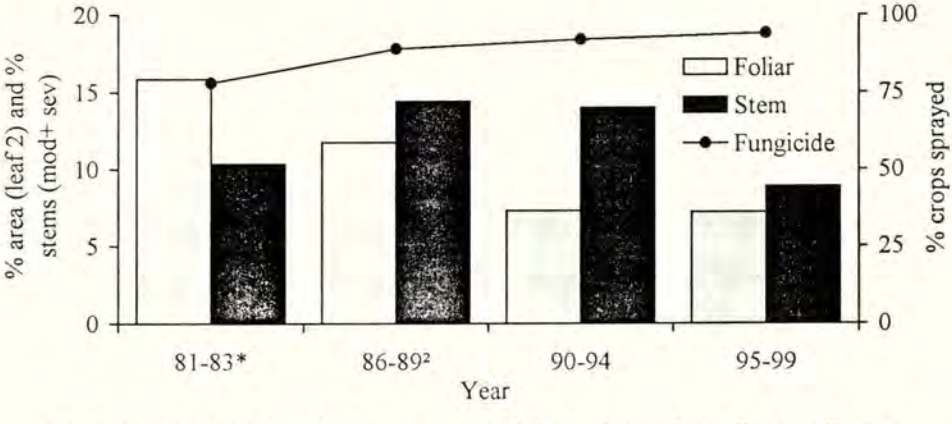

Figure 2. Winter barley: five-year means of foliar and stem-base diseases (* mean of three years and ² four years only).

The combined percentage yield loss for foliar and stem base diseases has shown a small decline from the five-year period, beginning in 1975 to the current period but a greater reduction in winter barley than winter wheat (Table 1).

Table 1. Mean percentage yield loss figures for foliar and stem base diseases.

	1975-79	1980-84	1984-89	1990-94	1994-99
Winter wheat	5.3	6.0*	5.2	3.7	3.6
Winter barley	-	10.1*	8.0†	5.4	4.5

* three years data only, † four years data only

The pattern of fungicide application at the key growth stages has varied for winter wheat (Figure 3). Apart from 1981, 1987, 1988 and 1994, a greater proportion of crops was sprayed around GS 31 than at any other timing. The percentage sprays at this timing containing an active ingredient effective against eyespot (cyprodinil, flusilazole and prochloraz) has fallen from 42% in 1995 to 16% in 1999. The proportion of crops treated at around ear emergence (GS 59) was consistently greater than that treated at flag leaf emerged (GS 39) until 1994 (Figure 3).

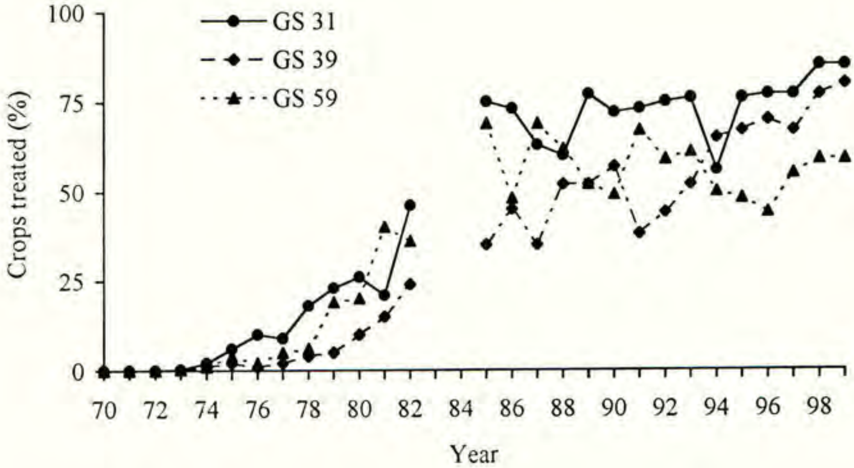

Figure 3. Percentage of winter wheat crops sprayed at key growth stages.

Sprays at GS 31 have also dominated in winter barley crops. On average 24% more crops were treated at this stage than at GS 37 and beyond. However, since 1993 the gap has closed to 14% (Figure 4).

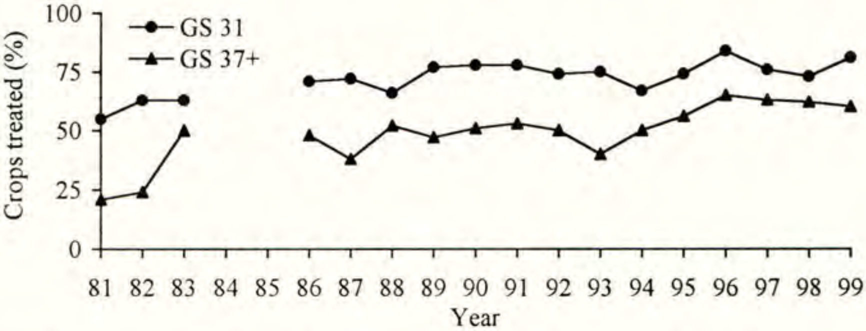

Figure 4. Percentage of winter barley crops sprayed at key growth stages.

Cultivar resistance is not well deployed in winter wheat, with over 70% of crops sown to cultivars with the Recommended List resistance rating (1999) of 5 or below for *S. tritici* (Figure 5) and 80% for eyespot (Figure 6).

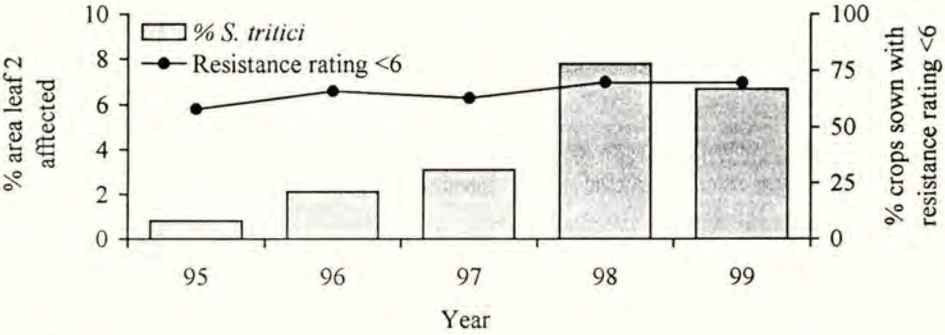

Figure 5. Per cent *S. tritici* and % crops sown with resistance rating of 5 or less.

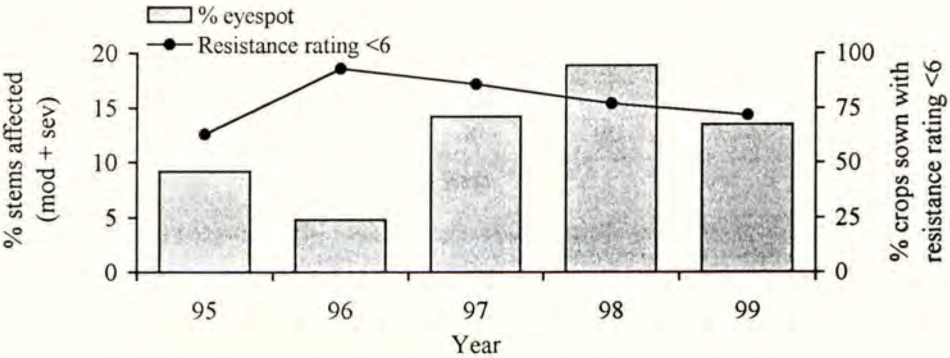

Figure 6. Per cent eyespot and % crops sown with resistance rating of 5 or less.

On average 36% of winter barley crops were of cultivars with a resistance rating of 5 or below for leaf blotch (Figure 7). The figure for net blotch was 15% (Figure 8).

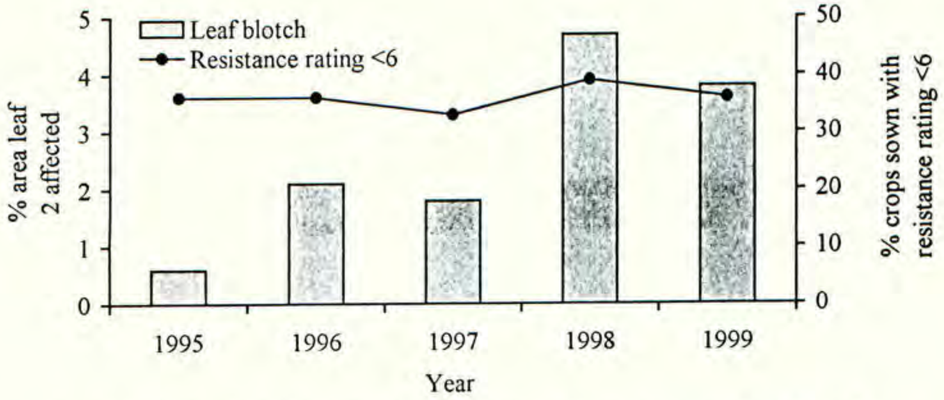

Figure 7. Per cent leaf blotch and % crops sown with resistance rating of 5 or less.

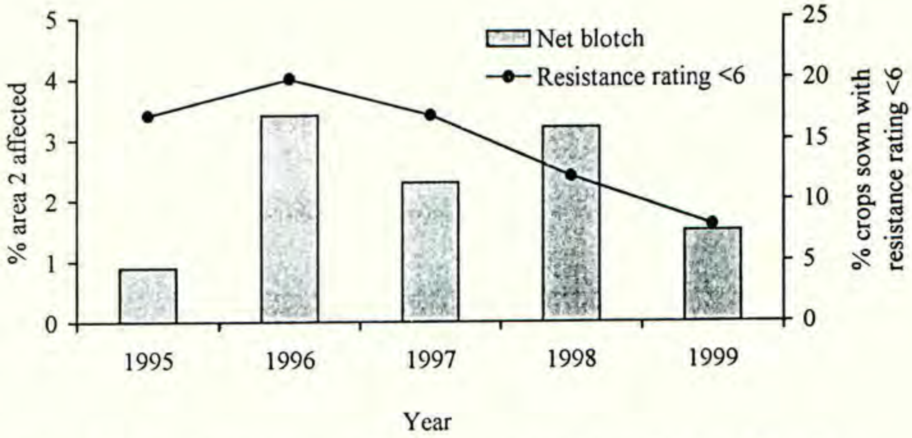

Figure 8. Per cent net blotch and % crops sown with resistance rating of 5 or less.

DISCUSSION

Three key issues arise from the results presented. The first is the rise in both the percentage of crops treated with a fungicide and the number of spray applications, although dose per application has reduced (Thomas & Turner, 1998); the second is, for winter wheat in particular, a failure in the deployment and availability of cultivar resistance to the dominant diseases and the third issue is the lack of evidence to suggest that fungicides are being applied in a rational manner.

It has been known since the early 1980s that the key spray timing to control foliar disease is at flag leaf emergence (GS 39) and not full ear emergence (GS 59) (Cook & Jenkins, 1988). This finding coincided with the period when there was a switch from *S. nodorum* to *S. tritici* as the dominant foliar pathogen of wheat. The lower risk from septoria glume blotch reduced the need to apply a fungicide at ear emergence. Advice on the optimum timing for fungicide application was promulgated by a number of means under the banner of 'Managed Disease Control' (Anonymous, 1984). However, data on fungicide timing from the survey revealed that it was only from 1994, 10 years later, that the percentage crops treated at GS 39 consistently exceeded that at GS 59. The poor control of eyespot is probably a reflection both of seasons where weather conditions favour the disease and the absence of fungicides applied around GS 31 with an active ingredient effective against the disease.

The percentage of crops drilled with winter wheat cultivars suceptible to disease has been consistently high. This was reflected in the higher levels of uncontrolled disease seen in seasons favourable to diseases such as *S. tritici* and eyespot, when optimum spray timings are difficult to achieve, as in 1998 and 1999. This contrasts with low levels of disease in the drier springs of 1995 and 1996. The situation with winter barley illustrates the benefit of cultivar resistance where levels of net blotch, in particular, were low and, in 1999, only 8% of crops were of susceptible cultivars.

In 1975-79, the total estimated percentage yield lost to disease was 5.3% (total foliar and stem base diseases) and in 1995-99 it was 3.6%. Fungicide use in 1975 amounted to 12% of crops with a mean number of applications of 0.1 but by 1999 it was 99%, with a mean number of applications of 2.5. National yields have increased in that time from 4.3 t/ha to 8.1 t/ha (Anonymous, 1971-1999). Increases have been due predominantly to improvements in cultivars and nutrition. Also, there have been 25 years of research into the control of cereal diseases with fungicides. It is interesting to speculate whether, in the absence of fungicides, and therefore with greater reliance for disease control having to be placed on cultivar resistance, crop rotations, cultivations and time of drilling, the severity of diseases would be substantially different. An indication of what is achievable has come from research on winter wheat grown in a stockless organic rotation, where mean yields of 7.2 t/ha and minimal disease incidence have been recorded (Cormack, 1999). A more sustainable system of cereal production, particularly in a climate of falling grain prices may be a better alternative than complete reliance on the use of fungicides (Walters & Hardwick, 2000).

Continued monitoring of disease is important to evaluate the impact of current and future changes in agriculture on the sustainability and competitiveness of the UK arable crop sector. Such changes include the introduction of new technologies, e.g. web- and CD-based information systems and diagnostic technologies for tailoring fungicide dose and choice. Technological advances in the industry, uptake of pesticide optimisation strategies and forecasting systems are essential if UK agriculture is to be competitive while minimising environmental impacts. The potential role of new technologies in maintaining the economic viability of cereals will need careful monitoring and validation. Improvements in crop production strategies may help to ameliorate the current trend in increased fungicide use, which in 1998 accounted for a total of 2,344 tonnes applied to the crop canopy in Great Britain (Garthwaite & Thomas, 1998). The survey data provide a vital benchmark by which the effectiveness of these technological advances and strategies can be assessed in the future.

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Margin over cost in disease management in winter wheat and spring barley in Denmark

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ABSTRACT

During 1990-99, 2-3 fungicide spray programmes applied in winter wheat caused a yearly variation in yield increase of 0.4-2.7 t/ha. Margin over cost varied from the financial equivalent of -0.5 t/ha to 2.0 t/ha. In winter wheat, with the dominance of *Erysiphe graminis* and septoria diseases, the yield increase contribution from an early application (GS 31-32) was generally only 30% of the increase from an ear application (GS 39-55). In most years septoria control in winter wheat was the major contributor to a positive net yield response from disease management. The yield increase in highly septoria-susceptible varieties was 2-3 t/ha and only 1-1.5 t/ha in more resistant varieties. For septoria control, the optimal dose of an effective fungicide varied between 25-75% of the full dose. The margin over cost from a flag leaf/ear application was variable, depending on the actual timing, with more than 1 t/ha, from an application at GS 51-55 being optimal. In spring barley the yearly yield increase from fungicide treatments varied between 0.1-1.3 t/ha. Margin over cost varied from the financial equivalent of -0.3 t/ha to 0.8 t/ha. The benefit was highest in varieties susceptible to *E. graminis* and *Puccinia hordei*. Optimal input varied between 12.5-25% of a normal dose of a broad-spectrum fungicide. The high variation in yield responses supports the idea of modifying input using a decision support system, which adjusts the dose according to timing, growth stage, variety resistance and efficacy of the product used.

INTRODUCTION

In the autumn of 1997, the Danish Minister of Environment and Energy appointed a committee (The Bichel committee) to assess the overall consequences of partial or total phasing out the use of pesticides. Crop losses in the zero-pesticide scenario due to weeds, diseases and pests were estimated individually in all crops. Winter wheat had an estimated loss in yield of 27-29% and spring barley of 17-19% (Anon., 1999a). In winter wheat and spring barley the loss due to diseases has been estimated at 7-9% and 6-7% respectively. Lower grain prices (650-750 DKK/t) and a 33-54 % tax on pesticides, as introduced in Denmark, will reduce the optimum pesticide input significantly (Anon. 1999b). Resistant varieties have a great potential for reducing expected losses resulting from disease. This could be used to advantage when reducing pesticide consumption. It is, however, not considered possible to resolve all problems with diseases in cereal crops in the foreseeable future by relying only on resistance (Anon. 1999b).

Reduction plans for pesticides and the need for reducing input costs for arable farmers have put the emphasis on minimising pesticide input in cereal production. Over the last 15 years experimental activity has focused on optimising input of fungicides, with regard to efficacy and margin over cost. This paper concentrates on yield responses and net yields from field trials carried out in winter wheat and spring barley in Denmark, with reference to yearly variations, and those due to application timing and dose rate.

METHODS AND MATERIALS

Field trials were undertaken at The Danish Institute of Agricultural Sciences (DIAS) or The Danish Agricultural Advisory Centre (DAAC). All of the trials were of a randomised complete block design with four replicates and a plot size of 25-32 m^2 at DIAS. The trial design at DAAC was a systematic complete block design with 5 replicates. The fungicides were applied with knapsack sprayers at low-pressure (2-3 bar) using flat fan nozzles in a volume of 200-300 litres/ha. Disease assessments reported in this paper were all made at DIAS, as per cent leaf area covered by the individual diseases. Attacks of septoria were found in almost all winter wheat trials with *Septoria tritici* dominant. *E. graminis* and *Puccinia striiformis* were found in fewer trials. In spring barley, *E. graminis* dominated, but *P. hordei*, *Rhynchosporium secalis* and *Drechslera teres* appeared in several trials. The plots were harvested with a plot combine harvester and the grain yield was corrected to 15% moisture content. Pesticides used in the trials are listed in Table 1.

Table 1. Prices used to calculate net yields (profits)*

Product	Price (DKK)	Normal application rate (l/ha)	Active ingredients (g/l)
Tilt top	380	1.0	125 g propiconazole+375 g fenpropimorph
Amistar	514	1.0	250 g azoxystrobin
Amistar Pro	315	2.0	100 g azoxystrobin + 280 g fenpropimorph
Folicur	400	1.0	250 g tebuconazole

*Application costs were estimated at 60 DKK/ha ; grain price was 750 DKK/t ; malting grain price was 900 DKK/t

RESULTS IN WINTER WHEAT

Every year many trials were carried out on a wide range of winter wheat varieties to follow the disease development and the benefit from use of fungicides (Table 2). These trials were a good indicator of the yearly variation in benefit from disease control. In a 10 year period, yield increases from fungicide control varied from 0.4 t-2.7 t/ha. Calculating margin over cost, only 50% of the years generated a positive net yield response to disease control. The variation in yield reflected severe attacks of yellow rust in 1990-91 and severe septoria in 1997-99. In the rest of the years mildew, and minor attacks of septoria, gave rise to moderate yield responses. Since 1993 Ritmo, still is a commonly grown variety in Denmark, has shown similar year on year differences in yield responses (Table 2). In wheat, with the dominance of mildew and septoria, the yield increase contribution from an early application (GS 31) was generally only

30% of the increase from an ear application (GS 45-55). In years with severe rust problems earlier applications may, however, contribute significantly more to the total yield response (Jørgensen & Nielsen, 1994).

Table 2. Variation in yield increases and margins over cost (expressed as t/ha) in winter wheat based on standard treatments with fungicides* in field trials in Denmark. (1990-1999).

Year	Yield increase in winter wheat (No. of trials)				Margin over cost in wheat	
	All varieties		cv. Ritmo		All varieties	cv. Ritmo
1990	2.71	(71)	-	-	1.96	-
1991	1.50	(67)	-	-	0.75	-
1992	0.35	(162)	-	-	-0.45	-
1993	0.43	(142)	0.44	(7)	-0.32	-0.31
1994	0.40	(178)	0.41	(16)	-0.35	-0.34
1995	0.47	(122)	0.71	(50)	-0.28	-0.04
1996	0.59	(141)	0.80	(64)	-0.16	0.05
1997	0.96	(266)	1.17	(57)	0.21	0.42
1998	1.65	(329)	1.84	(80)	0.90	1.09
1999	1.35	(438)	1.58	(112)	0.60	0.83

* 1990-1997: 2-4 treatments with 25-50% of propiconazole+fenpropimorph. 1998-99: 2 treatments with 25%-50% propiconazole+fenpropimorph/tebuconazole and azoxystrobin. Cost equivalent = 0.75 t/ha.

Several trials have indicated that the optimal dose for septoria control varies considerably from year to year. Although the highest yield increase for septoria control nearly always occurs from the full dose, the optimal margin over cost has, over 3 years, varied between 25-75% of the full dose (Figure 1). The economic loss if using a too high or a too low dose is relatively small in years with severe disease attacks. In years with moderate attacks, a high input may give rise to a direct loss. Based on experiences from trials, the decision support system 'PC-Plant Protection' recommended approximately 30% of the normal dose for septoria control. Depending on the season, 1 or 2 treatments may be recommended (Henriksen *et al.*, 2000).

Depending on the level of varietal resistance the yield response from disease control varied significantly (Table 3). In the 1998 and 1999 seasons all trials were dominated by relatively severe attacks of *S. tritici*. The varieties Stakado and Terra were, in those years, among the most resistant varieties giving 1-1.5 t/ha yield responses, whereas cvs Hussar and Trintella had been among the most susceptible and highly responding varieties, giving 1.5-3 t/ha in yield increase. A relatively good correlation was found between level of attack at GS 75 in different varieties and the yield responses following a 2-3 spray program (Figure 2). In order to adjust fungicide input to these significant differences in varietal response, varieties should be specifically treated according to disease susceptibility and response to fungicides.

Depending on the time of application significant differences in the control of septoria and yield response can be obtained. In 1998 and 1999 the optimal time had been GS 51-55 (Figure 3) whereas in 1997, little difference was seen between the application at GS 39 and GS 55 (results not presented). Results have shown that 75-100% of normal dose of azoxystrobin at GS 39, in certain years, can give similar margin over cost as 25% of normal dose applied at GS 51-55.

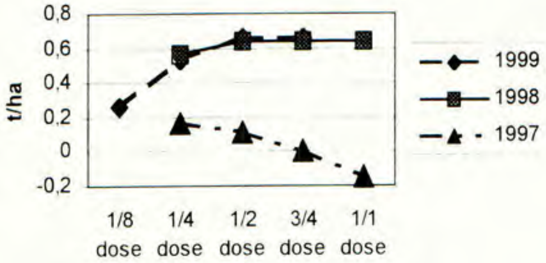

Figure 1. Margin over cost from fungicide treatments at GS 39-51 in winter wheat, 1997-99, using azoxystrobin for septoria control. (Trial nos: 1997 =4; 1998 =12; 1999 =16).

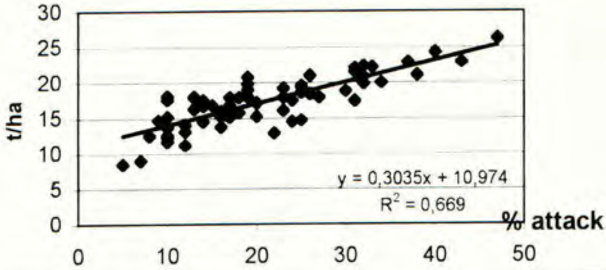

Figure 2. Per cent attack of septoria on two upper leaves and yield increase from fungicide treatments at GS 31 and 39-51 in different varieties of winter wheat, 1998-99, using 25-50% of propiconazole+fenpropimorph for 1st application and 50% azoxystrobin for 2nd application.

Table 3. Variation in attack of septoria on two upper leaves and yield increases in different winter wheat varieties, (1998-1999)*

	1998		1999		Average
Variety	% Septoria in untreated (GS75)	Yield increase (t/ha)	% Septoria in untreated (GS 71-73)	Yield increase (t/ha)	Margin over cost in wheat (t/ha)
Ritmo	73	2.94	46	1.33	0.83
Cortez	37	2.52	40	1.51	0.71
Hussar	86	3.18	59	1.99	1.28
Pentium	58	2.18	47	1.55	0.56
Trintella	68	3.27	43	1.90	1.28
Terra	38	1.44	-	-	(-0.25)
Stakado	-	-	16	1.23	(0.31)
LSD_{95}	9	0.52	7	0.55	

*Following a 2 fungicide treatment with full dose in 1998 (cost equivalent = 1.69 t/ha) or 2 treatments with 40-50% dose in 1999 (cost equivalent = 0.92 t/ha). 2 trials in each year.

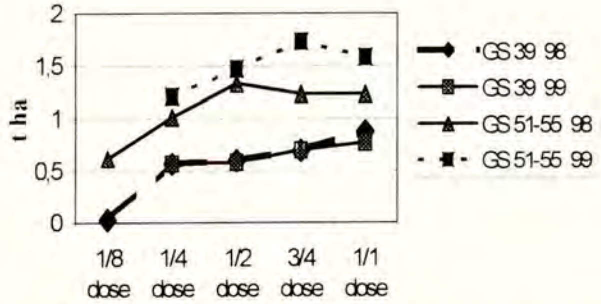

Figure 3. Margin over cost from fungicide treatments at GS 39 and GS 51-55 in winter wheat using azoxystrobin for septoria control at different dosages, (1998-99). 2 trials carried out in each year.

RESULTS FROM SPRING BARLEY

In spring barley a low input of fungicides has been shown to give the best margin over cost in most seasons. The yearly variation in yield increases from a standard fungicide treatment in a wide selection of varities has been between 0.08-1.29 t/ha. Accordingly the economic return from fungicide treatment varied from the financial equivalent of -0,3 to 0,9 t/ha. Fungicide treatments were only profitable in every 2nd year (Table 4). Best responses were seen in years with severe attacks of *P. hordei* and *E. graminis* (1990, 1993, 1998) or wet seasons, which gave rise to attacks of *D. teres* or *R. secalis* (1998, 1999). Cv. Alexis has been widely grown throughout the 10 years for malting purposes; it is very susceptible to barley rust and showed a similar variation in yield responses.

In most seasons, one treatment with only 25% of the normal dose of a broad-spectrum fungicide provided the optimal input. This is shown for the mildew susceptible variety Optic in Figure 4, using the co-formulation of azoxystrobin+fenpropimorph. In 37 trials, cv.Alexis on average gave a positive response to fungicide treatment, in particular when the benefit of increased screening is taken into consideration (malting grain price is reduced 0.75 DDK for each unit below 90 mm). Also, in this variety, 25% of normal dose gave similar or better results to 50% of normal dose, with a split application giving intermediate results (Figure 5).

Also, in spring barley the level of resistance differs significantly between varieties, giving rise to differences in yield response from disease control (Table 5). Varietal mixtures have been among the most resistant "variety", whereas cv. Alexis has been amongst those giving the highest yield response. The 1998 and 1999 seasons were dominated by humid conditions which gave rise to significant levels of disease and good yield responses. In order to adjust fungicide input for these significant differences in response, varieties should be considered individually, or in groups, which is possible in a decision support system.

Table 4 Variation in yield increases and margin over cost in spring barley (expressed as t/ha), based on standard treatments* in field trials in Denmark, (1990-1999).

Year	Yield increase in spring barley (no. of trials)				Margin over cost in spring barley	
	All varieties		cv. Alexis		All varieties	cv. Alexis
1990	1.29	(146)	1.14	(31)	0.88	0.73
1991	0.42	(119)	0.30	(26)	0.01	-0.11
1992	0.08	(62)	0.07	(12)	-0.33	-0.34
1993	0.57	(62)	0.69	(27)	0.16	0.28
1994	0.23	(73)	0.15	(29)	-0.18	-0.26
1995	0.23	(61)	0.38	(47)	-0.18	-0.03
1996	0.15	(62)	0.10	(26)	-0.26	-0.31
1997	0.27	(69)	0.20	(21)	-0.14	-0.21
1998	0.59	(89)	0.98	(24)	0.18	0.57
1999	0.58	(178)	0.41	(17)	0.17	0.00

*1-2 applications with 25-50% of propiconazole+fenpropimorph per ha. Cost equivalent = 0.41 t/ha

Table 5. Mean % disease on 3 upper leaves and yield increases in spring barley based on standard treatments* in 4 field trials, (1998-1999)

	1998			1999			Average
Variety	% mildew	% rust	Yield increase (t/ha)	% mildew	% Rhynchosporium	Yield increase (t/ha)	Margin over cost (t/ha)
Mixture	0.9	4.1	0.79	0.4	2.1	0.97	0.39
Alexis	0.0	22.2	1.35	0.0	2.5	1.18	0.77
Optic	4.9	1.7	0.97	1.7	1.3	1.02	0.50
Scarlet	0.6	10.4	0.79	0.9	1.9	1.09	0.44
Henni	2.3	2.3	0.84	5.4	4.0	1.41	0.63
Linus	5.6	2.0	0.88	2.9	3.3	0.96	0.43
LSD_{95}	0.9	2.0	0.42	0.6	0.5	0.41	

*2 treatments applied, with 25% dose of propiconazole+fenpropimorph in 1998, and 25% dose of azoxystrobin+fenpropimorph in 1999.

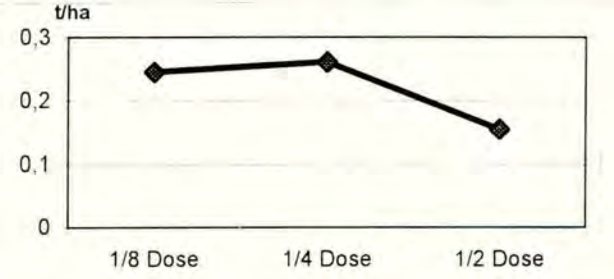

Figure 4. Margin over cost from fungicide treatment in the spring barley variety Optic using azoxystrobin+fenpropimorph at 3 different dose strategies applied at GS 32-37. Average of 10 trials from 1998-99

DISCUSSION

For many years, Denmark has been working on removing the most harmful pesticides and generally minimising the use of pesticides. In 1986, the first pesticide action plan was introduced with the aim of reducing the pesticide use by 50%. So far the sale of active ingredients has dropped by 48%, while the treatment frequency index (TFI) had dropped by 15% by 1998. A 40-50% reduction scenario for TFI is generally estimated to be realistic without causing significant yield and economic losses. A prerequisite is, however, that all available information on how to minimise reliance on pesticides is used and made available to farmers. Since the start of the action plans farmers have learnt to focus on margin over cost rather than focusing on total yields.

Figure 5 Margin over cost from fungicide treatment in the spring barley variety Alexis, using azoxystrobin+fenpropimorph at 3 different dose and timing strategies. Average of 37 trials from 1997-99 with and without considering the quality screening of the grain. Single treatments were carried out at GS 32-37 and split treatments at GS 32-37 & 59.

The fungicide dosages applied today are a result of using thresholds and putting the emphasis on margin over cost. The new pesticide action plan from 1999 concentrates on providing target points for each pesticide usage in individual crops. The target points for fungicides in wheat are 0.7 TFI and 0.3 TFI for spring barley. These are expected to be achievable goals before 2003.

Trials, as described in this paper, carried out over a 10 years period have shown that the benefit from the use of fungicides varies significantly and treatments should therefore be optimised by adjusting input according to variety, disease severity and timing. This can typically be organised in decision support systems like 'PC-Plant Protection', the German system 'Pro-plant' or the English system 'Dessac'.

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Economics of pest control in cereals in the UK

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ABSTRACT

The economics of cereal pests in the UK are reviewed. Estimates of the mean potential loss from damage if untreated, the area treated and cost of treatment, the economic response to this treatment and the residual losses to agriculture from the currently adopted strategy are estimated for the main pests.

INTRODUCTION

The proportion of cereal crops treated with an insecticide in England and Wales has increased progressively in response to increased cereal prices following the entry of the UK into the EC (Figure 1; Garthwaite & Thomas, 1999). A further factor was the widespread epidemic of BYDV following the mild winter of 1988/89 (Morrison & Spence 1989), following which the use of a BYDV vector spray, regardless of the risk of virus infection, became a routine treatment on many farms. The wheat blossom midge outbreak of 1993 resulted in an increased usage of organophosphorus (OP) insecticides in 1994 (Oakley *et al.*,1998a).

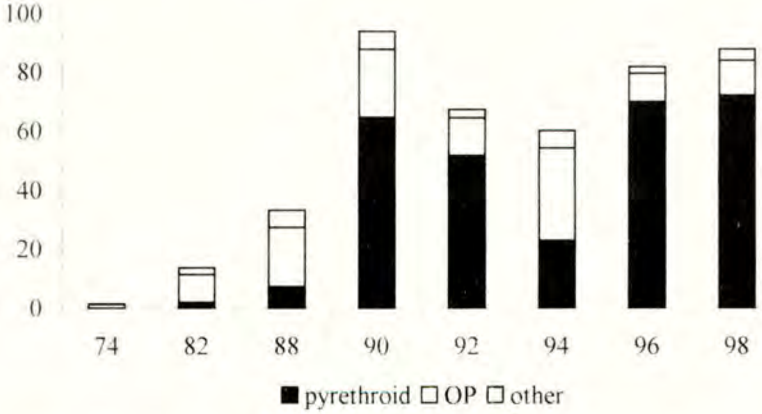

Figure 1. The annual area of cereal crops treated with insecticide sprays in England and Wales as a percentage of the area grown (Source: MAFF Pesticide Usage Surveys).

Given the reduction of UK grain prices to world market levels as part of the reform of the Common Agricultural Policy (CAP) it is timely to consider the economics of cereal pesticide use and consider whether and how strategies for control need to adapt to meet changing situations.

RESULTS

BYDV vector control

The greatest usage of insecticides on cereal crops is of autumn applied pyrethroid insecticides for BYDV vector control. The problem with rationalising pesticide use is that there are two vector species involved with different biology. The bird-cherry aphid (*Rhopalosiphum padi*) causes problems in warmer autumns, whereas the grain aphid (*Sitobion avenae*) causes problems in mild winters. The Infectivity Index system of forecasting had correctly forecast a low risk of bird-cherry aphid vected BYDV in 1988, but a mild winter subsequently allowed grain aphid numbers to increase in winter cereals, consequently giving rise to a severe BYDV infection (Morrison & Spence, 1989; Harrington *et al.*, 1994). The resulting loss of confidence in the forecasting system has subsequently led to a prophylactic approach to applying insecticides for the control of aphid vectors of BYDV.

A yield response of up to 2.5 t/ha may be obtained by a successful spray applied to a crop of September emerged wheat or barley and around 1 t/ha for a crop emerging in early October (Oakley, 1997). Given that most sprays are applied in tank mix and may cost little more than £1 per hectare it would appear that even a low frequency of occurrences of risk would justify a prophylactic approach. However, the time of application can be critical for successful control for yield penalties of a tonne per hectare resulting from delayed application. A separate application incurs an extra cost of £7 per hectare (Nix 2000), so that there are several economic questions to apply to the selection of a strategy.

Pyrethroid sprays are used to reduce the secondary spread of virus out of initial foci of infection established by winged migrant aphids or wingless aphids transferring from cereal stubbles or grass. The movement of aphids out of foci tends to coincide with the start of reproduction of the first wingless generation of aphids in the crop. This event can be predicted by the use of a heat sum, based on the biology of the aphids, of 170 days degrees above 3°C, enabling the timing requirement of sprays to be established. The two species differ in their susceptibility to frost, the lethal temperature for 50% of bird cherry aphids being -0.5°C compared to -8°C for grain aphid (Williams, 1987; Williams & Wratten, 1987). The temperature relationships can be used to analyse meteorological records and determine whether an increased BYDV risk would have developed from either vector species reproducing through several generations on the crop.

As an example of this approach the meteorological records for ADAS Bridgets in central southern England for 1959-1999 have been examined to determine the frequency of weather which could impact on strategies for BYDV control (Table 1). A cold October, which could prevent significant spread in an early sown crop emerged by the start of that month, occurred in 10% of years, so that on 90% of occasions a prophylactic spray would have been justified. Mild autumn conditions, favouring a late build-up of bird-cherry aphid, occurred in 7.5% of years and mild winters allowing build up of grain aphid in 22.5%. Due to some overlap of the two types of event the frequency of either or both occurring was 25%. In such seasons significant spread of BYDV could occur in crops emerged by early November or in earlier emerged crops sprayed by that time, necessitating a second application. There was a tendency to increased frequency in the 1990's, which could be an indication of climate change.

Table 1. The frequency of significant weather events (in years per decade) impacting on BYDV risk in central southern England.

Mean temperature	Decade				%
	60's	70's	80's	90's	
Cold October < 8.6°C	0	1	1	2	10.0
Warm November > 8.6°C	0	1	0	2	7.5
Mild winter > 5°C	1	1	3	4	22.5

The prophylactic approach is obviously justified for the first spray to early sown crops with a 90% probability of a treatment costing as little as £2 per hectare producing a return of a tonne or more of crop. The situation regarding later sown crops or second sprays to earlier sowings is economically justified by a 25% probability of a high return, but such an approach would result in the treating of four times the necessary area of cereals. A considerable saving could be made by a forecasting system able to warn when a risk of spread if a particular situation was imminent.

Summer aphids

Summer aphid problems can be caused by the grain aphid or the rose-grain aphid (*Metopolophium dirhodum*). Oakley *et al.* (1998b) utilised survey data and yield responses from aphicides applied to experiments during the period to calculate the mean potential and actual yield losses for the decade from 1987 to 1996. The potential yield loss had no treatments been applied averaged 0.21 t/ha (range 0.03 – 1.08 t/ha); after treatments, the residual yield loss averaged 0.09 t/ha (range 0.01 – 0.32 t/ha).

The MAFF Pesticide Usage Survey of arable crops (Garthwaite & Thomas, 1999) takes place in alternate years. Ignoring 1994 when an outbreak of the orange wheat blossom midge (*Sitodiplosis mosellana*), distorted pesticide usage, treatment cost from 1988 to 1996 varied between £1.9 million and £6.1 million per annum, at 1996 prices, giving a mean annual cost of £3.4 million. This would suggest that the pesticide usage was generally profitable, yielding an annual return of around £5 million at 2000 prices. The variations in usage from year-to-year do not fully reflect the aphid incidence pattern, again suggesting that improvements in the decision-making strategy adopted are possible. As with BYDV farmers have increasingly tended to adopt a prophylactic strategy by applying aphicides in tank mix with fungicides to avoid the extra cost and inconvenience of later additional sprays. Usage of the more expensive pirimicarb, as opposed to dimethoate or pyrethroids, has tended to decline as cereal prices have fallen.

Orange wheat blossom midge

Since the outbreak year of 1993, numbers have fluctuated somewhat from year to year, with hotspots of infestation persisting in some areas cropped more intensively with wheat. A survey carried out in 1998 found 10% of English wheat crops suffered damage to more than 10% of grains and subsequent economic yield loss, whilst a further 22% suffered between 5 and 10% grain damage, which made them liable to result in reduced Hagberg falling number. In 1993, 21% of crops suffered economic yield loss and a further 29% from potential quality problems. The 1993 outbreak attracted national concern when 6.5% of harvested grain were damaged resulting in a yield loss of around 2% of the national crop. In 1998, the proportion of damaged grains was 4.4% and levels have subsequently risen so that the 2000 crop will have suffered losses nearly as great as those in 1993.

Wheat blossom midge is favoured by intensive wheat rotations, reducing the need for migration between fields. The introduction of take-all seed treatments, allowing multiple wheat cropping, is likely to further increase the importance of this pest.

Wheat bulb fly

The wheat bulb fly (*Delia coarctata*) affects wheat sown after root crops, early harvested crops and set-aside mainly in eastern and north eastern England. The area of wheat sown in these situations each year averages 444,000 ha, but estimates of the proportion of fields potentially at risk, which have egg numbers above the economic threshold of 2.5 million eggs per hectare, varies considerably from year to year (Young & Cochrane, 1993). In the period from 1984 to 1999 this proportion has varied between 3 and 44% of fields with a mean of 21% (Figure 2).

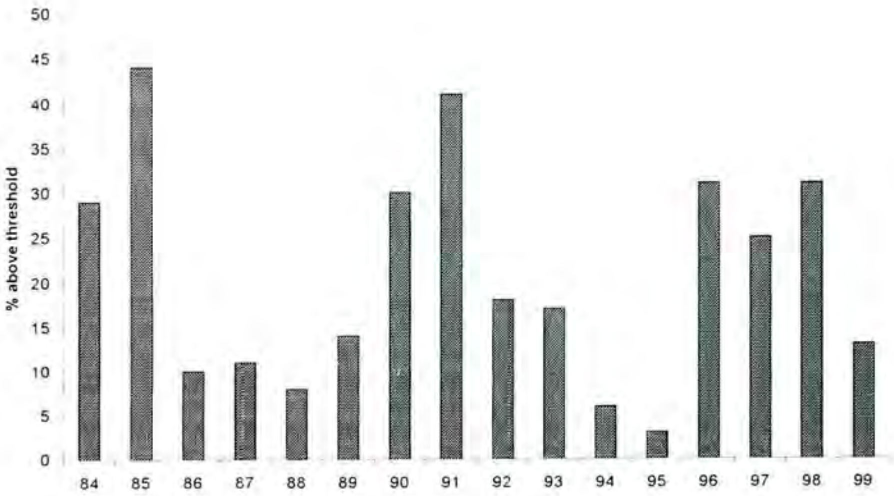

Figure 2. The estimated proportion of wheat crops in risk situations with egg populations above the economic threshold between 1984 and 1999.

Young & Ellis (1996) estimated that damage costs vary between £5.8 and £33.0 million per year, with the net benefit from insecticide strategies ranging between £2.1 million and £14.8 million. Taking into account current costs and grain prices, the economic benefits of different treatment strategies have changed and more care will now have to be taken in selecting cost effective treatment strategies. On the basis of average responses to treatments in field experiments, and using 2000 prices and costs, the average national loss is now estimated at £10.4 million. In years of lower incidence many of the potential treatment strategies are now unlikely to recover the cost of treatment if applied to all crops potentially at risk (Table 2).

The strategy of not using a seed treatment, but waiting to assess the degree of attack and using a deadheart spray if required, is now the most cost-effective option up to a 27% probability that egg numbers will be above threshold levels. Above this level it becomes more cost-effective to use seed treatment to all crops plus a deadheart spray where required. The use of an egg hatch spray is no longer justified unless the probability that egg numbers will be above threshold is greater than 80%. At present no method is available to determine the need for treatment on a field to field basis, soil sampling being too expensive and laborious for advisory use. An improved method of forecasting risk at farm level is needed to support the use of seed and egg hatch treatments. The estimates also indicate that it is no longer profitable to use a seed treatment, egg hatch and deadheart spray on the same crop.

Table 2. Cost:benefit analysis of different wheat bulb fly control strategies at 2000 prices for mean, highest and lowest incidence levels estimated between 1984 and 1999.

Strategy	National benefit (£million)		
	mean 20.1%	highest 44%	lowest 3%
Loss if no treatment applied	-10.4	-21.0	-1.4
Net benefit from:			
Seed treatment to all crops	-1.6	3.0	-5.3
Seed treatment to crops at need*	3.0	6.0	0.4
Seed treatment plus egg hatch spray to all crops	-10.2	0.6	-15.5
Seed treatment plus egg hatch spray to crops at need*	4.0	8.0	0.5
Seed treatment to all plus deadheart spray to crops at need	-1.2	3.9	-5.0
Deadheart spray to crops in need	1.0	2.0	0.1

(* New decision support system required to enable these strategies to be applied)

Slugs

The area treated with molluscicides has decreased since 1994, reflecting a trend to earlier drilling (Table 3). Previous years of high usage were associated with wet autumns, such as 1994, delaying drilling and making the preparation of a good seedbed difficult. Molluscicide usage remains a fairly haphazard affair with pellets applied in response to visible damage rather than in timely anticipation of it. The general adoption of quad bikes to apply pellets has allowed a faster response that may have improved the effectiveness of a reactive approach. However, this approach can lead to an excessive application of pellets. It has been known for treatments to be applied on up to six occasions to the same crop whenever fresh damage is detected. Whilst an application of pellets to the seedbed after drilling may be cost effective, later applications are unlikely to significantly improve yield.

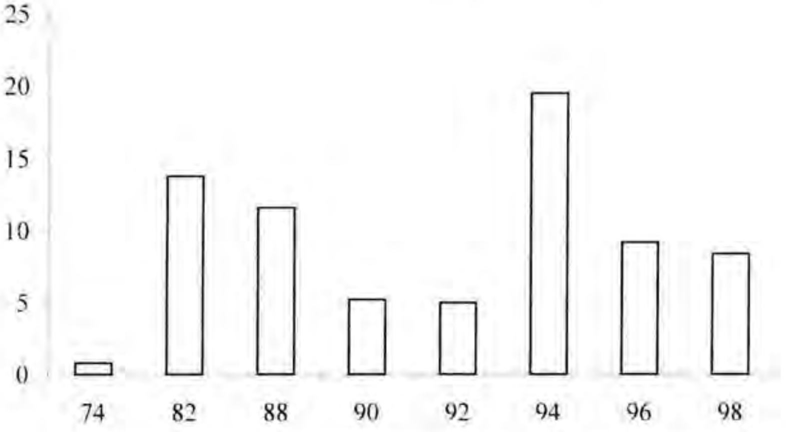

Figure 3. The annual area of cereal crops treated with molluscicides in England and Wales as a percentage of the area grown (Source: MAFF Pesticide Usage Surveys).

Other pests

The areas of crop affected by damaging numbers of other pests are relatively low, but their distribution is patchy and at the farm level several pests can have a significant impact on economics. Milder weather, an intensification of wheat growing and earlier sowing have recently led to an increased incidence of two of these pests.

The gout fly (*Chlorops pumilionis*) has two generations per year. The autumn generation of adults lay their eggs on early sown winter cereal crops and the larvae cause the attacked shoot to swell at the expense of the others on the plant. Crops are generally able to compensate for some loss of plant, but in the autumn of 1999 many crops had levels above the tentative economic threshold of 25% plant infestation (Oakley *et al.*, 1990). The spring generation of adults lays its eggs on crops at the stem extension to flag leaf emergence stage, causing the ears to remain within the boot. Such damage was increasingly prevalent in the summer of 2000. Gout fly was generally well controlled by four species of parasitoids (Frew, 1924). The peak activity of these parasitoids tends to coincide with the application of BYDV vector treatments and summer aphicides. The widespread use of these materials, which adversely affect the parasitioids, may be a contributory cause to the outbreak.

The cereal ground beetle (*Zabrus tenebriodes*) has increased in importance in southern England, as in France (Jullien, 1999), and now affects crops as far north as Cambridgeshire. In 1992, 150 fields were reported as damaged, causing losses estimated at £300,000; currently more than 500 fields are affected, with potential damage around £1 million were chlorpyrifos not applied. The pest is restricted to all cereal rotations and is favoured by warm autumns. Damage is likely to continue to spread under the combined effect of climate change, CAP reform and take-all seed treatment.

DISCUSSION

Information on the precise level of incidence of many of the pests is short. However, sufficient is available to allow an approximate costing of the position with regard to potential damage, actual damage after control measures have been applied and the cost of control (Table 3). The 1997/98 winter was a very mild one and consequentially there was a high risk of grain aphid vected BYDV, which was very evident in a few early sown crops which were not protected, the potential loss is estimated at 1 t/ha. Summer aphid numbers were very low, and parasitoids, which also overwintered well in the mild winter, combined with a wet summer to reduce aphid numbers from a mean of 0.56 aphids/ tiller at GS 59 to 0.36 aphids/tiller at GS 79 (Oakley *et. al*. 1998b). Wheat blossom midge numbers started to resurge in milder districts under the influence of a warm wet May, and a survey of crops grown in England showed a mean of 4.4% of grains to be damaged by the pest. Wheat bulb fly was favoured by wet weather in July 1997, and the area of wheat affected by above economic threshold populations was estimated to be 138,000 ha. Generally good conditions allowed early sowing in good seedbeds reducing the risk of slug damage.

Table 3. Cost (£ million) of estimated potential and actual damage from cereal pests in Great Britain compared to the cost of control measures applied to the 1997/98 crop.

	Potential damage	Actual damage	Cost of control *	Profit
BYDV vectors	240.0	0.5	9.3	230.2
summer aphids	0.1	0.1	3.9	- 3.9
wheat blossom midge	10.0	8.3	1.1	0.6
wheat bulb fly	17.3	5.9	1.9	9.5
slugs	5.0	2.5	4.3	- 1.8
other pests	5.0	2.5	0.9	1.6
TOTAL	277.4	19.8	21.4	236.2

(* based on: Garthwaite & Thomas, 1999)

The high returns from BYDV vector control in a mild winter may suggest that a generally prophylactic approach is well justified. But for other pests the picture is less satisfactory, especially considering the decline in cereal prices since 1998. Further improvement in the efficacy of pesticide use would appear both possible and desirable in these areas. Information on incidence is poor and a more accurate assessment of the potential and actual losses resulting from pest damage is needed to allow a fuller assessment of the industrys' needs for pest control.

ACKNOWLEDGEMENTS

We thank MAFF and the HGCA for funding the studies used as a basis of this review.

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SESSION 6B

ADVANCES IN FORMULATION AND APPLICATION TECHNOLOGY

Chairman: Professor M Ford
Portsmouth University, UK

Session Organisers: Dr D Stock
Zeneca Agrochemicals, Bracknell, UK

and

Professor M Ford
Portsmouth University, UK

Papers: 6B-1 to 6B-4

Triggered controlled delivery

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ABSTRACT

Most encapsulated agricultural pesticides have previously been designed to release their contents by (slow) Fickian diffusion through the capsule wall. Certain applications require zero, or minimal, release of the capsule contents until the capsule is exposed to a particular agent or environment which causes the contents to be released rapidly. In this paper we show how such fast release has been accomplished by a pH trigger mechanism employing acid triggered polyurea and base triggered aminoplast systems.

INTRODUCTION

Safety, environmental and commercial pressures have focused an ever increasing need to deliver pesticides to the required target in the required quantity and at the required time. Many types of delivery systems have been developed including for example emulsifiable concentrates, oil-in-water emulsions, water dispersible granules, water dispersible powders and micro-capsule suspensions. Each of these formulation types has associated advantages and disadvantages. The benefits offered by microencapsulation, have, however been highlighted by drivers to improve operator safety, cost efficacy and to minimise the impact of chemicals on the environment. For microencapsulated pesticides these benefits include reduced mammalian toxicity and extended biological activity, reduced evaporative losses, reduced phytotoxicity, controlled environmental degradation, reduced leaching into groundwater and consequently reduced levels in the environment.

It should be noted moreover that microencapsulation is a well established technology which is used in many and varied applications to deliver a wide range of effects beyond those of agrochemicals. Examples of such effects include colour control such as in carbonless copy paper, flavours such as in food additives, drugs as used in pharmaceutical applications, and fragrances as used in scratch-and-sniff devices.

Two main types of microparticle delivery vehicles are commonly employed. In matrix carriers the material to be delivered is embedded throughout a 'solid' usually polymeric particle, while in reservoir microcapsules the material to be delivered is typically contained within the core 'cavity' of a polymeric shell. One major advantage of reservoir microcapsules over matrix delivery systems is the very high payloads, coupled with a protective barrier, that can be achieved using the former. Loadings as high as 90 wt% of the capsule are readily obtainable.

Although microcapsules may be made in either aqueous or organic continuous phases, carriers for the delivery of agrochemicals usually use water. Colloidal stability is maintained by stabilisers adsorbed on the capsule wall. The typical size of microcapsules range from sub-micron to a few hundred microns. The capsules may be applied *via* the continuous phase in which they were made or they can be isolated and/or fabricated for use as a dry product.

The contents of micro-capsules can be released by a variety of methods, including force, solvent extraction, temperature, pH and diffusion. Force is normally exerted by either pressure or tearing and is used for example in adhesive and scratch-and-sniff applications. Solvent leaching is usually practised with dry products such as in anti-perspirants and in food flavourings where the solvent is water. Examples of temperature and pH release are found in respectively the food and cosmetics industries in relation to waxes and changes in skin pH.

Most micro-capsules designed for use agricultural release their contents by Fickian Diffusion as described by the equation:

$$dM/dt = release.rate = \frac{(4\pi r_o r_i)P(C_i - C_o)}{r_o - r_i}$$

The release rate is a function of the particle size ie surface area ($4\pi r_o r_i$), the concentration gradient from the inside to the outside of the capsule (C_i-C_o), the wall thickness (r_o-r_i) and the permeability (P) of the encapsulated material through the wall. Permeability is a function of the solubility and diffusion coefficients for the core materials and can be influenced by the monomer composition and the cross-link density. Many pesticides have a very low solubility in water which thus provides a supplementary barrier to that of the wall until after application and drying.

Unless so designed, the capsule walls do not rupture or degrade in use. Typically encapsulated pesticides have been designed to release slowly over an extended period to take advantage of the above-mentioned benefits. However, there are instances where negligible release is desired before a certain point in time when total and fast release is required. Examples of such fast release applications find use in: (i) reducing mammalian toxicity, (ii) mixtures of two active ingredients which may react with each other or be otherwise incompatible, but for which rapid release of at least one active ingredient is required on application, and (iii) beneficial insect protection. In this paper we show how such fast release has been accomplished by a pH trigger mechanism.

Waterborne microcapsules may be made by a variety of processes including solvent evaporation (Pekarek *et al*, 1994) co-acervation (Bakan, 1980) and interfacial polymerisation (Koestler, 1980).

In the solvent evaporation method a polymer is dissolved in a mixture of a solvent and a non-solvent and the mixture is emulsified in water. Upon evaporation of the solvent through the continuous aqueous phase, and depending upon the spreading coefficients of the components, the polymer separates to form a capsule wall. In the coacervation method a discontinuous phase is typically dispersed into an aqueous continuous phase containing one or more dissolved polymers. By changing the conditions in the continuous phase the polymers become insoluble and precipitate as coatings on the non-continuous phase.

The interfacial polymerisation method has been used to prepare a range of different microcapsule wall chemistries including polyester, polyamide, polyurea and aminoplast structures. The interfacial method has been used here for the preparation of pH triggerable polyurea, and aminoplast structures.

METHODS AND MATERIALS

The following general *in situ* interfacial polymerisation method has been used for the preparation of both polyurea and aminoplast microcapsules and the trigger chemistry described below has been designed to retrofit the procedure.

In the *in situ* process all of the wall forming monomers or oligomers and the materials to be encapsulated are mixed to form an 'oil' which is dispersed under appropriate shear conditions into an aqueous phase containing usually an emulsifier, and a colloid stabiliser. The droplet size is controlled by the degree of shear and the amount of emulsifier. After emulsification the physical conditions of the continuous phase, such as the temperature and optionally the pH, are changed such that when the monomers or oligomers in the oil droplet diffuse to the oil-aqueous interface they are induced to polymerise to form the microcapsule wall.

DISCUSSION

Our approach to making chemically triggered fast release capsules is to incorporate custom designed 'weak links' into the capsule walls during the interfacial polymerisation process. The weak links are designed so that they can be cleaved by either acids or bases, which are applied at a chosen moment, thereby generating punctures in the capsule wall. The wall thickness (r_o-r_i) in the denominator of the above equation is thus reduced to 'zero' therefore resulting in fast release of the capsule contents.

Acid triggered polyurea microcapsules

Acid triggerable polyurea microcapsules have been made by incorporating oligoacetals into the capsule walls employing the above general procedure which is further elaborated below with reference to the polyurea system. Acetals are ideal 'weak links' in that they are very stable under neutral or alkaline conditions but they are readily hydrolysed by acid catalysis.

In the general *in situ* process for polyurea capsules (Scher, 1981) wall forming materials comprise toluene 2,4-diisocyanate (TDI) and polymethylenepolyphenylene isocyanate

(PMPPI). PMPPI is oligomeric and, having an isocyanate functionality >2, is used for cross-linking. The oil comprising TDI, PMPPI and the pesticide to be encapsulated is dispersed into water at ambient temperature when there is generally relatively little hydrolysis of the aromatic isocyanates. The temperature of the emulsion is raised to about 50°C, when some of the isocyanate molecules at the water-oil interface are hydrolysed to carbamic acids which decarboxylate to give amines. The free amines then rapidly react with unchanged isocyanates to generate the polyurea wall at the interface.

The *in situ* method differs from the 'two phase' interfacial process where the oil containing one or more monomers is emulsified, and a further monomer(s) is (are) then added to the aqueous phase from where it (they) diffuses to the oil-water interfaces and polymerise with the monomer(s) in the oil to form the capsule wall.

The oligoacetals are readily prepared by the condensation of aldehydes and diols. For example such oligomers have been made by coupling benzaldehyde, cinnamaldehyde and phenylglyoxal with variously octane-diol, decane-diol, cyclohexane-1,4-dimethanol, diethylene glycol and tetraethylene glycol.

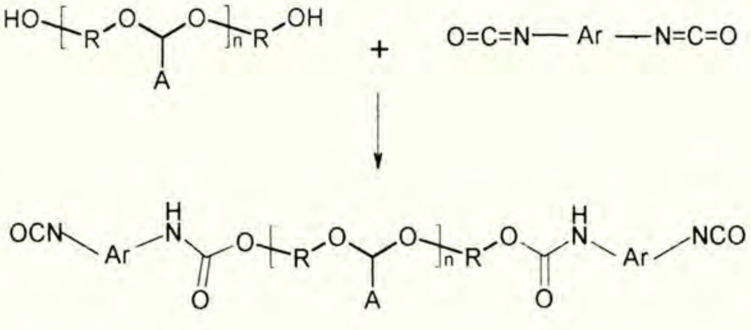
The rate of hydrolysis of the oligoacetal and thus the release rate from capsules with walls containing oligoacetals depends primarily upon the nature of the acid catalyst and also, but to a lesser degree, the nature of the aldehyde. Prior to incorporation into the capsules the susceptibility of the oligomers to hydrolysis was screened in a heterogeneous mixture of the neat oligoacetal in various molarity acids. Results (Table 1) for a diethylene glycol-benzaldehyde (DEG-BA) oligomer of about Mn 800 show that hydrolysis rates can be changed by orders of magnitude by varying the nature of the acid catalyst.

Table 1. Hydrolysis data for a diethyleneglycol-benzaldehyde oligomer

Catalyst	Molarity	% Hydrolysis	~ Time
HCl	0.05	100	6 min
trihydroxy-benzoic acid	0.1	100	40 min
oxalic acid	0.1	100	50 min
adipic acid	0.1	20	24 h
NaOH	conc	0	24 h

Total cleavage within minutes was effected by the stronger acids. As anticipated, sodium hydroxide (concentrated slurry) caused no hydrolysis of DEG-BA over a 24 hour test period. The choice of catalysts was guided by their pKa values, and by their speculated potential to be absorbed into the microcap wall.

For incorporation into the capsule walls the α,ω-hydroxy oligoacetal is capped by reaction with an excess of TDI (Scheme 1, Ar = $-C_6H_3(CH_3)-$), generally dissolved in the material to be encapsulated, to give an α,ω-isocyanate oligomer. The ratio of the oligoacetal:TDI determines the degree of chain extension.



Scheme 1: Isocyanate capped oliogoacetals

Usually PMPPI is added to the capped oligoacetal solution and the oil is dispersed into an aqueous phase when wall formation is effected (Van Koppenhagen *et al*, 2000a) as described above. The isocyanate groups of the TDI capped oligomer undergo interfacial polymerisation in the same manner as those of 'free' TDI and PMPPI. This generates a thermoset wall where the wall properties depend upon the composition and proportion of the oligoacetal incorporated.

The bioefficacy of the acid triggerable capsules was demonstrated using an encapsulated herbicide (Fusilade DX[1], fluazifop-P-butyl) which was exposed to a pH 1.5 solution of para-toluenesulfonic acid and then applied at rates between 0.018 to 0.140 kg/ha to a variety of grassy weeds including *Echinochloa crusgalli* (crabgrass), *Setaria faberi* (giant foxtail), *Setaria viridis* (green foxtail), *Setaria lutescens* (yellow foxtail), and *Brachiaria platyphylla* (broadleaf signalgrass). Weed control by the acid triggered capsules (Sample B) was compared relative to a non-triggered microcapsule formulation (Sample A) and non-encapsulated herbicide (Table 2).

Table 2: Control of grassy weeds using acid triggered Fusilade microcapsules

Test Sample	Acid, pH	Average Weed Control, % (7 days)
A	--	29.8
B	1.52	51.0
fluazifop-P-butyl	--	65.3

The average weed control of 30% after 7 days for capsules which had not been triggered (Sample A) suggested that there was some slow release. However there was a significant increase to about 50% in weed control (Sample B) in capsules that had been triggered. This

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[1] 'Fusilade' is a registered trademark of Zeneca Limited, UK

compared with a weed control of about 65% using non-encapsulated herbicide applied at the same rates.

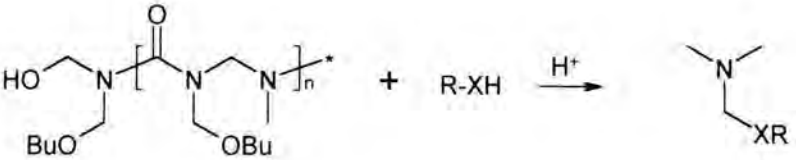
Base triggered aminoplast microcapsules

This technology has been developed as part of an Integrated Pest Management strategy for beneficial insect protection. The approach employs a capsule which does not readily release its contents when applied in the field but which, if ingested by crop consuming pests, is triggered by the conditions in the pests' gut. In this manner beneficial insects which do not consume the crop are protected.

The larvae of certain target crop consuming *Lepidoptera* species have particularly alkaline guts where the pH may be as high as 11. Examples of such *Lepidoptera* include *Heliothis spp* (Tobacco budworm), *Helicoverpa spp* (Cotton bollworm) and *Spodoptera spp* (Southern armyworms). Triggerable aminoplast microcapsules, based on amino-resin chemistry, which have minimal release at neutral pH but which undergo fast release when exposed to about pH 9-10 have been thus made by incorporating appropriate oligoesters into the capsule walls employing the above general procedure. The procedure is further elaborated below in relation to the aminoplast system.

In the general *in situ* process (Scher & Rodson, 1990) wall forming materials comprise an alkylated amino resin pre-polymer and usually a tetra-mercapto cross-linking agent such as pentaerythritol tetrakis(3-mercaptopriopionate). These materials are dissolved in the material to be encapsulated to give the 'oil' phase, which is dispersed into water at ambient temperature and about pH 7. The pH of the aqueous phase is reduced to between 2 and 3 and the resulting oil in water emulsion is heated to about 50°C. This causes the amino-resin and the cross-linker to polymerise at the oil-water interface to form a shell completely enclosing each droplet.

Commercially available amino-resins are extensively used in the coatings industry. The resins are based on urea, melamine, benzoguanamine and glycoluril polymers which range from water soluble materials having high methylol levels to oil soluble materials in which the methylol groups have been etherified to varying degrees typically with C1-C4 alcohols. The chemistry of amino-resin cross-linking is complex (Blank, 1979). Coatings applications usually employ high temperatures and anhydrous conditions when, in the presence of acid catalysts, methylol or alkyl ether groups on the resin can be exchanged with nucleophiles such as hydroxyl, carboxyl, amide or mercapto groups. This reaction is reversible for the products of the hydroxyl, carboxyl, amide moities which are readily re-protonated. The thioether linkage formed in the thiol reaction is less readily re-protonated and thus less reversible. The principles are illustrated by the generalised and simplified reaction between a butylated urea-formaldehyde resin and a nucleophile RXH in Scheme 2.



Scheme 2: Generalised reaction between a nucleophile and a butylated U-F resin

Our preferred microencapsulation process uses substantially butylated urea-formaldehyde pre-polymers which are soluble in many pesticides and polymerisation is effected in the presence of water at relatively low temperatures.

The base triggerable weak links have been made by the mixed esterification of a mutifunctional alcohol such as pentaerythritol with α-hydroxy and α-mercapto acids and are substituted for pentaerythritol tetrakis(3-mercaptopriopionate) in the general method described above.

For incorporation into the capsule walls, the pH triggerable crosslinker is admixed with the aminoplast prepolymer and material to be encapsulated. The oil thus produced is emulsified in the manner previously described and the conditions in the continuous phase are adjusted so that interfacial polymerisation occurs at the oil-water interface to generate a thermoset wall where the wall properties depend upon the composition and proportion of the triggerable unit incorporated (Van Koppenhagen *et al*, 2000b).

Insecticides are absorbed mainly by contact and ingestion mechanisms. In the contact mechanism the chemical is absorbed through the cuticle and is distributed *via* the haemolymph. In the ingestion mechanism, absorption into the circulatory system is *via* the gut. In order to test the efficacy of the trigger system it was thus necessary to demonstrate that there was minimal knock-down by contact and a high level of knock-down by ingestion.

Base triggerable capsules containing the insecticide chlorpyrifos were tested for contact activity using the sucking pest *Lygus hesperus* and for ingestion activity using *Heliothis virescens*, a foliar feeding *Lepidoptera* with an alkaline gut. Non-triggerable chlorpyrifos microcapsules and non-encapsulated chlorpyrifos were used as reference materials. Results confirmed that triggered release formulations had similar gut activity to chlorpyrifos technical and that there was minimal knock down by the contact mechanism.

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Applying biological agents: needs and new developments for controlling foliar pests

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ABSTRACT

In the laboratory, many organisms have been shown to be effective bio-control agents, yet relatively few have been developed commercially. The wide gap between laboratory and field performance is partly because users have expected to apply them as if they were chemical pesticides through conventional sprayers. In practice, much more attention is needed in the development of formulation and application techniques to take account of specific requirements of bio-pesticides.

INTRODUCTION

The importance of chemical pesticides in providing effective crop protection over the last 50 years cannot be over-emphasised, yet the public perceive a need to revert to "organic farming" with emphasis on biological control. Release of parasitoids and predators within the glasshouse environment has been very effective against certain pests, but in arable and orchard situations, protection of high yielding crops requires rapid deployment of effective control techniques when needed. Chemical pesticides will continue to be required and some of the newer chemical pesticides, being more selective have less impact on non-target organisms, but there is now greater interest in using bio-pesticides, as one alternative in integrated pest management programmes. Many pathogens have been considered as suitable bio-pesticides based on laboratory data under carefully controlled conditions, but so far relatively few bio-pesticides are commercially available.

While it has been suggested that bio-pesticides have to fit in with existing application technology, the impact of shear stresses when pumping organisms through nozzles under pressure may have detrimental effects, including damage to spores that reduces their viability (Nilsson & Gripwall, 1999), although some biological agents are remarkably robust. There is therefore a place for innovative methods, which are relatively easy to implement. These include very selective techniques of application, for example, where insects collected in pheromone or equivalent traps are infected with a bio-pesticide and then released to spread it to where the pest is active. This was initially done with the Rhinoceros beetle *Oryctes rhinoceros* by dunking them in a viral suspension, which was subsequently spread when the beetles mated (Bedford, 1981). Similar techniques can be developed for other pests, but there is still a need to adapt existing spraying methods.

This paper explores some of the factors related to their use in the field in comparison with chemical pesticides.

PATHOGENICITY OF THE BIO-PESTICIDE

Much of the commercial interest in bio-pesticides has focussed on pathogens that are relatively easy to mass culture. Thus *Beauveria bassiana* has been considered as a bio-pesticide to control a number of pests, including the coffee berry borer (*Hypothenemus hampei*). Part of the failure to provide adequate control is undoubtedly due to its poor activity against a particular pest, although other factors, discussed below, may be equally important. In the development of a biological control of locusts, *B. bassianaa* was also suggested, but preference was given to *Metarhizium anisopliae* var *acridum* (previously referred to as *M. flavoviride*) due to its greater activity under laboratory conditions. Furthermore comparisons of different isolates in the laboratory led to most of the subsequent development being with isolate IMI 330-189 (Bateman *et al.*, 1996; Morley Davies *et al.*, 1996). Careful development of this isolate with appropriate formulation gave good control even at low humidities (Bateman *et al.*, 1993).

Major differences between strains of *Bacillus thuringiensis* have long been recognised, and form an integral part of genetically engineering crops with more than one type of Bt to widen efficacy and delay selection for resistant pest populations.

BEHAVIOUR OF THE PEST

The majority of chemical pesticides will act following contact of the spray deposit with the pest. In contrast many bio-insecticides have to be ingested, although pathogens such as *Metarhizium* act as a contact insecticide. Similarly myco-herbicides have to penetrate the outer leaf barrier as discussed below. Clearly it is essential to optimise the deposit of bio-insecticides, where it can be ingested, but most spray application systems are very inefficient in terms of spray distribution within crop canopies.

Most sprays are downwardly directed over a crop canopy, so the majority of pesticide is deposited on the upper leaves and especially the upper surfaces of broad-leaved crops. Much of the spray is lost on the soil, especially when spray volumes are increased. The "umbrella" of leaves protects pests on the lower surface of leaves, so control relies on any translocation through the leaf lamina or re-distribution by dew or fumigant effects. While a large deposit of a chemical pesticide may be re-distributed by these mechanisms, particulate bio-pesticide deposits are less likely to be effective, unless spray nozzles are positioned to deposit directly on surfaces where the pest is feeding. Even with chemical pesticides, the dose required is significantly less if deposited on the most appropriate surfaces (Javed & Matthews, 1999). A range of equipment can be used to improve application of bio-pesticides, including enhancement of underleaf coverage (Bateman *et al.*, 2000).

DOSE TRANSFER

Chemical pesticides, applied with conventional hydraulic nozzles, are deposited in droplets of very variable sizes. A 'medium' quality spray with a fan nozzle may have a VMD of 250 µm, but there may be up to 30% of the spray volume in droplets smaller than

100 µm, while some of the spray is contained in a relatively few droplets, larger than 500 µm diameter. Some have claimed that the success of such sprays is due to the wide range of droplets produced so that some may reach their intended target. However when considering bio-pesticides, it is more critical to know how many of the spores/ nematodes/viral particles are transported in droplets of differing size. Lello *et al.* (1996) and Mason *et al.* (1998) showed that when applying the relatively large entomopathogenic nematodes, significant volumes of spray contain no nematodes. Jones (1998) gives the number of organisms <10 µm that can be accomodated in droplets of different size.

Where a critical mass of the bio-pesticide is needed on a target pest, it is essential to optimise droplet size so that a high proportion of the spray contains an appropriate dosage. The cost of more specific bio-pesticides also demands that losses resulting in overdosing with droplets larger than necessary must be avoided. Optimising the dose of *Metarhizium* at $1 - 5 \times 10^{12}$ conidia per litre with 70 - 100 µm droplets depending on the target species and speed of kill required ensures an adequate dosage should be deposited on a locust. Langewald *et al.* (1999) successfully applied 5×10^{12} spores in as little as 0.5 litre per hectare primarily against *Oedaleus senegalensis*.

When applying baculoviruses to control pine beauty moth on lodgepole pine in Scotland, droplet size was optimised for collection in the tree canopy. Infection was better with a threshold dosage approximating an LD50 dose as the number of encounters between droplets and the larvae was more important than increasing the dose per droplet (Evans, 1994). Thus, the number of droplets per unit area is also crucial on surfaces inhabited by the pest to ensure transfer of an adequate dose, especially where ingestion of the bio-insecticide is essential. The actual droplet distribution over a surface will be influenced by formulation by affecting spread from the point of initial impaction. The form of the deposit may subsequently affect the behaviour of the pest by repellency or some other factor. Various models have been developed to assess variables affecting deposits of discrete droplets (e.g. Salt & Ford, 1996; Ebert *et al.*, 1999), but the ability of secondary recycling of some biological agents increases the complex interactions between the "pesticide" and the pest.

Due to the size of nematodes, relatively large droplets are required, and experiments have shown that by optimisation of droplet size using a rotary atomiser fewer nematodes were required to obtain similar control to that with a hydraulic nozzle (Lello *et al.*, 1998). Although a specialised technique, a new rotary atomiser disc designed to avoid centrifuging the nematodes from the carrier liquid has improved the carriage of IJs and their deposition on leaf surfaces. Thus compared with a hydraulic nozzle application similar control of *Liriomyza brioniae* was achieved with about 17 per cent of the nematodes, by using the modified disc (Piggott *et al.*, 2000).

DEFENCE BARRIERS

Bio-pesticides have to overcome the natural barriers that organisms have evolved to protect against infections. This is a particular problem with the development of myco-herbicides, where genetically diverse weed bio-types can have some resistance to the pathogen (Greaves *et al.*, 1998). Plants have complex leaf surfaces with waxy layers to reduce water loss but they can also prevent invasion by pathogens. While chemical pesticides can be formulated with surfactants that can transfer an active substance through the barrier, particulate bio-pesticides simply mixed with a wetter (often Tween 80 or Triton X-100) are generally prevented from entry. Many surfactants used with chemical pesticides are incompatible with bio-pesticides, so surfactants of biological origin are more suitable. Only a small proportion of a high volume spray is retained and deposits can dry quickly. Thus the extended period of leaf wetness, needed for microbial herbicides, is not achieved. To over come these problems, novel systems of dose transfer need to be considered. Pesticides can be formulated in oil as pointed out by Bals (1969) to enhance their activity and this has been shown to be true with some bio-pesticides. It may be necessary in some circumstances to apply a bio-pesticide separately from another liquid or suspension, that can affect the leaf surface, and thus increase the entry of the bio-pesticide. Chapple *et al.* (1996) devised a twin nozzle system in which the spray containing the pesticide can be mixed with another liquid before reaching the leaf surface. Alternatively the sprays from each nozzle can be kept separate so that the bio-pesticide reaches the leaf surface at some interval later. Such a technique has yet to be used for a bio-pesticide but has been used to apply a latex film to the soil surface to reduce evaporation. Similarly a system of sand-blasting weeds has been proposed to reduce the dose of a chemical herbicide needed to control certain weeds (Kudell, 1997).

PERSISTENCE IN FOLIAR ENVIRONMENT

A problem with many bio-pesticides is their inability to survive desiccation at low humidity. This was considered to be a major consideration when the use of *Metarhizium* to control locusts was proposed due to dry desert conditions. Fortunately the conidia are lipophilic and could be suspended in oil that enhanced their deposition on the cuticle of locusts. The oil formulation not only overcame the humidity problem, but very importantly it was compatible with existing locust control technology.

Entomopathogenic nematodes have been used predominantly as a soil-applied drench (>750 l/ha) to provide a moist environment in which the nematodes can seek their prey. One example of this is the application of *Steinernema feltiae* to control vine weevils (*Otiorhynchus sulcatus*). In contrast, when sprayed on to foliage, the drying of the deposit and exposure to ultra-violet light has prevented successful utilisation of the nematodes so far (Georgis & Kaya, 1998). To overcome these problems, formulation with a polyacrylamide gel has been shown to enhance the effect of applying IJs on leaf surfaces (Piggott *et al.*, 2000), although addition of polymers may affect droplet size spectra.

Unfortunately many bio-pesticides are adversely affected by ultra-violet light. To some extent this can be overcome by formulation with a sunscreen (Burges & Jones, 1998), thus germination of *Metarhizium* conidia exposed to UV was increased by formulating in oil and by adding a sunscreen (Moore *et al.*, 1993).

DISCUSSION

Bio-pesticides that have been developed commercially such as *B. bassiana* have generally been relatively easy to mass-produce, but are not necessarily the most effective in the field. Efforts to apply such products as if they were similar to chemical pesticides often fail because insufficient attention has been given to the special requirements of a living organism. The success of a particular isolate of *Metarhizium* against grasshoppers has undoubtedly been due to the very large international investment that enabled a full development programme to be followed in much the same way agrochemical companies develop a chemical pesticide. Formulation and application technology formed a significant component of this research once the effectiveness of the selected isolate had been identified in the laboratory.

A major advantage of a bio-pesticide is its selectivity, as this enables other naturally occurring biological agents to complement their application for longer-term control. This is particularly important as deposits of most bio-pesticides have a relatively short persistence so there is a need to enhance and rely on a high level of initial activity without disrupting the impact of natural enemies.

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Adjuvant technology to reduce spray application volumes on potatoes

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ABSTRACT

Potatoes require intensive, high-volume agrochemical spray inputs to ensure crop yield and quality are maintained. The economic and environmental benefits of lowering spray application volumes are well recognised, but potatoes present a challenge in accomplishing this due to the dense, layered canopy of the crop. Two novel organosilicone surfactant blends, Du-Wett and Bond Xtra, were used to reduce conventional spray volumes on potatoes from 500 to 200 litres/ha. Extensive studies of spray retention, distribution, phytotoxicity and field efficacy established adjuvant prescriptions for full season spray programmes, including applications of insecticides, fungicides, nutrients and plant growth regulators. The organosilicone blend technology permitted spray volumes to be more than halved, and application costs cut by up to 40%, without reducing agrochemical efficacy or crop yield and quality.

INTRODUCTION

Potatoes require intensive, high-volume agrochemical spray inputs to ensure crop yield and quality are maintained. This may include up to 15 applications in a season of sprays containing mixes of fungicides, insecticides, foliar nutrients and plant growth regulators. In the undulating terrain commonly cropped in New Zealand, potato growers employ conventional high-pressure, ground-based sprayers delivering up to 500 litres/ha to maximise coverage and distribution of sprays on the crop. The economic and environmental benefits of reducing water volumes in spray applications are well recognised but difficult to achieve, due to the dense, layered canopy of potato foliage. Two novel organosilicone surfactants have been shown to have potential to reduce spray volumes in row crops, by improving the retention and coverage of sprays (Gaskin *et al*., 2000). This paper reports further studies with these surfactants, which aimed to reduce spray volumes on potatoes by more than 50% without adversely affecting disease and pest control.

MATERIALS AND METHODS

Two novel adjuvants, Du-Wett (blend of organosilicone and organic surfactants; Elliott Chemicals Ltd) and Bond Xtra (mix of synthetic latex and organosilicone surfactant;

Loveland Industries, USA), were investigated for their effects on spray application and efficacy. Du-Wett is a novel superwetter intended for use where improved retention and coverage of horticultural sprays is desired. Bond Xtra is a sticker-spreader type adjuvant designed to improve spray deposition, coverage and rainfastness of agrochemical sprays. The adjuvants included for comparison were Citowett (alkylaryl polyglycol ether; BASF), Spray Stay (terpene polymer/nonionic surfactant blend; Wiltpruf Products) and LI 700 (phosphatidylcholine/ surfactant blend; Loveland Industries). Chemicals included a wide range of fungicides, insecticides, nutrients and plant growth regulators routinely used in potato foliar spray programmes, both alone and in tank mixes of up to five products.

Spray retention on outdoor-grown potted plants (cv. Ilam Hardy) was determined throughout a growing season, using a laboratory tracksprayer, as described previously (Gaskin *et al.*, 2000). Treatments were applied in either 500 or 200 litres/ha spray volume. Plants were sectioned to determine spray distribution; tops (growing tip plus two top fully expanded leaves) and bottoms (remainder of plant). Retention is presented as mg mancozeb/g dry weight foliage, which is a good indicator of retention per surface area of foliage ($R^2 = 0.98$). All experiments were analysed as factorial designs and least significant difference (LSD) tests were used to compare treatments.

A field trial was conducted throughout a season (June-November) in 1999, in the major growing district of Pukekohe, New Zealand. Potatoes (cv. Ilam Hardy) were commercially planted in rows 0.8 m apart. Plots were 8 m long by three rows, using outer rows as guards. The trial design was a randomised block with four replicates, excluding untreated plots. The latter were sited as a two row guard through the centre of the trial to reduce uneven disease pressure on treated plots. Treatments were applied with a CO_2 powered plot sprayer (TX-8 hollow cone nozzles operated at 300 kPa, delivering 200 or 500 litres/ha with varying speed).

All treatments had mancozeb applied at c. seven day intervals, depending on weather, from crop emergence to harvest, to control late blight (*Phytophthora infestans*). Additional pesticides were programmed in sprays as required to maintain crop health. The standard spray programme with spreader surfactant, Citowett (25 ml/100 litres), was applied at 500 litres/ha. Prior to forecasted rain, this was substituted by a sticker option, Citowett plus Spray Stay (SS) (Table 1). Whenever a systemic a.i. was incorporated in the spray mix, e.g. to control potato aphids (*Aulacorthum solani* and *Macrosiphum euphorbiae*), Citowett was replaced by LI 700 (LI). The research treatments (numbers 2-9, Table 1) were applied in reduced spray volumes of 200 litres/ha. These consisted of either Du-Wett (DW) and/or Bond Xtra (BX) as protectant spray surfactants, and generally, the addition of LI whenever a systemic a.i. was included in the spray mix. The varying adjuvant combinations used in each treatment (i.e. as protectant spreader, protectant sticker and systemic spreader) during the trial are described in Table 1.

At weekly intervals, plots were inspected for late blight infection and severity was determined on four dates (28/9, 12/10, 20/10, 29/10) by matching infected leaves on 10 stems/plot with a standard key (Anonymous, 1947). Plots were inspected weekly for the presence of aphids. When infestation occurred, counts were made on 10 leaves/plot and a systemic insecticide (methamidophos+"systemic" adjuvant option) included in the spray mix. Three DAT aphid counts were repeated. At 4 DAT samples of tubers (2 kg) were taken from treatments 1, 5, 9 and 10 (Table 1) and analysed for methamidophos residues. Weekly assessments were made for crop tolerance to sprays, over a four week period in August. Chlorotic symptoms were noted (% of crop) and scores for vigour (height and density) were made on a 1-5 scale (1=poor, 3=average, 5=excellent). At harvest, on 14 November, tubers were hand dug from a 2 m length in the centre row of each plot and weighed to determine yield. Data was subjected to analysis of variance and Duncan's New Multiple Range Test was used to determine significant differences ($P < 0.01$) between treatments. Percentage data was transformed (sqrt x+0.5) prior to analysis.

Table 1. Adjuvant treatments (ml/100 litres) for full-season pesticide programme (BX=Bond Xtra; DW=Du-Wett; SS=Spray Stay; LI=LI 700).

Tmt no.	Spray vol. (litres/ha)	With protectant spray Spreader	or	Sticker	With systemic spray
1[1]	500	Citowett (25)		Citowett+SS (25+80)	LI (500)
2	200	BX (165)		BX (165)	BX (165)
3	200	BX (330)		BX (330)	BX (330)
4	200	BX (165)		BX (165)	BX+LI (330+500)
5	200	BX (330)		BX (330)	BX+LI (330+500)
6	200	DW (10)		BX (165)	DW+LI (100+500)
7	200	DW (100)		BX (165)	DW+LI (100+500)
8	200	DW (10)		BX (330)	DW+LI (100+500)
9	200	DW (100)		BX (330)	DW+LI (100+500)
10	untreated	-		-	-

[1] Standard full volume programme. Note a.i.s and a.i. rates were identical in all treatments.

RESULTS AND DISCUSSION

Spray retention and distribution

DW and BX are organosilicone blends whose properties have been optimised for horticultural, as opposed to herbicidal, use. In particular those characteristics which can lead to excessive wetting and run-off (Holloway *et al.*, 2000), or undesirable stomatal infiltration (Gaskin *et al.*, 2000), have been modified. In the retention study, some run-off from easily-wet potato foliage was observed with use of the organosilicone blends, but within the dense canopy of the mature crop much of this was re-captured on older leaves (Figure 1). Reduced-volume (200 litres/ha) protectant sprays of mancozeb plus azoxystrobin, containing BX in particular, consistently directed more chemical to the lower portion of the plant relative to the standard full-volume spray (500 litres/ha) containing either Citowett or Citowett plus SS. Meanwhile, retention of reduced-volume sprays, containing either DW or BX, on the upper, fully exposed canopy was always equal to or better than standard full-volume sprays (Figure 1). Previous work has confirmed that as potato size and canopy density increase, the use of superwetter adjuvants can improve spray retention (Gaskin *et al.*, 2000). This endorses the importance of matching organosilicone surfactant concentration with application volume (Stevens *et al.*, 1994).

More spray was retained on potato plants from reduced-volume applications (200 litres/ha) containing DW or BX plus LI, relative to the full volume systemic sprays (500 litres/ha) containing LI surfactant alone (Figure 2). Retention was consistently improved when each of four very different agrochemicals was tank-mixed with a protectant fungicide (mancozeb) and systemic insecticide (methamidophos). Differences in retention observed with different mixes of a.i. are attributed to the effects of co-formulants on the physical properties of sprays (Gaskin *et al.*, 2000).

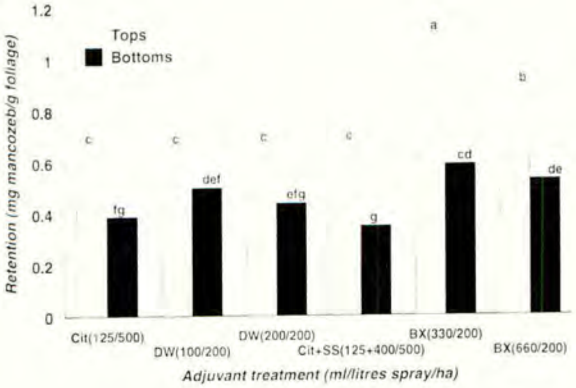

Figure 1. Influence of adjuvants and spray volumes on distribution of fungicide sprays (mancozeb + azoxystrobin mix) on mature potato plants (means sharing common letters are not significantly different. LSD, $P < 0.05$).

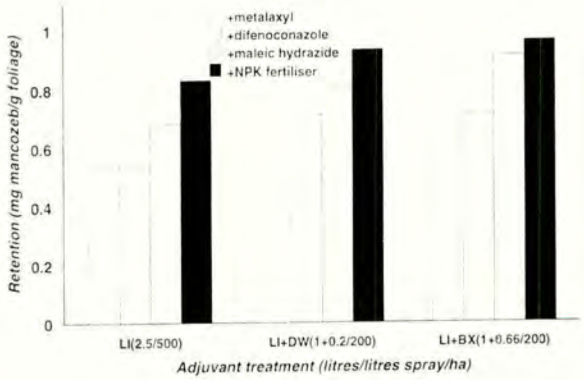

Figure 2. Influence of adjuvants and spray volumes on retention of pesticide spray mixes on mature potato plants (all mixes contain mancozeb+ methamidophos+a.i. as indicated).

Field efficacy

The first signs of late blight were detected in mid-September and the disease continued to develop in untreated areas to the point of total defoliation in early November. Disease severity was very low in all treated plots for the duration of the trial, with no differences between treatments (Table 2). Reduced-volume mancozeb sprays with the addition of either BX or DW prevented late blight development in potatoes under significant disease pressure, providing equivalent control to the standard full volume spray treatment (Tmt 1, Table 2). There were no differences between BX and DW treatments ($P < 0.01$), nor between adjuvant rates, although mean infection levels tended to be numerically less with DW and at the higher use rate.

Table 2. Effect of reduced-volume pesticide applications on late blight infection.

Tmt no.	Adjuvant[1]	Rate (ml/100 L)	Infection (% leaf area) 28-9-99	12-10-99	20-10-99	29-10-99
1[2]	Citowett	25	0.07	0.13	1.30	1.43
2	BX	165	0.16	0.07	1.76	1.83
3	BX	330	0.04	0.13	1.11	1.23
4	BX	165	0.01	0.05	1.31	1.36
5	BX	330	0.06	0.18	1.21	1.38
6	DW	10	0.01	0.13	1.47	1.59
7	DW	100	0.02	0.02	1.06	1.08
8	DW	10	0.06	0.12	1.04	1.16
9	DW	100	0.08	0.06	0.90	0.96
10	untreated	-	4.2	18.1	26.7	56.2
	LSD ($P < 0.01$)		NSD[⊛]	NSD	NSD	NSD

[⊛]NSD = no significant differences between treatments, excluding untreated.

[1] Full season treatment combinations as described in Table 1.

[2] Standard 500 litres/ha, treatments 2-9 at 200 litres/ha.

Reduced-volume insecticide treatments (methamidophos) with the addition of BX or DW provided equivalent aphid control to the standard full volume treatment, under substantial pest pressure (Table 3). The high rate DW sprays gave numerically better control, but differences between adjuvant rates were not significant. There were no subsequent aphid infestations in the crop during the season. Methamidophos residues in potato tubers at 4 DAT were 0.02, 0.03, 0.04 and < 0.01 (undetected) mg/kg for treatments 1, 5, 9 and 10, respectively. These are all below the permissible maximum residue limit (0.1 ppm).

Table 3. Effect of reduced-volume pesticide applications on aphid control, crop vigour and yield.

Tmt no.	Adjuvant[1]	Rate (ml/100 L)	Aphids/leaf Pre-treat	4 DAT	Mean vigour (1-5 scale)	Yield (t/ha)
1[2]	Citowett	25	3.3	0.05	3.5	68.9
2	BX	165	2.5	0.05	4.1	70.9
3	BX	330	1.3	0.03	3.3	65.8
4	BX	165	3.0	0	3.4	66.9
5	BX	330	2.8	0.05	3.7	65.6
6	DW	10	2.8	0.03	3.8	65.6
7	DW	100	3.0	0	3.6	63.3
8	DW	10	3.0	0.03	3.2	64.1
9	DW	100	3.5	0	2.9	70.2
10	untreated	-	-	24.6	-	-
	LSD ($P < 0.01$)		NSD	NSD	NSD	NSD

[1] Full season treatment combinations as described in Table 1.

[2] Standard 500 litres/ha, treatments 2-9 at 200 litres/ha.

Crop vigour was generally above average in all treatments and there were no differences between them (Table 3). Some early growth differences were attributed to fertiliser and planting variations, and to frost effects in late August, but there were no visual differences between treatment plots from September onwards. At harvest, all treatments yielded equally (Table 3) and there was no sign of tuber blight in any sample.

Efficacy of the reduced-volume spray programmes, utilising DW and BX adjuvants, was equivalent in all respects to the standard full volume spray programme. Disease and pest control, crop health and productivity were not compromised by cutting spray volumes of pesticide applications throughout the season by more than half.

The use of reduced-volume sprays on potatoes is being adopted by major commercial growers in New Zealand. The benefits are well recognised; programmes are often more cost effective (Table 4) and with lower environmental impacts. The organosilicone adjuvant technology allows more hectares to be sprayed per day and more area to be covered between rain. It gives growers the ability to shorten spray intervals under fast growing conditions and inclement weather, or the option of reducing tractor size to decrease soil compaction in wet conditions.

Table 4. Work rate and spray application cost comparisons for adjuvants (Travel speed 8 km/h; tank size 2000 litres; block size 60 ha; labour and machinery cost NZ$75/h).

Application factor	Protectant sprays		Systemic sprays	
Adjuvant	Citowett	DW	LI	LI+DW
Adjuvant rate (litres/ha)	0.125	0.2	2.5	1+0.2
Spray volume (litres/ha)	500	200	500	200
Work rate (incl. fill, mix, turn time) (ha/h)	4.9	8.1	4.9	8.1
Spray application costs/ha ($NZ)	15.3	9.3	15.3	9.3
Adjuvant cost/ha ($NZ)	1.4	7.6	42.5	24.6
Total cost/ha ($NZ)	16.7	16.9	57.8	33.9
Relative cost ratio	100	101	100	59

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Specifying the requirements for optimised application and formulation by computer simulation – an holistic approach

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ABSTRACT

A finite-difference model for the movement of pesticide through a barley leaf is described. The model considers the leaf to consist of a number of layers possessing different solubility and mobility for pesticides. Response is modelled via appropriate, experimentally determined tolerance distributions where the determining variable is the concentration of the pesticide at any particular time. The model has been compared with experimental data for the proportion of *Erysiphe graminis* spores germinating at various distances from a single deposit of Dinocap. A good agreement was obtained when basing the tolerance distribution on concentration. The effect of varying partition coefficients and flow speeds on the area of control for a range of threshold values and times is demonstrated. The effect of varying droplet size is also investigated. The potential of this type of model is thus shown for the design of treatments in precision crop protection. The range of values that the parameters should ideally assume for a particular application can be investigated and the results borne in mind when designing a suitable treatment.

INTRODUCTION

The problem of pests and diseases infecting crops and thus reducing their yield has large economic effects. One aspect of the crop protection industry is spraying. The first concern in agricultural spraying is that as much of the spray as possible is conveyed to the crop. However, getting the spray onto the crop is not the end of the story. The formulation should be distributed over sufficient of the leaf surface to generate the required level of control and to maintain yield.

This is not a stationary process, rather the distribution of the formulation changes with time as it spreads out over the leaf and perhaps moves into the leaf. The aim is therefore to maintain levels of active ingredient above critical thresholds in the right places at the right times. This is particularly difficult given the distance of the system from equilibrium.

There are many variables in a spraying operation which can be controlled. First, are the factors to do with spray transport and capture. These include the nozzle dependent parameters and the spray formulation. Once the droplets reach the leaf surface the formulation is again important as the presence of adjuvants affects the rate of deposit spread and the penetration of the active ingredient into the leaf. The way in which the spray is formulated and applied also allows a degree of control over the distribution of the deposits on the leaf surface: the number and placing of deposits and their size. The parameters of primary importance in determining the movement of the active ingredient into and through the leaf are the diffusion coefficients of the active ingredient within the different domains of the leaf, the partition coefficients between domains and the magnitude of any possible mass transport within the leaf.

It is the behaviour of the droplets once they have formed deposits on the leaf which is to be considered here so the parameters of interest are the specification of these deposits on the leaf surface and the properties of the active ingredient within the leaf.

Parameter optimization can be undertaken to define combinations of parameters which may result in improved spraying operations. It is not easy to define what makes a better spraying application since there are a number of objectives such as minimizing drift. However, minimizing the applied mass of active ingredient for a given level of control is perhaps the most important single aim.

Such optimization may be achieved either by conducting field trials or via a numerical modelling approach. A problem with field trials is the large associated heterogeneity which makes it difficult to control individual parameters and to identify the desired combination of parameters for optimal treatments. No such problem exists with a numerical approach.

The knowledge of where the optima of physical and chemical parameters lie that may be obtained from this approach will inform the process of developing improved formulations and applications.

DIFFUSION MODEL

The mathematical modelling approach adopted here requires a model leaf to be defined as a domain over which the relevant transport equations may be solved. The first requirement for the model is that it should include enough detail to retain the most important features of the system but at the same time making as many simplifying assumptions as possible. This is to render the system more amenable to analysis. With this in mind, it was decided that a model representing the leaf by a number of layers was appropriate. The first requirement is that it should include both upper and lower cuticles with the remaining body of the leaf between these layers.

Schönherr & Baur (1994) report a very pronounced division of the cuticle into two very different regions. Therefore each of the cuticles should be split into two layers; the limiting skin and the sorption compartment in the terminology of Schönherr and Baur.

The simplest model for the body of the leaf between the cuticles, neglecting mass transport, is to have a single diffusion coefficient and solubility. This seems reasonable since the significant diffusion within the leaf all takes place in similar aqueous domains.

Mass transport takes place within the vascular system of the leaf. To model individual elements of the vascular system would introduce too great a complexity into the model. Therefore, it is necessary to approximate the movement in the phloem or xylem by a unidirectional flow throughout an appropriate layer. The speed of this flow is such as to ensure the appropriate mass flux through a cross-section of the leaf perpendicular to this flow. All non-diffusive transfer is confined to these layers and differing flow rates between them, including counter-flow, can be considered. Given an appropriate flow speed, it seems unlikely that the error in this approach could be reduced by introducing more complexity, with the extra unknowns this would introduce. It should be possible to obtain an idea of the magnitude of any error by varying the thickness of the flow layers.

In reality, the elements of the vascular system are sandwiched between layers of typical leaf material so that the xylem and phloem are within the second and fourth layers respectively of the body of the leaf. These layers are therefore taken as those containing flow. The layer between the xylem and phloem is very thin in comparison to the other layers. It has been shown that the effect of removing this layer, and saving computational effort, is negligible. The differing solubility and mobility of any active ingredient in these layers can then be considered.

There are a number of different ways of representing the source of diffusant. Perhaps the most widely applicable is to assume a reservoir of carrier containing a decreasing mass of active ingredient which partitions into that part of the cuticle directly below the deposit.

Transport by diffusion is described by the diffusion equation (1) where C is the concentration of active ingredient, D the diffusion coefficient and t the time variable. To account for mass-flow in the vascular system of the leaf, the convection-diffusion equation (2) is used. This modifies the diffusion equation to account for a flow, of velocity v, along the leaf in the direction of the x-axis.

$$\frac{\partial C}{\partial t} = D\nabla^2 C \tag{1}$$

$$\frac{\partial C}{\partial t} = D\nabla^2 C + v\frac{\partial C}{\partial x} \tag{2}$$

At the interface between two layers, the easiest assumption to make is that the active ingredient is able to move across the interface instantaneously. The differing solubilities in each layer may be accounted for by maintaining the concentrations in a defined ratio, the partition coefficient. If layers l and $l+1$ have partition coefficient σ_{l+1} then the concentrations at the interface are linked by equation 3. Similarly, σ_1 is the partition coefficient for the source's interface with layer 1.

$$C_{l+1} = \sigma_{l+1} C_l \tag{3}$$

Figure 1 depicts an example of a model leaf which includes vascular considerations but represents the cuticles by single layers. The subscripts refer to the particular layer from 1 to 7. C_0 is the concentration in the residual deposit and the D's, C's, σ's and L's are respectively the diffusion coefficients, concentrations, upper partition coefficients and thicknesses for each layer.

The system of equations describing a model leaf as outlined above is too complicated in general to be solved analytically. A numerical method to approximate the true solution of the system of equations is therefore required. A finite difference method was chosen because of its simplicity in cases, such as this, where the geometry makes a simple rectangular mesh appropriate. A classical explicit finite difference scheme is used. It is second-order accurate in most parts, the exception being the equation to account for the flow which is only first order. The model is implemented via a computer program written in Microsoft Visual Basic.

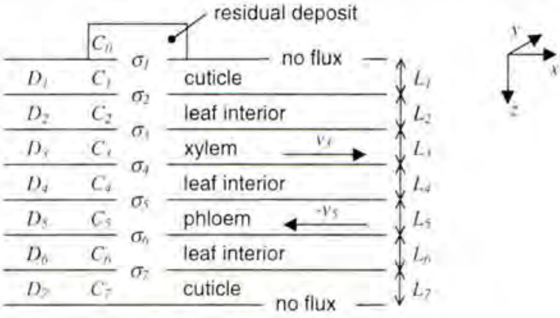


Figure 1. A 7-layer model for a barley leaf.

A population of fungal spores respond to an applied dose by either germinating or not. It is possible to estimate the probability of non-germination at each dose via repeated trials. It is assumed that some function of the threshold dose required by each individual member of the population for a non-germination response is normally distributed. This distribution is known as the tolerance distribution and allows the proportion of the population responding at a given dose to be estimated.

The ability of the model to adequately replicate features of real systems was validated by comparing the results of the model for the germination of spores of *E. graminis* around a single deposit of Dinocap with experimental results. The concentrations of active ingredient generated from the model were converted into percentage levels of control using tolerance distributions derived from germination trials on an agar medium containing Dinocap.

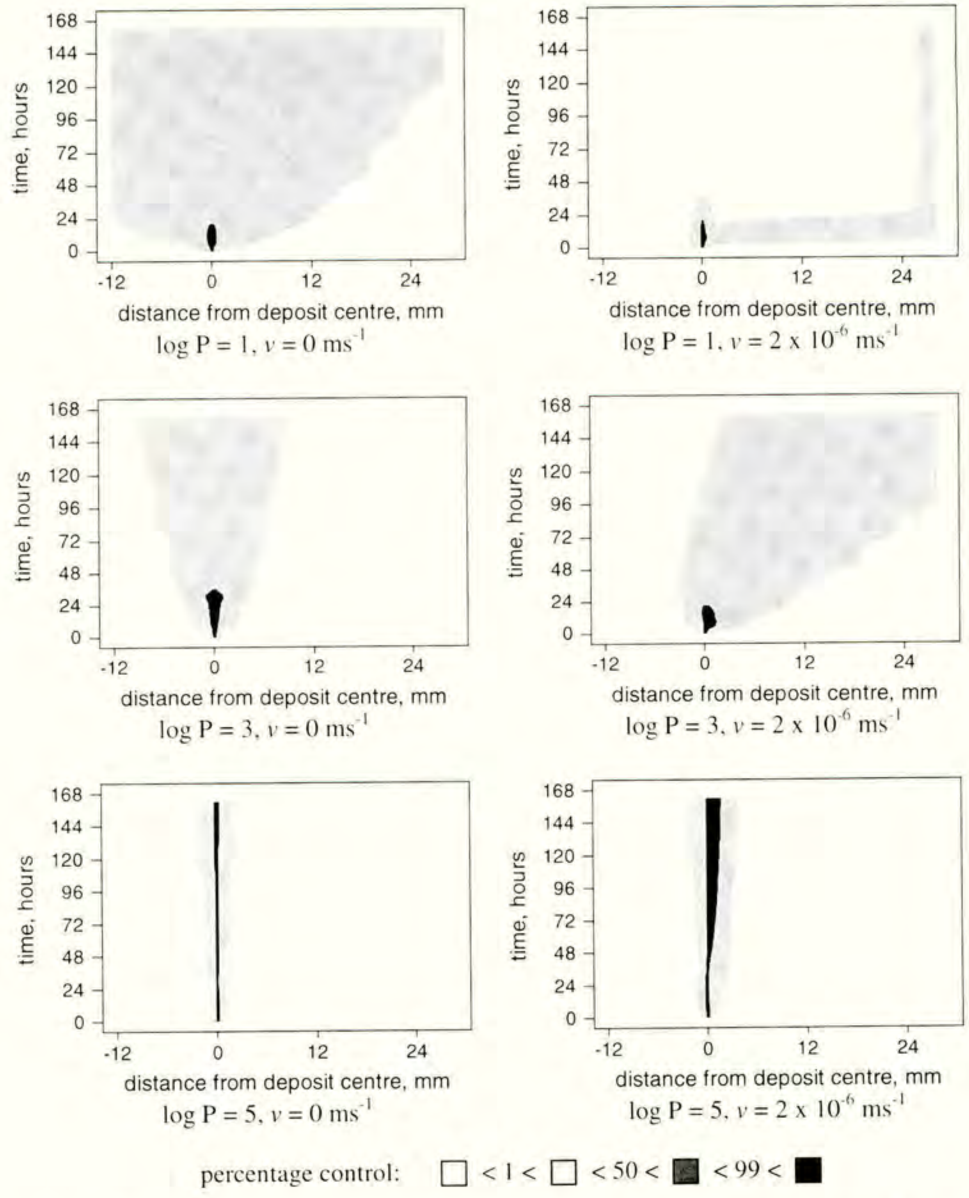
USING THE MODEL

The potential of the model to be used as a tool for optimization of parameters will be demonstrated here. Different strategies must be employed for the application of pesticide spray depending upon what type of pest is to be countered.

It is the concentration of active ingredient at the leaf surface which is of importance when an attempt is being made to limit the germination of fungal spores or when the pest is sedentary insect pests or their eggs. For pests such as fluid feeding aphids or fungal infections it is the systemic movement of the active ingredient through the leaf which is of interest with the active ingredient required at sites within the leaf.

Penetration of the leaf is largely determined by the relative solubilities of the active ingredient in the formulation, cuticle and body of the leaf. These solubilities may be characterized by the octanol-water partition coefficient, log P.

Three different values of log P have been considered from the slightly hydrophobic value of 1 through 3 to the strongly hydrophobic value of 5 which is similar to that of Dinocap. The two flow regimes considered are those of no flow and an estimate of a typical flow speed, v of 2×10^{-6} ms^{-1}. The concentration profiles at the surface of a typical barley leaf over a one week period were obtained using a five-layer implementation of the model including two layers for each cuticle and only considering movement along the axis of the leaf. The deposit contained 84 ng of active ingredient.



log P = 1, $v = 0$ ms^{-1}

log P = 1, $v = 2 \times 10^{-6}$ ms^{-1}

log P = 3, $v = 0$ ms^{-1}

log P = 3, $v = 2 \times 10^{-6}$ ms^{-1}

log P = 5, $v = 0$ ms^{-1}

log P = 5, $v = 2 \times 10^{-6}$ ms^{-1}

percentage control: □ < 1 < □ < 50 < ▨ < 99 < ■

Figure 2. Variation in control at the leaf surface with time as affected by log P and v.

Using the tolerance distribution estimated for Dinocap, which has a mean of -4.17 log kgm^{-3} and a standard deviation of 1.48 log kgm^{-3}, these concentrations were converted to values for the proportion level of control. This tolerance distribution is similar to that for Fluquinconazole which has a mean of -4.06 log kgm^{-3} and a standard deviation of 0.679 log kgm^{-3}. The 1, 50 and 99% levels are shown in Figure 2. The effects of log P and vascular flow on the area maintained at each level of control can be seen as can the interaction between them. The pesticide has a greater mobility within the leaf than in the cuticle so it can be observed that greater spread of active ingredient occurs in the cases where a lower log P results in more penetration of the leaf. Similarly, if there is a flow within the leaf then this has a much stronger effect with lower values of log P. It can be seen that the greatest protection for the longest time occurs with low log P if there is no flow but with higher values if there is a flow.

The effect of the size of the deposit was investigated using the same 5-layer implementation of the model as above though now without any flow. It can be seen from Figure 3 that halving the diameter of the formulation residue has very little effect on the area of control obtained over a large range of threshold concentrations. However, if droplets of half the diameter are used then, for a given applied volume, eight times as many droplets can be applied leading to a much greater area of control. However, the use of smaller droplets is not without risk; for instance they present an increased likelihood of off-target drift.

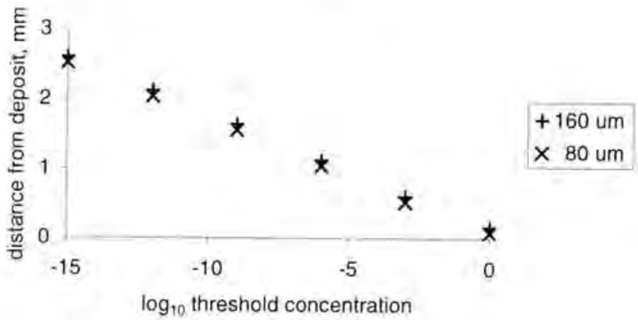


Figure 3. The range of control at different threshold concentrations for two deposit sizes.

CONCLUSIONS

The potential of this method for optimizing the parameters of a spraying operation has been demonstrated. Mathematical modelling of the form employed here will allow the development of understanding of the interactions between parameters and of the range of values which should provide the desired level of control for the minimum inputs. Mathematical modelling places few constraints on the parameters so most combinations can be easily investigated before designing and undertaking costly field trials.

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