SESSION 9C

FATE, EXPOSURE AND EFFECTS – RISK ASSESSMENT OF PESTICIDES

Session Organisers	Dr M S Lant and Mr S J Maund *Zeneca Agrochemicals, Bracknell*
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UK TECHNICAL POLICY ON THE CONSUMER RISK ASSESSMENT OF PESTICIDE RESIDUES

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ABSTRACT

A Joint FAO/WHO expert Consultation on the consumer risk assessment of pesticide residues was held in York, UK in May 1995. The Consultation recommended a number of important new approaches, including the use of supervised trials median residue levels (STMRs), rather than maximum residue levels (MRLs), in predicting long-term (i.e. chronic) dietary intakes and the routine assessment of short-term (i.e. acute) risk by the comparison of intake estimates based on the MRLs and portion size consumption data with an acute reference dose (acute RfD). The approach currently taken within the UK is described together with the recommendations of the Consultation and how the PSD propose to respond to these recommendations in carrying consumer risk assessments in the future.

INTRODUCTION

The application of pesticides to crops or stored commodities may result in residues remaining on the foodstuffs at the point of consumption. In order to ensure that the risk to the consumer arising from the consumption of foodstuffs containing pesticide residues is acceptable, the Pesticides Safety Directorate (PSD) requires data from the applicant on both the magnitude and nature of the residues that may occur in crops at harvest or outloading from store. These data are used to make an estimation of dietary intake of pesticide residues in food and compared with acceptable intakes derived from mammalian toxicological studies. Where the consumer risk arising from the exposure to the pesticide is estimated to be above acceptable levels, risk management measures are taken, or if these are not appropriate, the approval is refused.

The existing UK technical policy on pesticide residues was published as an Appendix to the 1988 Advisory Committee on Pesticides Annual report (ACP, 1990). This technical policy together with the World Health Organisation publication "Guidelines for predicting the dietary intake of pesticide residues" (WHO, 1989) have formed the basis of national consumer risk assessments of pesticide residues for a number of years.

However, the limitations of the approach on the estimation of dietary intake as outlined in the 1989 WHO publication has been identified over the last few sessions of the Codex Committee on Pesticide Residues (CCPR). Whilst agreeing that Theoretical Maximum Daily Intakes (TMDIs) represent a gross overestimate of actual dietary intake, many member governments objected to recommended MRLs where TMDIs exceeded the ADI. This was even the case where further data were available which would allow a more realistic estimate of dietary intake to be calculated. In addition, the WHO publication did not provide the methodology for conducting risk assessments for active ingredients where the primary toxicological concern relates to short-term (i.e. acute) exposure.

Joint Food and Agricultural Organisation (FAO) /WHO expert consultation

A Joint FAO/WHO expert Consultation on Guidelines for Predicting Dietary Intake of Pesticide Residues was held in York, UK from 2th-6th May 1995 (WHO, 1995). The main objective of the Consultation was to review the existing guidelines and to recommend feasible approaches for improving the reliability and accuracy of methods for predicting dietary intake of pesticide residues. The Consultation recognised the importance of science in assessing consumer risk and the emphasis was on *the best use of the available data*, in order to ensure that intake estimates were as realistic as possible. The Consultation reluctantly agreed to retain TMDIs for the cases where no data are available which would allow a more realistic estimate of dietary intake to be made. However, it was recognised that TMDIs represent crude overestimates of actual dietary intake and that the current tiered approach was too prescriptive. The Consultation defined a more refined intake calculation to be known as the National Estimated Daily Intake (NEDI) which will replace the existing Estimated Maximum Daily Intake (EMDI) and Estimated Daily Intake (EDI) estimates carried out at national level. It was envisaged that the use of the NEDI would allow greater flexibility in that one or more of a number of "factors" could be used and incorporated into a "best estimate" of dietary intake.

RISK ASSESSMENTS FOR LONG-TERM (I.E. CHRONIC) DIETARY INTAKES

The calculation of a NEDI would incorporate one or more of a number of "factors" to obtain a "best estimate" of dietary intake as given in the following equation:

$$\mathrm{NEDI} = \Sigma\ F_i \times \mathrm{RL} \times K$$

where,

F_i - Food consumption data for a given food commodity

RL_i - Appropriate Residue Level corresponding to that commodity (e.g. supervised trials median residue level or residue in edible portion)

K - A correction value that takes into account the reduction or increase in residue when one or more of the appropriate "factors" are used (e.g. decrease in residue on processing)

The "factors" which the Consultation identified as being appropriate to consider in refining dietary intake for long-term exposure are listed and most of these are discussed in more detail below:

- Supervised trials median residue
- Residue definition
- Use of monitoring and surveillance data
- Total diet (market basket) studies
- Residues at or below the limit of determination
- Effects on residue levels due to storage, processing or cooking practices
- Edible portion
- Proportion of crop or food commodity treated
- Proportion of crop domestically produced and imported
- Food consumption data including that of sub-groups of the population

- Other known uses of the pesticide

Use of supervised trials median residue (STMR)

Currently PSD use the MRL, or highest residue, as a starting point for dietary intake estimations carried out nationally. However, it is recognised that normally the majority of trial results are well within the MRLs.

The Consultation considered the STMR, identified from the residue trials considered comparable with the maximum rates and timings approved, as a more appropriate starting point for long-term (i.e. chronic) dietary intake estimation because it was the most likely residue resulting from the "worst case" use of the pesticide. PSD propose to follow this approach and in particular intend to estimate STMRs routinely when evaluating residue trials data. When STMR data are available then it is recommended that a NEDI would be calculated straight away without the calculation of the TMDI. This would not only give a more realistic estimate of dietary intake but would give a improved representation of the risk assessment process to consumers.

STMRs will have a significant impact on intake estimates since, for a typical residue trial population, the STMR is 3-5 times lower than the MRL. The way MRLs are estimated will not change, being based primarily on the highest residue level reported in the trials data.

Residue definition

At the present time only one residue definition for each commodity is established nationally. However, frequently this is a compromise between the desire to include all residue components of toxicological significance for the purposes of the risk assessment and the need to establish a simple residue definition (i.e. the indicator molecule concept) suitable for practical routine monitoring and enforcement of the MRL, at reasonable cost.

The Consultation proposed that, **where appropriate**, two different residue definitions should be established, one for enforcement and monitoring purposes which might use a marker compound, the other more comprehensive definition for the consumer risk assessment. PSD propose that this approach is used in future but recognising that it will only be necessary to establish separate residue definitions in about 10% of cases.

In choosing the appropriate analytes and the analytical method for the testing of the residue trials samples, the applicant must consider the needs of both risk assessment and compliance. In practice this will mean generating the data in such as way as to give the regulatory flexibility to establish two separate residue definitions where appropriate.

Use of monitoring and total diet data

The most realistic estimate of dietary intake are derived from monitoring and total diet data. Currently, PSD do use Working Party on Pesticide Residues (WPPR) monitoring data to refine intake estimate where theoretical intake estimates lead to an exceedance of the ADI, for established pesticides. However, the number of commodity/compound combinations where

Historically, data on the proportion of crop treated and the proportion of crop domestically produced and imported have been used routinely by PSD in refining dietary intake estimates for **all** commodities, where data were available.

The Consultation proposed that when reliable data are available these are only used when considering long-term dietary intake and then only for commodities which are ***sufficiently** homogenous in the food supply.* This would generally only apply to those crops which are bulked (e.g. cereal grain) or processed e.g. oilseed rape and where the use pattern is well established. It is envisaged, given the limitations, that PSD will not be able to use this "factor" very frequently.

RISK ASSESSMENTS FOR SHORT-TERM (I.E. ACUTE) DIETARY INTAKES

In considering the authorisation of the use of pesticides, PSD has not in the past routinely carried out consumer risk assessments based on short-term exposure, though in specific cases (e.g. organophosphorous pesticides in carrots) such assessments have been performed.

Toxicological considerations and acute reference dose (acute RfD)

The Consultation recommended that the potential for various acute toxicological effects should be routinely assessed for all pesticides during evaluation and that the establishment of a 'short-term ADI' to be called the 'acute reference dose' (acute RfD) is considered together with ADI. PSD propose to follow these Consultation recommendations and in particular propose to establish acute RfDs on a routine basis.

Residue and consumption data considerations

The Consultation recommended that short-term dietary intake estimates should use the MRL, when considering whole raw commodities and use consumption data appropriate to the toxicologically relevant duration of intake (e.g. portion size data). PSD propose to follow these Consultation recommendations and in particular propose to carry out estimates of short-term dietary intakes on a routine basis. These short-term dietary intake estimates would be called National Estimates of Short-Term Intake (NESTI).

The Consultation also recognised that significant variation can occur in the residue levels in individual units comprising a single composite sample. PSD propose that where significant variation in residue levels in the individual units comprising composite samples could be anticipated and the intake based on the MRLs in composite samples are near unacceptable levels (relative to the acute RfD, see below), additional field trial data would be required without compositing the field trials samples.

SUMMARY OF PROPOSED APPROACH FOR THE RISK ASSESSMENT FOR SHORT-TERM AND LONG-TERM DIETARY INTAKE

A schematic representation of the proposed approach to consumer risk assessment is presented below:

sufficient WPPR monitoring data have been available has limited the application of these more realistic intake estimates.

The Consultation recommended that where sufficient data are available, these should to be used when considering long-term dietary intake. However, the Consultation noted that data over two or more years are required which *are sufficiently representative of the food supply.* PSD propose to follow the approach recommended by the Consultation. Where sufficient already existing WPPR monitoring data are not available to allow a realistic intake estimate to be made, consideration would be given to allowing the approval holders the opportunity to generate representative monitoring data for relevant commodities, where appropriate.

Residues at or below the limit of determination (LOD)

Currently where all the comparable trial results are below the LOD, PSD assume the residue to be at the LOD in intake calculations. Other countries have use other approaches such as assuming the residue to be at 1/2 the LOD.

The Consultation recommended that when refining the intake calculation (i.e. in calculating a NEDI), a residue of zero, rather than the LOD, could be used in certain circumstances. A residue level of zero would be used if (i) supporting information suggested that residues were essentially zero (e.g. exaggerated dose rate trials or metabolism data) **or** (ii) there was no UK use on the commodity or no use on the commodity in countries exporting to the UK. PSD propose to use this approach in future.

Effects on residue levels due to storage, processing or cooking practises

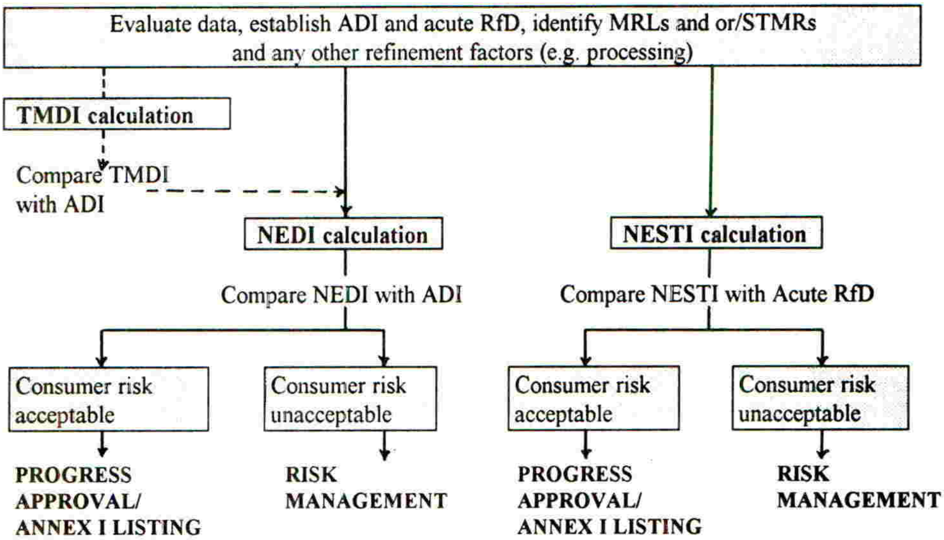
The Consultation noted that residue levels in raw commodities are affected (normally dissipated) by storage, transport, preparation, commercial processing and cooking. In addition, some pesticides may degrade during processing, to form toxicologically significant degradation products. The Consultation recommended that data on the effects on residue levels (including the production of any degradation products) due to storage, processing or cooking practices should be used to refine the intake calculation to make a “best estimate” of dietary intake.

This recommendation reflects the current UK practice. It is proposed that the mean reduction or concentration factor should be applied to the STMR estimated from the raw agricultural commodity as described in section 3.1. The STMR estimated in this way for the “processed” (i.e. stored/ transported/ processed/ cooked) commodity would be referred to as the STMR-P.

Edible portion

The Consultation recommended that the residue in the edible portion of food commodities should be used in estimating dietary intakes rather than those in the whole commodity, where these data are available e.g. residue in the banana pulp rather than the whole banana. This recommendation reflects the current UK practice.

Use of data on the proportion of crop or food commodity treated and the proportion of crop domestically produced



CONCLUSIONS

A Joint FAO/WHO expert Consultation proposed a number of important new concepts which will help improve the accuracy of dietary intake estimates and ensure that the best (i.e. most realistic) estimate is derived using all the available data. The JMPR have already implemented these concepts into their work and in the UK the new approach will soon be discussed by the ACP. Once agreed the new UK approach will be published as part of the Registration Handbook (PSD, 1995). It is envisaged that full discussion within the European Union will start before the end of 1996 and it is hoped that a harmonised approach to consumer risk assessment can be agreed the following year.

ACKNOWLEDGEMENTS

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REFERENCES

ACP (1990) *Advisory Committee on Pesticides 1988 Annual Report*, London HMSO

PSD (1995) *The Registration Handbook*, issued jointly by PSD and the Health and Safety Executive, distributed to all UK approval holders.

WHO (1989) *WHO Guidelines for Predicting Dietary Intakes of Pesticide Residues.* Report prepared by the Joint UNEP/FAO/WHO Food Contamination Monitoring Programme in collaboration with the Codex Committee on Pesticide Residues. World Health Organisation, Geneva.

WHO (1995) *Recommendations for the revision of the guidelines for predicting intake of pesticide residues.* Report of a FAO/WHO Consultation. WHO, Geneva.

DE-795: AN ENVIRONMENTAL AND EXPOSURE ASSESSMENT

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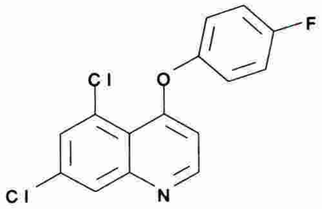
ABSTRACT

DE-795 is a new protectant fungicide with activity specific to powdery mildews. In accordance with Directive 91/414/EEC, studies have been carried out to provide data for the regulatory assessment of DE-795 and its metabolites on cereals (the target crop) and in the environment. On mature winter wheat DE-795 was the major residue, with a number of very low-level metabolites in straw and grain. Further degradation of these initial metabolites resulted in their incorporation into natural plant components, indicating they are likely to have low toxicological significance. Although DE-795 also forms the major residue in animal tissues, the large safety margin is demonstrated by the calculated theoretical maximum daily intake for DE-795 being <1% of the ADI. In soil, DE-795 and its principal metabolite were indicated to have no leaching potential. In soil and aquatic systems DE-795 is only slowly degraded, although hydrolysis under acidic conditions and aqueous photolysis are more significant processes. However, the low toxicity to non-target organisms has indicated that the persistence is likely to have minimal environmental impact under normal use conditions.

INTRODUCTION

DE-795 (Fig. 1), chemical name 5,7-dichloro-4-(*p*-fluorophenoxy)quinoline (IUPAC) and proposed common name quinoxyfen, is a new protectant fungicide with activity specific to powdery mildews. The main mode of action at cellular level in *Erysiphe* is the inhibition of primary appressorial formation. The initial target crops are cereals. DE-795 applied to cereals early in the season (GS 30-32) at a rate of 250 g a.i./ha shows efficacy for 4-6 weeks. A further application (150 g a.i./ha) can be made up to GS 49 to ensure the flag-leaf and ear are protected. One key attribute of DE-795 is its ability to protect new, untreated foliage. In addition to crop exposure some of the fungicide will reach the soil. This paper summarises the findings of studies carried out to provide data for the regulatory assessment of DE-795 and its metabolites on the crop and in the environment, in accordance with Directive 91/414/EEC (Anon, 1991).

Figure 1. Structure of DE-795



WHEAT METABOLISM

Radiolabelled DE-795 was applied (by spraying to run-off) to winter wheat at GS 32 and at a rate equivalent to 250 g a.i./ha. A separate application was made at GS 49 to previously untreated plants. Samples were taken at intervals to maturity for analysis.

Results showed that DE-795 was the major residue in the straw at maturity (up to *c.* 3 mg/kg). The main metabolite ('metabolite A') at up to *c.* 0.5 mg/kg was found in the leaf surface washes and initial straw extracts and was very polar in nature. Acid hydrolysis of 'metabolite A' indicated that it did not comprise of conjugated parent or related compounds. The behaviour during derivatisation and ion-pairing indicated that 'metabolite A' was multicomponent and consistent with it being comprised of small-chain organic acids. Several other metabolites were seen but these were present at very low levels (up to *c.* 0.4 mg/kg in total). One of these matched 2-chloro-10-fluoro[1]benzopyrano-[2,3,4-de]-quinoline (CFBPQ) (Fig. 2), a photolysis product observed in an aqueous photolysis study, indicating that initial breakdown of DE-795 on the leaf surface may be due to photodegradation. The levels of non-extractable residue (NER) in the straw reached up to *c.* 2 mg/kg, although alkaline hydrolysis released the majority of the NER. Enzyme hydrolysis of these extracts indicated that the NER did not comprise conjugates either of parent or related compounds. Further investigation into the incorporation of radioactivity into the natural components of straw concluded that the majority was associated with lignin and cellulose, and therefore likely to be of low toxicological significance.

Mature grain contained total residues up to *c.* 0.06 mg/kg, with analysis showing that the levels of DE-795 were not significant (<0.002 mg/kg). The NER could also be partially released by acid hydrolysis. Investigation into the incorporation of radioactivity into natural plant components concluded that up to *c.* 50% of the total residue found in the grain was associated with starch, indicating that the grain residue is likely to be of low toxicological significance.

In conclusion, the wheat metabolism study showed that DE-795 was the only residue of significance in straw and grain.

Succeeding Crops

The low levels of radioactivity (<0.004 mg/kg DE-795 equivalent) taken up from soil treated with radiolabelled DE-795 into the raw agricultural commodity of turnip, cabbage and sunflower indicated that DE-795 is very unlikely to be taken up by succeeding crops.

RESIDUES IN OR ON TREATED PRODUCTS, FOOD OR FEED

Field trials were undertaken throughout Europe in 1993 and 1994 on both wheat and barley with single and double application treatment regimes. In northern Europe the DE-795 residues in wheat grain were all less than the limit of quantitation (0.01 mg/kg) or not detected (<0.002 mg/kg) for both treatment regimes. The corresponding residues in wheat straw were all <1 mg/kg. In southern Europe a similar pattern was observed in both grain and straw, although in one trial 0.09 mg/kg was found in the grain and 7.22 mg/kg in straw following the double application. Barley is predominantly grown in northern Europe, hence the field trials were only conducted in this zone. The DE-795 residues in barley were consistently higher than in wheat with up to 0.02 mg/kg in grain following a single application and 0.15 mg/kg following the double treatment. The corresponding straw residues were 0.13-3.93 mg/kg and 0.38-5.25 mg/kg respectively. The higher barley residues were possibly due to the faster growth rate (and hence shorter harvest interval) for this crop.

In order to establish acceptable maximum residue levels (MRLs), it is necessary to investigate the potential transfer of DE-795 residues both in cereal process products and all components of the diet derived from livestock. Trials to investigate the effect of processing grain into flour and on the baking of bread were undertaken with DE-795 applied to wheat at double the normal application rate to ensure that a residue could be detected in the grain. However, even at this higher rate only a residue greater than the limit of detection (0.002 mg/kg) but below the limit of quantitation (0.01 mg/kg) was found. The results from the various process fractions showed that the residue was associated with the husk since the fractions containing it (wholemeal flour, finished fine and coarse offals and wholemeal bread) were also found to contain detectable but not quantifiable residues except for the finished coarse offals, which contained a residue at the limit of quantitation. The presence of trace residues did not have any effect on the baking process. Similarly no concentration of residues from barley grain were observed in the brewing process fractions.

Metabolism of DE-795 in the goat indicated that DE-795 was the only significant residue in edible tissues. Allowing for incorporation of barley (as the worst-case) as part of the diet, the estimated maximum exposure of cattle to DE-795 is *c.* 2 mg/kg feed. Maximum residues found in the tissues of lactating cows after 28 days oral administration of 2 mg/kg feed/day were in the peritoneal fat at 0.09 mg/kg which was approximately three times that found in the subcutaneous fat. In liver, kidney and skeletal muscle the residues were all <0.01 mg/kg. The maximum residue found in milk was 0.015 mg/kg with typical plateau concentrations of 0.008 mg/kg reached within 3-7 days, declining to <0.001 mg/kg within four days after dosing ceased. The lipophilic nature of DE-795 also resulted in concentration into the higher fat content milk process products, with a 10-14 fold increase in residues in cream and butter. Skimmed milk showed a correspondingly lower residue whilst yoghurt showed no concentration of the whole milk residues.

A hen residue study using radiolabelled DE-795 with 28 days dosing at 0.1 mg/kg feed, showed that the total residue in edible tissues was <0.01 mg/kg, and 0.003 mg/kg in eggs with DE-795 concentrated in the yolk (0.01 mg/kg).

ENVIRONMENTAL FATE

Soil

Based on laboratory sorption studies, where it showed very strong adsorption (Koc 15415-34985 ml/g, depending upon soil type) and an aged column leaching study using a notional worst-case sandy soil (≤ 0.3% applied radioactivity (AR) in the leachate), DE-795 can be classified as having no leaching potential. The aged leaching study further indicated that the principal soil metabolite, 5,7-dichloro-4-(*p*-fluorophenoxy)-3-hydroxyquinoline (3-OH-DE-795) (Fig. 2), would also have no leaching potential.

Laboratory studies have demonstrated that DE-795 is persistent in soil, with DT_{50} values under aerobic conditions ranging 224-508 days in five soils (DT_{90} 730-1673 days) assuming first-order kinetics. The DT_{50} was not related to soil organic carbon or biomass, with the likelihood of strong soil adsorption reducing the availability of residues for degradation. Eight field dissipation trails performed throughout Europe during 1993 and 1994 confirmed the results of laboratory studies. Formulated material (EF-1186 SC) was applied in a single application to represent maximum soil exposure. The slow rate of degradation was confirmed, with first order DT_{50} values of 123-454 days (DT_{90} 784-834 days). In addition, the strong adsorption observed in laboratory studies was also seen in field samples with >90% of the DE-795 residues present in the top 10 cm horizon. To further evaluate the potential for soil accumulation, five-year field accumulation studies are underway (started 1993) to determine the plateau levels from typical use. Mathematical modelling (PELMO 1.5; Klein, 1993) indicated a plateau concentration of 0.094 mg/kg in the top 30 cm of soil after six years in a realistic worst-case scenario *i.e.* three years use/one year fallow, assuming 50% crop interception.

5,7-Dichloro-4-(*p*-fluorophenoxy)-3-hydroxyquinoline (3-OH-DE-795) was identified as the principal aerobic soil metabolite. In a 200-day laboratory study it did not exceed 8% AR at any time in three agricultural soils, although it reached 27% AR in Speyer 2.2 standard soil (an atypical soil type). Its formation was such that no plateau and decline could be detected in any soil during the study, and so a DT_{50} could not be calculated for the metabolite. The weight of evidence suggests that it is as persistent as DE-795. A minor metabolite, 5,7-dichloro-4-hydroxyquinoline (DCHQ) (Fig. 2), was also formed especially in an acidic soil (pH4.2), reaching 6% AR at 100 days. Non-extractable residue (up to 25% AR) and small amounts of CO_2 (<2% AR) were also seen. 3-OH-DE-795 was detected under field conditions, however, soil concentrations in the top 20 cm from dissipation studies were generally low ($\leq$ 0.01 mg/kg).

The degradation of DE-795 in soil under anaerobic conditions was also slow, with a DT_{50} of 289 days (DT_{90} 959 days), with 3-OH-DE-795 formed as the only metabolite reaching 9% AR at 32 days. Minimal photolysis of DE-795 occurred on the surface of soil, with an estimated DT_{50} of >1 year in natural sunlight (southern England). This indicated that soil photolysis will not be a significant route for the dissipation of DE-795 in the environment when exposed to sunlight conditions typical of northern Europe.

Water and Air

At 25°C in the dark, DE-795 was hydrolytically stable at pH7 and pH9, but slowly degraded at pH4 (DT_{50} 75 days) to give DCHQ. This explained the degradation pathway in acidic soil. More rapid degradation occurred in the presence of light where photolysis DT_{50} values for DE-795 in solution at lat. 52°N (calculated from a measured quantum yield of 0.012) were 1.7 hours in June and 22.8 hours in December, assuming average light intensities and weather conditions (Frank and Klöpffer, 1989). The main degradate was CFBPQ, with DCHQ formed as a minor product.

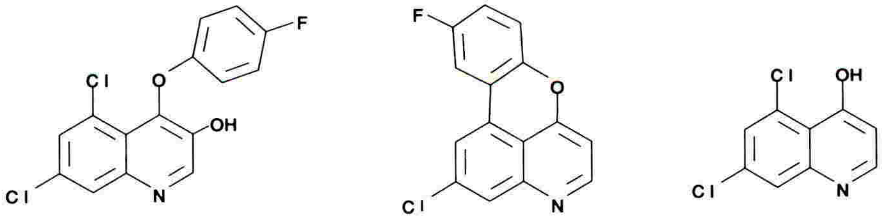
In a water/sediment study in the dark under aerobic conditions (anaerobic in the sediment) DE-795 was moderately persistent with DT_{50} values of 35 and 150 days in sandy loam and clay loam systems (DT_{90} 117 and 498 days) respectively. Rapid partitioning occurred into the sediment such that the corresponding surface water DT_{50} values were 3 and 7 days (DT_{90} 9 and 22 days). 3-OH-DE-795 was slowly formed in sandy loam sediment where it reached 41% AR at 100 days, with only DE-795 indicated in the water. In the clay loam system 3-OH-DE-795 was not found, although an unidentified component was seen in both the water (up to 5% AR) and sediment (up to 7% AR) after 60-100 days. Non-extractable sediment residues reached 14-16% AR at 30-60 days, depending upon sediment type, with no significant CO_2 detected in either system. The results have indicated that if DE-795 should enter water bodies following application, it will adsorb to sediment, thus reducing the relevance of the aqueous photolysis product (CFBPQ), as will the recommended use of a five metre 'no spray' zone for agricultural practice.

DE-795 has been shown to be essentially non-volatile from soil and only slowly volatilised from plant leaf surfaces. Any DE-795 that is volatilised rapidly degrades in air (indirect phototransformation) with a calculated DT_{50} of 1.88 days.

Definition of the Residue in the Environment

Based upon the environmental fate profile, DE-795 and 3-OH-DE-795 are the environmentally-relevant residues in soil and sediment, whilst DE-795 alone is considered the only relevant residue in water and air. DCHQ is not considered relevant in water since it is only seen under acidic conditions (pH4) and so will not form extensively in the environment.

Figure 1. Structure of DE-795 Metabolites



3-OH-DE-795 CFBPQ DCHQ

ECOTOXICOLOGY

DE-795 was shown to have no effect to soil micro-organisms, and only low toxicity to earthworms, birds, bees and other beneficials in the field. For aquatic non-target organisms, DE-795 showed low toxicity to fish but was toxic to *Daphnia* and algae. However, the likely concentration of DE-795 in natural waters, based on data from environmental fate studies, will be reduced by its strong and rapid sorption to soil/sediment, its rapid aqueous photolysis and the label requirement to use a five metre 'no spray' zone to reduce spray drift, for example to ponds and streams.

CONCLUSIONS

In accordance with Directive 91/414/EEC, laboratory and field studies have been carried out to provide data for the regulatory assessment of DE-795 and its metabolites on the crop and in the environment.

The wheat metabolism study showed that only DE-795 formed the residue definition at maturity. There were also a number of low-level metabolites in straw and grain, of which the main 'metabolite' was polar and multicomponent. Further degradation of these initial metabolites resulted in their incorporation into natural plant components, indicating they are likely to have low toxicological significance.

The ADI for DE-795 has been defined as 0.2 mg/kg/day. Using data from the field trials, the proposed MRLs in wheat and barley grain are 0.05 mg/kg and 0.2 mg/kg respectively. The FAO/WHO Cultural and Global Diets for Europe (1993) model was selected to give a worst-case theoretical consumption of DE-795. Even using 0.2 mg/kg as the MRL for both wheat and barley, the highest theoretical intake in an individual country would be Italy at 0.8% of the ADI. The overall worst-case, taking the highest consumption for each commodity independent of country, increased the theoretical maximum daily intake to 1% of the ADI. Other routes of exposure: air, water, meat and dairy products are all insignificant at the levels of residue that are found or are likely to be found in the commodities. In addition, in terms of acute hazard DE-795 is essentially non-hazardous by the oral route. Hence it is extremely unlikely that any European diet will lead to an intake of DE-795 which exceeds the ADI.

In soil, DE-795 and its principal metabolite (3-OH-DE-795) were indicated to have no leaching potential and so will not be a concern for groundwater contamination. In soil and aquatic systems DE-795 is only slowly degraded, although hydrolysis under acidic conditions and aqueous photolysis are more significant processes. However, the low toxicity to soil non-target organisms and other beneficials in the field have indicated that the persistence will be likely to have minimal environmental impact under normal use conditions.

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REFERENCES

Anon. (1991) Official Journal of the European Communities No. **L 230**, 19.8.1991.

Klein, M (1993) PELMO 1.5 - Pesticide Leaching Model, Benutzerhandbuch. Fraunhofer Institut für Umweltchemie und Ökotoxikologie, Schmallenburg, Germany

Frank, R; Klöpffer, W (1989) A Convenient Model and Program for the assessment of Abiotic Degradation of Chemicals in Natural Waters. *Ecotoxicology and Environmental Safety* **17**, 323-332.

POTENTIAL OPERATOR EXPOSURE TO INSECTICIDES: A COMPARISON BETWEEN KNAPSACK AND CDA SPINNING DISC SPRAYERS

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ABSTRACT

Spray treatments were undertaken in cotton and blackcurrants to compare operator contamination when using a high volume Lever Operated Knapsack (LOK) sprayer with hand lance held in front of the operator and a low volume Controlled Droplet Application (CDA) spinning disc sprayer (the ULVA+). Despite using a more concentrated spray mix, the ULVA+ gave significantly lower levels of contamination ($p > 0.001$) in these trials. Most contamination with the LOK sprayer occurred due to operators walking through airborne spray or treated foliage which the ULVA+ technique avoids. Practical suggestions are made to minimise operator contamination with both types of sprayer.

INTRODUCTION

Operators of manually carried sprayers are required to work in close proximity to spray emissions thereby increasing the risk of contamination during the spraying operation. The potential for exposure will largely be determined by the type of sprayer, crop characteristics and practices adopted by the operator and is a critical variable in assessing the degree of risk posed to spray operators during the spraying process i.e.

Degree of Risk = Exposure x Hazard (potential of pesticide to cause harm)

Although manually carried sprayers are widely used in developing agriculture, suitable protective clothing is often not available and is, in any case, frequently impractical for use in hot climates (Tunstall and Matthews, 1965). Furthermore the level of operator training and awareness of the potential risks involved in working with pesticides is often inadequate. This has given cause for concern and a desire to establish safer working practises. The most commonly used manually carried sprayer is the Lever Operated Knapsack (LOK) sprayer with hand lance. The use of such sprayers can, however, be laborious due, in part, to the requirement to fetch and carry large amounts of water to the fields as this often has to be transported some distance, particularly in semi arid regions.

An increasingly widely used alternative to knapsack sprayers in the tropics are battery operated spinning disc sprayers (Cauquil, 1987). These apply minimal volume rates by using relatively even sized droplets of the appropriate size for the target - a technique referred to as Controlled Droplet Application (CDA). Larger drop sizes of around 200-300µm are typically used for CDA herbicide treatments at 10-30 l/ha as a placement technique to avoid drift. For insecticide and fungicide spraying smaller droplet sizes are normally used at volume rates of 1-20 l/ha compared with 150-300 l/ha with knapsack sprayers thus significantly improving workrates. With this technique droplets are dispersed by wind and gravity onto the target surface. Specific Ultra Low Volume (ULV) oil based formulations were initially used (drop size 50-100 µm : volume rates 1-3 l/ha). This technique, however, has now, been largely superseded by Very Low Volume (VLV) spraying using standard water miscible formulations (drop size 75-150µm:volume rates 10-20 l/ha) e.g. over 1.3 million hectares of cotton in West Africa are now treated with the VLV technique. VLV spraying offers improved flexibility allowing for a wider choice of products and control strategies to be employed (Clayton, 1992). As the spray mix is more concentrated than that used with knapsack sprayers, a series of trials were undertaken to assess the levels of operator contamination with each technique.

There are four potential sources of operator contamination during the spraying process:-

- contact during mixing, filling and cleaning
- contact with airborne spray material
- contact with treated vegetation
- contact with leaking or contaminated sprayer parts

This paper discusses trials in cotton in Côte d'Ivoire and blackcurrants in the U.K. using knapsack and spinning disc sprayers. The objective was to examine the contamination occurring under actual field conditions and propose practical measures to minimise this.

MATERIALS AND METHODS

Spray Equipment:

Two types of sprayer were examined, a conventional LOK sprayer with single hand lance and the ULVA+ spinning disc sprayer. The LOK sprayer used hollow cone nozzles with flowrates in the range 500 - 750 ml/min at pressures of ~ 3bar (300 kPa). The ULVA+ was set to produce drop sizes in the range 100-120µm VMD (Volume Median Diameter) using 5 batteries and flowrates of around 150 ml/min as used for VLV treatments (Clayton, 1992).

Field Methodology:

Spray operators were dressed in disposable 'Tyvec' or cotton suits with gloves and face masks and a fluorescent dye incorporated into the spray mix to analyse spray deposits. This dye could be extracted from the various suit sections, gloves and mask filters and the deposit quantified with the aid of a spectrofluorimeter. The experimental techniques used were similar to those outlined earlier in Thornhill *et al* (1995) and Merritt (1989) and comply with recent guidelines issued for operator exposure studies (Chester, 1995).

Simultaneous spray treatments were made with either the LOK or ULVA+ sprayers in mature cotton and blackcurrants of 1.0 -1.4m height. In Côte d'Ivoire spray treatments were made by local farmers in cotton on plot sizes of 400-1000m^2 with the LOK sprayers and 3000-5000m^2 with the ULVA+. The difference in plot size reflects the increased workrate with the VLV technique as spraying started and finished at the same time with each sprayer. Similar plot sizes were used to compare treatments in the U.K on a 5 ha blackcurrant crop. Spray treatments with both the ULVA+ and LOK sprayers were generally made at right angles to the prevailing wind direction. Adjacent plots were separated by at least 20m to avoid any cross contamination. Windspeeds were typically between 0.8-2.2 m/sec for all treatments with temperatures of 25-30° C in Côte d'Ivoire and 18-22° C in the U.K.

Two fluorescent tracer dyes were used during these trials; sodium fluorescein and Helios OB (Ciba-Geigy, Basle, Switzerland). Sodium fluorescein is a water soluble dye and was used at concentrations of 0.5-1.0 g/l with water + 0.1% Agral 90 surfactant for high volume LOK applications and 5-10 g/l in water for ULVA+ treatments. Trials in Côte D'Ivoire also used Helios OB as an emulsifiable concentrate formulation. This allowed qualitative assessments to be made using a UV lamp to illuminate actual spray deposits on the operator. A photographic record of the spray contamination could then be made. For each paired treatment the same fluorescent tracer was always used with each sprayer. Spraying generally took around 5-15 minutes and thereafter spray deposits were allowed to dry on the various suit, gloves or mask surfaces. A sample of the 'tank mix' from each sprayer was taken immediately after treatment and a 100µl of spray solution transferred onto a section of unsprayed material using a micropipette. This sample was left in sunlight for approximately the same period as the spray treatments and subsequently used as a known standard for fluorimetric analysis. Recovery of the spray dye from the various suit sections is generally over 90-95 % (Merritt 1989) although this can depend on the exposure to sunlight, the sample substrate and extraction procedures used. Such variations are therefore minimised by preparing a known standard under similar conditions to the actual samples.

Laboratory methodology:

Spray deposits were extracted from the various materials using either water and 0.02 M NaOH solution for fluorescein dyes or a 90:10 mix of Acetone and Hexane solvents when using the Helios dye. Samples were left for around 1 hour in solution being agitated routinely throughout. A sample of each dye solution was then transferred into a cuvette from which a reading could be taken with a spectrofluorimeter (Sequoia Turner model 450). The instrument was calibrated using known concentrations of dye solution.

RESULTS

Results are expressed as the mean amount of spray material recovered from various parts of the body in µl per litre of spray applied or parts per million (ppm). i.e. as a proportion of the total volume applied. From this a direct comparison of contamination levels can be made irrespective of differences in volumes applied (refer to Tables 1 and 2 and Figure 1).

e.g. A contamination level of 100µl/litre applied = 100 ppm = 0.01%
Thus applying 300g a.i. /ha would theoretically equate to:-
300g x 0.01% = 0.03g or 30mg a.i. on the suit section.

The results in tables 1 and 2 are fairly similar although the levels of contamination were marginally higher in cotton. With the LOK sprayer the majority of contamination occurred on the front of the body, particularly the legs, thighs and lower abdomen. Much of this contamination is due to operators having to walk through the treated foliage and can be avoided in some situations by simply holding the spray lance downwind in the adjacent row (refer to results in Figure 1 with LOK 2 treatments - taken from recent work in Pakistan).

Table 1. Operator contamination in cotton on different parts of the body (µl/litre of spray applied - mean of 6 replicates)

	Body Area (cm²)												
Sprayer Type	Hood (1200)	Mask (172)	R Arm (1350)	L Arm (1350)	Gloves (900)	R Leg (1250)	L Leg (1250)	Rthigh (1900)	L thigh (1900)	F torso (2750)	R torso (2750)	F abdo (3550)	R abdo (3550)
ULVA+													
mean	9.3	0.05	63.1	133.0	33.6	11.9	21.3	13.1	6.1	33.9	30.4	39.7	65.8
Std Dev.	13.2	0.1	80.5	218.2	39.6	8.8	20.4	17.5	8.8	15.2	38.6	54.5	109.3
LOK 1													
mean	45.6	3.2	322.5	191.0	269.4	444.3	416.2	413.3	383.2	209.3	45.7	477.4	139.7
Std Dev.	65.7	1.8	137.8	82.1	69.2	98.0	91.9	116.8	88.7	91.9	36.6	160.3	48.1
LOK 2 *													
mean	1.8	0.7	29.7	76.3	23.6	62.7	42.6	52.6	45.9	60.9	26.2	25.0	38.0

* *LOK 1 treatments with spray lance held in front of the operator- same row*
LOK 2 treatments with spray lance held downwind in adjacent row.

Figure 1. Operator contamination in cotton on different parts of the body - mg a.i /ha. (assumes an applied dose rate of 300g a.i. per hectare))

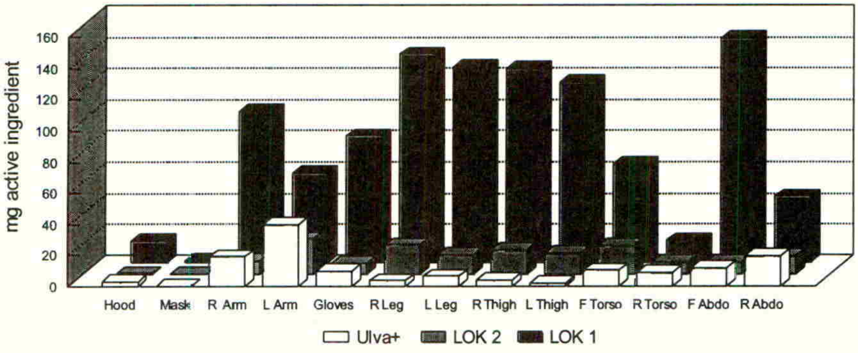

Table 2 Operator contamination in blackcurrants on different parts of the body (µl/litre applied - mean of 12 replicates).

	Body Area (cm²)										
Sprayer Type	Hood (1200)	Mask (172)	R Arm (1350)	L Arm (1350)	Gloves (900)	R Leg (1250)	L Leg (1250)	Rthigh (1900)	L thigh (1900)	F torso (2750)	R torso (2750)	Abdo (7100)
ULVA+												
mean	15.0	1.4	47.0	51.3	29.5	20.1	27.9	18.6	16.1	36.1	24.0	57.9
Std Dev.	31.4	3.3	74.7	93.9	47.0	21.4	31.6	24.9	18.4	56.8	36.7	95.1
LOK												
mean	23.3	1.2	101.8	77.5	75.0	172.4	208.3	309.2	175.8	87.2	12.0	270.9
Std Dev.	33.9	1.5	79.1	47.8	46.1	51.0	123.8	488.2	158.2	42.2	8.9	130.1

Contamination with the ULVA+ sprayer in both trials was significantly lower (P > 0.001) using ANOVA analysis than that found with the LOK sprayer when treatments were made holding the spray lance in front of the operator. Where contamination does occur with the ULVA+ sprayer this is found mainly on the upper part of the body, particularly the arms which are closest to the spray emission.

There is considerable variation between replicates (refer to standard deviations in tables 1 and 2) indicating that operator contamination is highly dependent upon wind conditions and operator use. There was little if any contamination on filter masks suggesting the risk from inhalation to be small with both types of sprayer.

DISCUSSION

Operator contamination studies serve as a useful tool to extrapolate data to assess the potential risks to operators from exposure to pesticides. These can be used in conjunction with other techniques such as analysis of body fluids and models of pesticide absorption .

We can, therefore, draw some useful recommendations from these studies. The most important point is to avoid walking through treated foliage. Contact with sprayed foliage is one of the major sources of contamination with the LOK treatments. Operators of knapsack sprayers should always spray to the side or rear (if possible), standing upwind and ideally should treat the adjacent downwind row to ensure they walk through untreated foliage. The ULVA+ sprayer is intended to be used in this manner where the atomiser head is held 1m above the crop in the adjacent downwind row. This accounts for the considerably lower levels of contamination found with this technique in comparison to the LOK sprayers with lance held in front of the operator. Paying due regard to the wind direction and walking in an unsprayed row should greatly reduce contamination with knapsack sprayers. Another solution to this problem, proposed a number of years ago, is the use of a tail boom to ensure the operator always walks away from the treated foliage and airborne spray.

VLV techniques using the ULVA+ sprayer have been used in a number of areas due to their ease of use and logistical advantages, but successful introduction requires the co-operation of agrochemical suppliers and local extension officers to train farmers in the correct use of this technique. There still remains the potential for misuse with such techniques particularly where the concept of spray distribution using the prevailing wind is not well understood.

These and other studies highlight the need to protect the skin from exposure to pesticides. A common misconception is often that the greatest hazard is due to inhalation of droplets rather than contact with the skin. Contact with pesticides during mixing and filling and handling the concentrate is also a major source of contamination which needs to be considered (Craig and Mbevi, 1993) and highlights the need for appropriate packaging of pesticide products to facilitate measurement and transfer of small doses of pesticides to sprayers. Frequently operators do not have access to gloves hence using soap and water to wash hands after mixing is often the most practical method to minimise pesticide exposure through skin.

The condition of spray equipment, particularly where spray tanks are carried on the back, is also important to avoid leakage onto the operator. Leaking hose pipes, taps and spray lances are also significant sources of contamination which need to be considered.

On the basis of this and earlier studies (Matthews and Clayphon, 1973) it is worthwhile reiterating a number of simple measures to minimise operator exposure to pesticides:-

- Ensure sprayers are correctly maintained and there are no leaks. Read the product label and wear appropriate protection when handling the concentrate.
- Ensure operators protect all areas of exposed skin during spraying using hard shoes or boots with long trousers, long sleeve shirts and hat. In many cases the use of national dress has proved quite acceptable as work clothing in hot climates (GIFAP, 1989).
- Always stand upwind from the point of spray emission and avoid walking through treated foliage wherever possible.
- Use soap and water to wash after handling concentrates and after spraying and immediately remove work clothing for washing.

CONCLUSIONS

Spray treatments with the ULVA+ spinning disc CDA sprayer at Very Low Volume (VLV) rates of application, of around 10l/ha, gave significantly lower levels of operator contamination than comparable treatments at high volumes with Lever Operated Knapsack (LOK) sprayers with hand lance. The majority of contamination with the LOK sprayers was due to operators walking through treated foliage and occurred mainly on the lower front of the body. If possible, holding the spray lance downwind to treat the adjacent row and avoiding contact with treated foliage can greatly reduce the levels of contamination. This is the standard method practised with the ULVA+ sprayer.

REFERENCES

Cauquil, J (1987) Cotton pest control: a review of the introduction of ultra low volume (ULV) spraying in sub-Saharan French speaking Africa. Crop Prot.6 (1), pp 38-42

Chester, G (1995) Re-issued guidance document for the conduct of field studies for exposure to pesticides in use.Proc of Workshop on Methods of Pesticide Exposure Assessment Eds. P.B. Currey *et al.* Plenum Press N.Y. pp 179-215

Clayton, J S (1992) New developments in Controlled Droplet Application (CDA) techniques for small scale farmers in developing countries -Opportunities for formulation and packaging. BCPC Conf. *Pests and Diseases* Vol 1 pp 333 - 342.

Craig, I and Mbevi, C (1993) Hand contamination received by spray operators during pesticide preparation. *Pesticides News* 19, pp. 3-5.

GIFAP (1989) Guidelines for personal protection when using pesticides in hot climates Groupement International des Associations des Produits Agrochemiques. Brussels.

Matthews, G.A. and Clayphon, J.E.(1973) Safety precautions for pesticide application in the tropics. PANS. Vol. 19 No 1, March

Merrit, C R (1989) Evaluation of operator exposure and spray displacement with hand operated herbicide application systems. BCPC conf. Weeds, pp623-630

Thornhill, E W; Matthews, G A and Clayton, J S (1995) Potential exposure to herbicides: A comparison between knapsack and CDA hand sprayers.BCPC conf. Weeds, Vol 3.

Tunstall, J P and Matthews, G.A (1965) Contamination hazards in using knapsack sprayers *The Empire Cotton Growing Review*, Vol XLII, No 3 pp 193 - 196.

ENVIRONMENTAL MANAGEMENT FOR ARABLE AGRICULTURE: AN ECO-RATING SYSTEM FOR PESTICIDE USE

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ABSTRACT

The University of Hertfordshire, funded by MAFF and in collaboration with ADAS and IACR-Rothamsted, is currently developing a computer-based decision support system to encourage and enhance best practice within arable agriculture such that environmental protection can be given a high priority without jeopardising profitability. A significant part of this system is focused towards the use and management of pesticides to ensure that protecting the crop does not conflict with protecting the environment. The software system aims to assess the farmer's use of pesticides. Using a multi-criteria approach, field techniques, pesticide choice and management practices such as storage, waste management and machinery calibration are all assessed. Although the system concentrates on field applications for crop protection, it also examines non-crop pesticides such as biocides and rodenticides. The eco-rating is derived by comparing actual practices with rules and heuristics describing best practice. Simple ranking and scoring techniques are used to derive an indicator of environmental performance which respect to the farmers use of pesticides.

INTRODUCTION

All pesticides in the UK carry mandatory label precautions regarding safeguards that are necessary when using these chemicals so that humans, wildlife and the environment in general are protected. These label precautions are assigned by the Pesticide Safety Directorate within the UK's Ministry of Agriculture, Fisheries and Food (MAFF) based upon comprehensive scientific data supplied by the product manufacturer. If the chemical is used in accordance with these precautions then environmental risk is minimised. Nevertheless, the use of these chemicals and their environmental impact is causing public and governmental concern. In 1994, over 830 pesticide poisoning incidents were registered by MAFF (1995), public concern is rising regarding pesticide residues in fresh produce and the National Rivers Authority recorded around 40 pollution incidents directly attributed to agricultural pesticides during 1993 (NRA, 1994). The UK Government has an established policy for optimising pesticide use and the safe management of these chemicals is given high priority by regulatory bodies (MAFF, 1996).

Compared with many other industries, agricultural practices at farm level are relatively unregulated. Few control procedures are in place to regulate either the quantities of chemicals applied to the land or the application techniques used. The need for the agricultural industry to apply best practice is clearly apparent. The introduction of environmental management systems such as BS7750 marked the beginning of a commitment to environmental management for many industries but not for agriculture. Maybe this is because the costs and effort required to introduce these systems is not seen to balance the few perceived market benefits.

There is substantial information on the environmental fate of pesticides, best practice and on environmental science in general. Guidance to farmers is available in a number of publications (e.g. MAFF, 1993). However, the uptake and implementation of this information appears to be slow (ACBE, 1996). One of the main reasons for this is that effective environmental protection is site specific. No two farms are identical; different crops are grown, various activities undertaken and there will be differences in soil type, underlying geology, climate and the presence of features such as surface water, groundwaters, woodlands and other habitats. Consequently, the general information available is rarely sufficient to allow the farmer to develop a coherent action plan specific to the farm. Much of the problem seems to lie with technology transfer. The information available is often produced by scientists for scientists or for policy makers and not in a format readily suitable for farmers. There is a need for a decision support system available which will help the farming industry distil information and produce a coherent action plan specifically designed for their own farm which will not jeopardise profitability, balancing implementation costs and environmental benefits.

OVERVIEW OF A DECISION SUPPORT SYSTEM FOR ARABLE AGRICULTURE

The University of Hertfordshire is currently developing a computer-based decision support system to encourage and enhance sound environmental management within arable agriculture. Like formal environmental management systems, the computerised system aims to assess current performance, encourage improvements, identify significant effects and determine estimates of emissions in the form of an inventory. Performance is measured by comparing actual practices with what is perceived to be best practice. The major activities of arable agriculture which significantly impact on the environment arise from the improper use of fertilisers, pesticides, from unsustainable soil practices and from changes in land use. Consequently, the system focuses on these areas. However, in order to ensure that whole farm assessments can be carried out and to give a more integrated approach to environmental protection, other modules allow more marginal activities to be assessed such

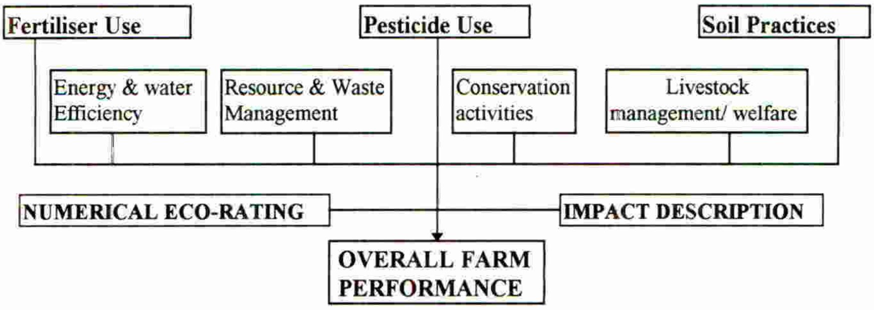

Figure 1: Computer System Structure

as energy and water efficiency, resource and waste management, conservation and the management and welfare of intensively kept livestock. Figure 1 shows the structure of the system. Individual eco-ratings are determined which are weighted and aggregated to give a single index relating to the farm. The system has three modes of operation. The core of the system is the assessment routines. However, in support of this there is a second operational mode known as the '*technical system*' which consists of a collection of modules allowing the user to explore 'what-if' scenarios. The third mode is a fully integrated information system which is context-sensitively mapped to enable quick data identification. Each farming activity (i.e. use of fertilisers, pesticides, etc.) has one or more elements in each operational mode. This paper describes the development of the project with respect to a farmer's use of pesticides. Other aspects of the system are described in previous papers (Lewis *et al.*, 1996a, 1996b)

PESTICIDE ASSESSMENT

Environmental performance with respect to a farmer's use of pesticides is represented within the system by the determination of a numerical eco-rating. Assessment is divided into two main parts: (i) assessment of field by field applications; and (ii) management techniques.

The eco-rating system

Generally, within the system the eco-rating used spans a positive-negative scale. Positive values represent an environmental gain, negative values represent environmental damage whereas the zero point indicates a neutral activity and the threshold of sustainability. With respect to the use of pesticides on arable crops, although there may be financial gains via increased yields and produce quality there is rarely a true environmental gain. Best practice therefore means a zero rating and the scale spans zero to a theoretical negative minimum. In contrast, for example, during the assessment of farmland conservation the selective control of grass weeds in a flower meadow or the careful use of pesticides for aquatic weed control to improve a watercourse would represent a true environmental gain. Therefore the eco-rating for conservation would span the full positive-negative scale.

Field applications of pesticides for crop protection

A database has been established which holds information on over 500 pesticides including insecticides, herbicides, fungicides and adjuvants commonly used in arable agriculture. Data is held by product brand name and information regarding approved crops, active ingredients and their concentrations within the formulation is stored. Also stored are data on maximum approved application rate, maximum number of applications and label precautions assigned by MAFF's Pesticide Safety Directorate derived from toxicity and other data provided by the manufacturer. The bulk of this data was obtained from the 1996 UK Pesticide Guide (Whitehead, 1996).

With respect to active ingredients a range of physico-chemical parameters are also stored which influence the environmental risk. Also stored are expert system rules representing best practice and regulations. Equation 1 is used to derive the pesticide eco-rating P_c. This is determined for each pesticide applied to the crop, weighted by application rate and summed to produce a field value. Each field value is then weighted by field size and aggregated to give a whole-farm value.

$$P_c = f(\mathrm{LR}, \mathrm{SER}) + \alpha\,(\Sigma^{ai} f(E_{ai} \,.\, Q_{ai})) \qquad (1)$$

Where: LR is the score derived from the label hazard relevant to the no-target group SER. α is a scaling factor. E_{ai} is the score derived from assessing the pesticides potential environmental impact based on its physicochemical properties. Q_{ai} is the proportion of active ingredient in the pesticide formulation

The equation has two parts. The function (LR, SER) provides an eco-rating specific to the product formulation. LR represents a value derived from the label precautions. A system of 85 label warnings is currently in use. These can be sub-divided into those effecting different non-target groups (known as 'Sensitive Environmental Receptors or SERs) such as humans, wildlife, bees and aquatic life with some labels falling into more than one group. Each label has been assigned a numerical score representing the level of environmental hazard. An example of this is shown in table 1.

Table 1. Examples of label precautions and assigned weighting values.

Hazard	Caption	Receptor Group	Score
48a	Extremely dangerous to bees...	Bees	- 5
48	Dangerous to bees ...	Bees	-4
47	Harmful to bees ...	Bees	-3
-	*none of the above, no label specific to bees*	Bees	0
51	Extremely dangerous to fish ...	Aquatic	-5
52	Dangerous to fish ...	Aquatic	-4

The scores within each receptor group are then summed and weighted according to the local site variables and conditions under which the pesticide was applied. For example if the field being assessed has surface water close by then the weighting factor attached to the aquatic receptor group would be 5 whereas if no surface water is present the value would be 0. Consequently the site specific risk is more properly represented.

The second part of the equation ($E_{ai} \,.\, Q_{ai}$) is derived from the physico-chemical properties of the active ingredients with the product. The value E_{ai} is calculated for each active ingredient, weighted by the proportion within the formulation (Q_{ai}) and summed. A range of parameters have been chosen to reflect the environmental fate and potential for damage of the active ingredient. These include solubility, vapour pressure and soil half-life. The octanol-water partition coefficient K_{ow} is used to reflect bioaccumulation and the organic-carbon partition coefficient K_{oc} used within the GUS formula (Gustafson, 1989) to represent mobility and groundwater risk. The data for each parameter is classified into one of five risk bands (very high, high, moderate, low and very low) and assigned an appropriate rating value. E_{ai} is determined by summing the parameter scores.

Once all the product values have been derived, practices are compared with regulations and the eco-rating adjusted accordingly. For example, checks are done to ensure that the maximum dose of pesticide and the maximum number of applications have not been exceeded. This methodology allows a complex activities to be assessed including illegal off-label applications, low dose and low volume spraying and tank mixes including the use of adjuvants.

Management practices

The environmental risks associated with pesticide use come not only from applications but also from management practices. These include storage, handling, waste management, application techniques, pollution prevention activities and machinery calibration. Due to the non-quantitative nature of the data a different approach to the one previously described was required to determine the eco-rating. A multiple choice questionnaire is used. This is divided into sections, e.g. waste management, storage, training, protection of field margins and application techniques, and options of both good and bad practices are given each rated according to the perceived environmental risk. The users choices are then assessed, scored on the eco-rating scale and a report produced. A similar methodology has also been used to assess the farmers use non-crop pesticides such as biocides and rodenticides.

The Technical System

The Technical part of the Decision Support System has been designed to assist the user to identify practical, cost-effective ways of improving their eco-rating. A simple module, *'The Pesticide Informer'* has been developed which helps the user identify the most appropriate, approved pesticide for a specific job which will have the minimum environmental impact. Assistance on pesticide waste management specifically waste minimisation and approved disposal of concentrates, dilute solutions and empty containers is available with the '*Waste Management Advisor*' module.

The Pesticide Informer module uses an icon system to highlight any environmental hazard associated with a specific pesticide. For example, if the pesticide presents a high hazard to aquatic species a fish-icon is shown, if a high hazard to bees exists then a bee-icon is displayed. Other icons highlight the hazards to groundwater, birds, wildlife and humans, specifically organophosphates, carbamates and chemicals subject to the Poisons Law. This approach offers the user a simple, visual means of identifying a pesticide which will protect the crop without unnecessarily harming the environment. This module is again based upon the pesticide label precautions assigned by The Pesticide Safety Directorate of MAFF and uses the GUS formula to determine the groundwater risk (Gustafson. 1989).

The Information System

The Information System comprises a large range of text files providing instant, on-line access to a wide range of information relating to pesticides and how to minimise their impact on the environment. Within the Legislation Database summaries of various laws and regulations can be found including: The Food and Environmental Protection Act 1985, The Control of Pesticides Regulations 1986 and the 'Authorisation' Directive. The Codes of Practice Library includes the three MAFF Codes of Good Agricultural Practice and the Pesticide Code of Practice (MAFF, 1990). The Science Library includes a text file presenting a brief introduction on minimising the environmental impact of pesticides.

CONCLUSION

The Pesticides eco-rating system and supporting software described here is part of a more general system designed to be used by consultants and farmers to review environmental performance and to monitor progress towards improvements. The system is broadly comparable with the aims and objectives of the more formal environmental management systems such as the UK's standard BS7750 and ISO14001 in that it helps identify priority areas for action, encourages continuous improvements and allows monitoring towards targets and objectives. With respect to pesticides and crop protection the software helps ensure that the pesticide is selected such that the yield and quality of the crop are protected, that all regulations are met, the local environment is protected and that the risk of causing damage is minimised.

ACKNOWLEDGEMENT

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REFERENCES

Advisory Committee on Business and the Environment (ACBE),(1996) 6th Progress report.

Gustafson, D I (1989) Groundwater Ubiquity Score: A Simple Method for Assessing Pesticide Leachability, *Environmental Toxicology and Chemistry* **8**, pp339-357

Lewis, K A; Skinner, J A; Bardon K S (1996a) A Computerised Decision Making Tool for the Environmental Management of Agriculture. *Proceedings of IAIA '96*, Lisbon.

Lewis, K A; Newbold, M J; Skinner, J A; Bardon, K S (1996b) A Decision Support System for Environmental Management of Agriculture. *Proceedings of Eco-Informa '96*, Florida.

MAFF (1995) Pesticide Poisoning of Animals 1994. *Report of the Environment Panel of the Advisory Committee on Pesticides.* MAFF Publications PB2351, London.

MAFF (1990) Pesticides: Code of Good Practice for the Safe Use of Pesticides on Farms and Holdings, HMSO, London.

MAFF (1993) Code of Good Agricultural Practice for the Protection of Soil. MAFF Publications, PB0617 London.

MAFF (1993) The Governments Expenditure Plans - Departmental Report. 1996

National Rivers Authority (NRA) (1994) Water Pollution: Causes and Control. *Information leaflet.*

Whitehead, R. *Ed.* (1996) The 1996 Pesticide Guide, *CAB* International and British Crop Protection Council, GB.

DEVELOPMENT OF A PESTICIDE DRIFT MODEL FOR ORCHARD AIR-BLAST SPRAYING

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ABSTRACT

A pesticide drift model is being developed for air-blast spraying in orchards. The model is numerically based with major components including a two-dimensional simulation of micrometeorological variables in and around the canopy, a Lagrangian in-canopy droplet transport and deposition module, and a characterization of air-blast sprayer emissions. Initially the model will provide (steady state) estimates of droplet deposition within the canopy and estimates of spray material leaving the canopy. Field trials in a mature pecan orchard in southern New Mexico, USA gathered data for model evaluation. Data collected included information on droplet size, number, and velocity distribution, vertical distribution of tree, stem/foliage area, density, size and orientation of plant canopy elements and vertical profiles of wind field, turbulence, temperature, humidity and radiation. Malathion was used as a tracer for assessment of surface deposition at sites from 54 m upwind to 253 m downwind of the spray line, vertically from ground level to 16.5 m at a distance of 18 m from the spray line and to 33 m height at a distance of 33 m downwind from the edge of the orchard. Rotorods, string collectors, high volume air samplers, filter papers, and magnesium oxide coated slides were used. LIDAR and a thermal scanner were both used to visualize and track the spray cloud.

INTRODUCTION

A number of mathematical treatments of ground and aerially applied spray movement are currently in use. The FSCBG model is a statistical simulation model based on mean flux-gradient treatment of the wind regime and analytical solution of Gaussian dispersion of the

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aerosols (Teske, *et al.* 1993). Walklate (1992) and others have used the same wind field approach but used random-walk routines to disperse the aerosols. Wang *et al.* (1995) used a statistical Lagrangian transport model to simulate the spray transport process. The current status of air-assisted spraying in crop protection was reviewed by Lavers *et al.* (1991).

This research focuses on the development of an improved modeling approach for evaluation and risk assessment of pesticide application to orchards using air-blast equipment. This paper overviews ongoing model development with descriptions of the orchard model components and a discussion of a field study in pecans which gave model evaluation data.

MODEL DEVELOPMENT

The numerical model is being developed under a joint project involving the Univ. of Connecticut, New Mexico State Univ., the Univ. of California at Davis and the Environmental Protection Agency. It is designed to simulate the movement and fate of pesticide spray droplets originating from an orchard air-blast sprayer, interacting with the canopy, and moving above and beyond the canopy edges. The model outputs include micrometeorological information (wind, turbulence, etc.), airborne concentrations, and deposition estimates within and outside of the modeled canopy. The initial model consists of three major coupled modules:

a. A two dimensional canopy micrometeorological module which simulates the wind, turbulence, temperature, humidity and radiation fields within and near heterogeneous canopies.

b. A Lagrangian spray droplet transport module which simulates movement of spray aerosol droplets within and near the canopy, deposition on leaves, twigs and branches, aerial concentration and ground deposition.

c. A sprayer module which simulates the emission of spray from an orchard air-blast sprayer including the spray drop size distribution, drop numbers and drop velocities. The sprayer module also includes the interaction of the spray "blast" with the first row of trees.

The initial version of the model, to be completed and evaluated in this three year project (1994-1997), will predict a steady-state solution of deposition at various locations (x, z) in the canopy and the spray material leaving and re-entering the canopy through the canopy top and the downwind edge.

Required meteorological inputs are solar radiation, wind speed, direction, turbulence, temperature and humidity measured above the canopy or at a nearby weather station. The canopy input description includes plant area index distributions and leaf, twig, branch size and orientation angle distributions.

The initial version of the sprayer module consists of measured mass and drop size distributions emitted by the sprayer as a function of sprayer characteristics. It will also include the penetration of the first row of trees as a function of wind and distance to the trees.

Lagrangian (LS) module for transport within and out of canopy

A Lagrangian random flight trajectory simulation module was developed to describe the transport and deposition of spray droplets in a pecan orchard. The aim of the module is to predict vertical profiles of the aerial concentration and flux, as well as the deposition on plant elements and the ground, of spray droplets from an air-blast sprayer. Results are calculated as a function of downwind distance, *x*, and height above the ground, *z*. The region in space described by the module is bounded on four sides: 1) on the upwind side by a planar surface starting in the "far-field" of the sprayer (taken initially to be in the first interrow downwind of the sprayer, 2) on the downwind side by a plane at a distance of 5 tree heights, $5 \cdot h$, from the downwind edge of the orchard, 3) on the bottom by the ground plane, $z=0$, and 4) on the top by a horizontal plane at a height, $z=2 \cdot h$.

The module requires input data regarding spray droplet number-size distribution at boundary 1, evaporation potential of the spray formulation, vertical distribution of tree stem and foliage area density and their characteristic sizes (e.g., length, width and orientation of leaves), and the calculated wind field and turbulence statistics. The Lagrangian simulation model used to calculate droplet trajectories is adapted from earlier studies (Walklate, 1992, Wang *et al.*, 1995). The turbulent air motion along a droplet trajectory is simulated using a two-dimensional (for a cross-wind, infinite line source) Lagrangian stochastic model based on Thomson's well-mixed criteria (Flesch & Wilson, 1992). Deposition of droplets on the plants and ground is calculated using algorithms based on findings of earlier studies (Aylor, 1975, 1982, Bache & Johnstone, 1992, McCartney & Aylor 1987).

The module uses input information on: spray droplet formulation, the size and orientation of plant canopy elements, vertical profiles of wind statistics, temperature, humidity, and radiation at various distances downwind from the source. The source is spray droplets released along a line from an air-blast sprayer being pulled at about 1 m s^{-1} for a distance of 10 *h* in the direction perpendicular to the average wind direction. The source is approximated mathematically in the model by an infinite line source.

The evaporation component of the LS module assumes that the volatility of the pesticide is negligible compared to water and uses the "hard core model" (Bache and Johnstone, 1992) to predict droplet diameter as a function of travel time. With this simplification, the input to the model is the volume fraction of the pesticide in water. The module can be modified to account for volatility of the pesticide fraction. It also requires as input the initial drop size distribution as a function of height above the ground, i.e., the number of droplets in each size class at the starting grid points at the sprayer.

The LS module assumes that deposition of droplets on plant elements is mainly due to impaction and sedimentation. The probability that a droplet will be deposited is calculated at each time step. This probability depends on the motion of the spray droplet and on characteristics of the plant canopy at location $x(t)$, $z(t)$. Descriptive canopy inputs required by the module are the density, dimensions and angle (with respect to horizontal) of plant elements as a function of height. Other canopy characteristics such as the zero-plane displacement height, *d*, and the roughness length, z_0 are obtained from the measured wind profiles.

Wind field and temperature field

At present the LS module assumes a steady wind field and requires as input, mean statistics as a function of height for U, W (not necessarily zero near an orchard edge), σ_u, σ_w and $<uw>$, the Eulerian time scale (integral of autocorrelation function) and d/dz of (U, σ_u, σ_w and $<uw>$). σ_u and σ_w are (the standard deviations of) the alongwind and vertical wind fluctuations and < > indicates a time average. The required profiles are obtained by fitting data (using nonlinear regression) obtained at the experimental pecan orchard site using 3-D sonic anemometers. The profiles of the wind statistics are continuous and differentiable. It is planned to link the modules and obtain many of the required statistics from the wind field module described in an earlier section.

This version of the LS module assumes spatially constant wet-bulb and dry-bulb temperatures and ignores the effect on evaporation of solar radiation directly absorbed by the droplet.

FIELD EVALUATION

A flood irrigated, mature pecan orchard near Las Cruces, NM, was chosen for the 1996 evaluation studies. The trees averaged 11 m in height and were spaced 9.1 m apart. Studies were conducted in late June and July, at a time when the leaves had fully expanded.

Wind field evaluation

A 23.8 m tower was erected in the orchard upwind of the spray line for collection of micrometeorolgical data for utilization in the spray model as well as the 1-D transilient turbulence model in canopy. Instrumentation was placed at 9 levels: 24.1, 18.7, 16.0, 11.9, 8.0, 6.75, 5.2, 1.5, and –0.01-0.02 m. This included Gill-3D (24.1 m), cup and vane (24.1 m), Wind Master-3D sonic (24.1 m), Campbell 3-D sonic (11.9 m) and ATI-3D sonic (6.75, 1.5 m) anemometers; infrared thermometer (16.0 m); humidity sensors (24.1, 18.7, 16.0, 8.0, 5.2, 1.5 m); Li-Cor quantum sensors (18.7, 1.5 m); net radiometers (18.7, 1.5 m); pyranometers (18.7, 8.0, 5.2, 1.5 m); thermocouples (–0.02 m) and ground heat flux plates (–0.01 m).

Field spray drift evaluation

A single spray line, between the sixth and seventh rows of trees from the downwind edge of the orchard was sprayed in a single pass of a power-take-off driven orchard air-blast sprayer operated at a liquid pressure of 1929 kPa and an exit air velocity of 50 m/s. Travel speed was 0.8 m s^{-1}. Rotorod and rotating magnesium oxide slide samplers were operated between the second and third rows of trees downwind of the spray line at 1.2, 6.6, 11, 13.5 and 16.5 m to provide droplet size and mass fraction for the aerosol transport module in and out of the canopy. Both types of samplers, as well as high volume air samplers, string arrays and ground plates were used over fallow land at 33, 66, 132 and 198 m downwind of the orchard. A combination of towers and a blimp were used with rotorods at 33 m downwind of the orchard to develop a spray cloud profile to 33 m in height to provide data for downwind transport outside the orchard. A total of eleven separate spray trials were conducted under a variety of meteorological conditions.

LIDAR and thermal imaging trials

A laser scanning method called LIDAR (Light Detecting and Ranging) mounted on a 12.2m tower 33m downwind of the orchard was used to visualize the movement of the pesticide spray cloud downwind and above the orchard. In addition a thermal sensor developed by the U.S. Army, termed ATLAS (Bleiweiss, et al, 1992), was used to visualize the aerosol cloud released from the air-blast sprayer.

Canopy characterization

An overall measurement of leaf area index (LAI) within the orchard was made using LiCor LAI 2000 instrumentation. There were two separate LAI determinations, one was an overall LAI of the pecan orchard canopy and the second was a vertical profile measurement. This incorporated vertical 1 m sections through the canopy from the ground to the top of the trees. These measurements were made early in the season, prior to leaf formation and then later in the season when the trees were leafed out, at the time of the spray runs used for model evaluation. This allowed calculation of the leaf material in the canopy. The overall "spatial" LAI for the whole orchard was done at intervals of 10-20 days throughout the growing season, starting before leaf formation.

In addition to the LAI measurements, the trees were photographed prior to leaf formation. Photographs were taken at 1 m intervals from ground level to the top of the canopy, in order to determine the branching structure of the trees. Images of the trees from three angles were incorporated in order to assess the three dimensional structure of the trees. Measurements were also taken to quantify tree morphology. The data included segment lengths, diameters, angles to vertical, azimuth and number of leaves per section. In addition leaves were collected from levels within the canopy and dry weight of leaf material per unit area was measured to estimate mass of leaf material as a function of the canopy height.

FUTURE ENHANCEMENTS

Future versions of the model are planned which will be dynamic, three-dimensional and include data assimilation and long range transport. In addition, the model will incorporate the spatial variation of temperature and humidity.

ACKNOWLEDGEMENTS

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DISCLAIMER

REFERENCES

Aylor, D E (1975) Deposition of particles in a plant canopy. *Journal of Applied Meteorology* **14**, 52-57.

Aylor, D E (1982) Modeling spore dispersal in a barley crop. *Agricultural Meteorology* **26**, 215-219.

Bache, D H; Johnstone, D R (1992) *Microclimate and Spray Dispersion*. Ellis Horwood, Chichester.

Bleiweiss, M P; Howerton, R A; Payne, K C; King, T A (1992) New technique for visualizing three-dimensional flow in the atmospheric boundary layer. *Flow Visualization VI*. Tanida, Y and Miyasiro, H eds. Springer Verlag, Berlin.

Flesch, T K; Wilson, J D (1992) A two-dimensional trajectory-simulation model for non-Gaussian, inhomogeneous turbulence within plant canopies. *Boundary-Layer Meteorology* **61**, 349-37.

Lavers, A; Herrington P; Southcombe E S E eds. (1991) Air-assisted Spraying in Crop Protection. BCPC Monograph No. 46. Proc. Symp., Association of Applied Biologists, BCPC, Univ. College, Swansea, U.K., Jan 7-9 1991.

McCartney, H A; Aylor, D E (1987) Relative contributions of sedimentation and impaction to deposition of particles in a crop canopy. *Agricultural and Forest Meteorology* **40,** 343-358.

Teske, M E; Bowers, J F; Rafferty, J E; Barry, J M (1993) FSCBG: An aerial spray dispersion model for predicting the fate of released materials behind aircraft. *Environmental Toxicology and Chemistry* **12**, 453-464.

Walklate, P J (1992) A simulation study of pesticide drift from an air-assisted orchard sprayer. *Journal of Agricultural Engineering Research* **51**, 263-283.

Wang, Y; Miller, D R; Anderson, D E; Mierzejewski, K; McManus, M A (1995) A Lagrangian transport model of aerial spray transport above an oak forest. *Agricultural and Forest Meteorology* **76**, 277-291.

IMPACT OF LOCUST CONTROL IN A SEMI-ARID ECOSYSTEM IN SOUTH AFRICA

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ABSTRACT

Outbreaks of the brown locust in the Nama Karoo, South Africa are controlled by spot application of ULV formulated insecticides against discrete hopper bands or adult swarm targets. With the phasing out of organophosphates and the recent introduction of deltamethrin (Decis) as the principal chemical used in control campaigns, the impact of deltamethrin on non-target organisms in the Karoo was investigated.

Grasshoppers were selected as invertebrate indicators and in three Karoo biotopes species diversity was monitored for one year in treated and untreated plots at timed intervals after application. Grasshoppers were reduced by 90% in the sprayed plots at 1d post application. However, the vagile and dominant species in the control plots were quick to recolonise the spray plots especially after the chemical residues had degraded. Apterous bushhoppers (Lentulidae and Eumastacidae) took longer to recover because of their poor dispersal ability (low vagility). These species indicate the worst case scenario of the impact of the chemical.

The impact of deltamethrin on reptiles was determined by first monitoring pesticide deposition and residues on hoppers during locust spraying operations. Potential concentration of deltamethrin that reptiles could ingest by feeding on hoppers was then determined from observations on the feeding behaviour of Karoo lizards in the laboratory. Subadult lizards eat a higher mass of locusts relative to unit body weight and are therefore more at risk from ingestion of sprayed locusts than adults, especially at high temperatures during summer. Ingestion of early locust instars poses the most risk to reptiles since more early instars can be eaten than later instars and more chemical may thus be ingested.

INTRODUCTION

Intense outbreaks of the brown locust, *Locustana pardalina* occur almost every year in the Karoo, South Africa. During the past 7 outbreak seasons 1988/89-1994/95, 219 000 hopper bands and 25 600 adult swarms were controlled by ground application of ULV insecticides, using either knapsack or vehicle-mounted mistblowers. Individual bands and swarms of the brown locust are controlled by spot application of insecticide whilst still densely clumped on the morning roost rather than the broad-acre spraying employed during desert locust control.

The impact of insecticide spraying during locust control in the Karoo is largely unknown and growing public concern has increased the need for a more judicious use of insecticides during locust control operations. Following the phasing out of organophosphates and the registration of deltamethrin by the South African locust control organisation in 1992, a study on the impact of deltamethrin on the non-target fauna in the Karoo was undertaken. Deltamethrin has a low toxicity to mammals and birds (Greig-Smith, 1993) but little data is available on the possible effect on non-target invertebrate populations and reptiles in sprayed areas of the Karoo.

Inherent with a comprehensive study of invertebrates in Africa, are problems of species identification, sorting and sampling. However, certain insect assemblages such as grasshoppers can be targeted to serve as indicators of disturbance (Kremen, 1992). Grasshoppers are known to be susceptible to deltamethrin spraying (Everts *et al.*, 1985). They are widespread in the Karoo and form an important component in the diet of many vertebrates in semi-arid ecosystems (Mullie & Keith, 1993). In addition, grasshoppers are taxonomically well described, closely related to the target species and relatively easy to sample. In an experimental approach, the effect of deltamethrin spraying on grasshoppers was monitored in the Karoo.

Reptiles can be exposed to insecticides in the Karoo from direct spray, secondary pick up from vegetation or by ingestion of sprayed locusts. To establish the concentrations of deltamethrin that reptiles could be exposed to, residues of deltamethrin were determined following spray operations in the Karoo. Observations on feeding behaviour on captive Karoo lizards were then undertaken in the laboratory to assess the concentrations of deltamethrin that lizards could ingest. Preliminary results of these field and laboratory studies are presented.

METHODS

Grasshopper sampling

The study was undertaken in the Hopetown district of the Northern Cape Province in the Karoo (30°12'S, 23°49'E) from 1995 to 1996. Three representative Karoo biotopes ranging from grassland (*Eragrostis* spp.) to mixed dwarf Karoo bushes (e.g. *Lycium* spp., *Pentzia* spp., *Salsola* spp.) were selected for the invertebrate study. The area had received good rainfall and was situated in a high frequency outbreak area of the brown locust. In each of the three biotopes, three plots of 0.25 ha (average area sprayed to control hopper bands) were sprayed with deltamethrin, whilst 3 closely situated upwind plots of the same size, served as controls. Using "Solo" knapsack mistblowers, a 7g/ℓ UL formulation of deltamethrin was applied by the South African locust control organisation, at a volume rate of 2.5ℓ/ha to give the registered rate of 17.5g a.i./ha.

Grasshoppers were sampled along 5 line transects (50 x 1m) in each of the 18 plots using a visual flushing technique (Samways & Moore, 1991). Grasshoppers were initially collected and identified using published keys (Dirsh, 1965) or by comparison with national reference collections. Individuals flushed in the transects were identified to species. Unidentified species were given a pseudonym and later collected and identified. Voucher specimens were housed in the national reference collection. The abundance of apterous cryptic bush-hopper species was determined by individually searching bushes and vegetation in each plot for 10 minutes. Data from all 9 treated and untreated plots were pooled for analysis. Grasshopper censuses were undertaken at 1, 17, 27, 64, 106, 254 and 362 DAT. Sprayed vegetation was cut from sprayed plots at 1, 6, 17, 27 and 64 DAT and deltamethrin residues analysed using high performance liquid chromatography (HPLC).

Pesticide residues

Locust control operations were monitored in the Prieska district of the Karoo in February 1996. Dead 3-5th instar locust hoppers were collected after spraying and frozen for analysis. Residues of deltamethrin on dead hoppers were determined by gas chromatography (GC) equipped with electron capture detection (ECD).

Lizard experiments

The common Karoo lizards, *Pedioplanis lineoocellata* and *P. namaquensis* were captured in the field and kept in a terrarium in the laboratory where the maximum feeding capacity per day of these lizards was determined. Individual lizards were starved for 3 days and then constantly supplied with a known mass of brown locusts for one day. The mass of brown locusts eaten by each individual was calculated by subtracting the mass of surviving locusts from the supplied mass of locusts. A total of 21 replicates were made using four nymphal instars (2nd-5th) of the brown locust.

The concentration of deltamethrin that lizards could ingest was calculated using the equation:

Mean conc. deltamethrin per dead locust X maximum hopper weight consumed per lizard (1).

RESULTS

Grasshoppers

Grasshopper numbers were initially reduced by 90% in the sprayed plots but showed gradual recovery, until 64 d post application when numbers in treated and untreated plots were similar and chemical residues had disappeared from the sprayed plots (Fig. 1). Thereafter, grasshopper populations naturally declined over autumn and winter but increased after the next summer rainfall at 362 d post application. Total abundance of grasshoppers in treated plots was, however, lower than in untreated plots at 362 d post application (Fig. 1). Nevertheless, species richness was equal and the Sorenson similarity index showed an 80% similarity in species composition between control and sprayed plots. Species diversity of apterous bush-hoppers (Lentulidae and Eumastacidae) took longer to recover than any other grasshopper species and only fully recovered after rainfall stimulated hatching the following summer (Fig. 2).

Chemical residues

The mean concentration of deltamethrin residues measured by GC on dead 3rd and 4th instar hoppers collected in the field was 0.16 mg/kg.

Lizards

Lizards fed on both dead and live hoppers in the laboratory. Smaller lizards consumed a higher

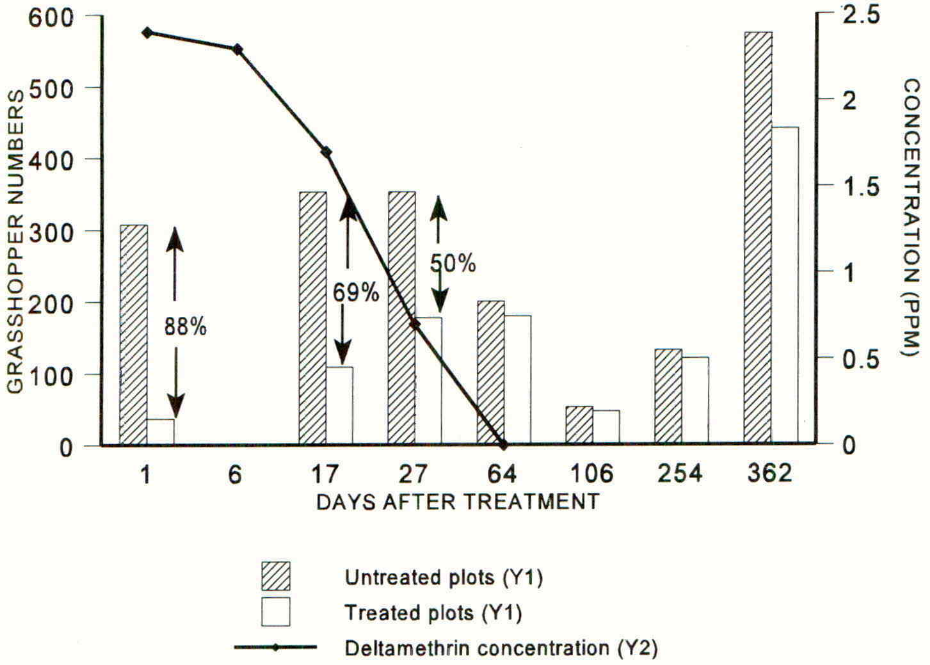

Figure 1. Recovery of grasshopper populations and degradation of deltamethrin at various DAT.

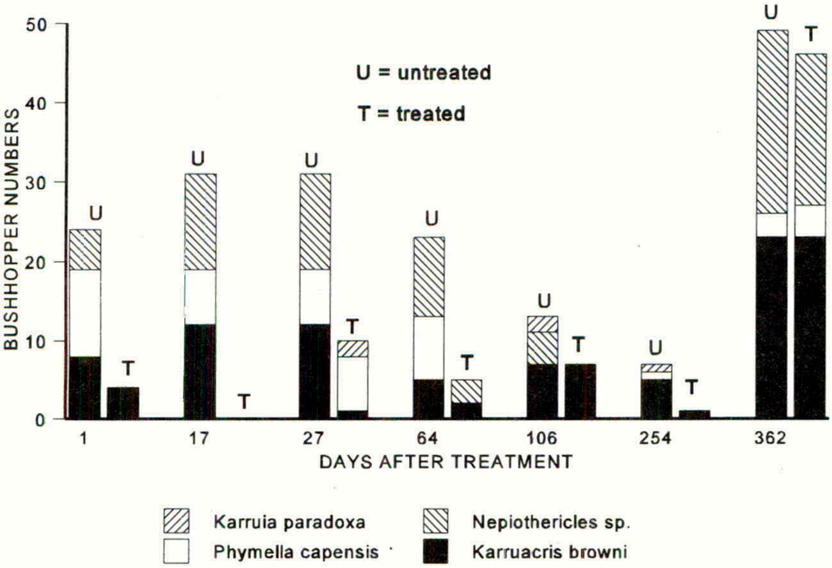

Figure 2. Recovery of apterous bushhopper species at various DAT.

mass of locusts per unit body weight especially at higher basking temperatures (Fig. 3). The mean mass of hoppers consumed by lizards for all instars was 0.38 g (range: 0.30-0.52 g; S.E. 0.014; n=21). Greater numbers of second instar nymphs were consumed than 3rd, 4th and 5th instars. The maximum mass of 3rd and 4th instars that lizards consumed in a day was 0.47 g. Therefore, from Equation (1), the max. concentration of deltamethrin that a lizard would have ingested from feeding on 3rd to 4th instars after control operations was calculated as 0.0752 mg. Mean lizard body weight was 2.15g and therefore, lizards could ingest a max. dose of 34 mg/kg.

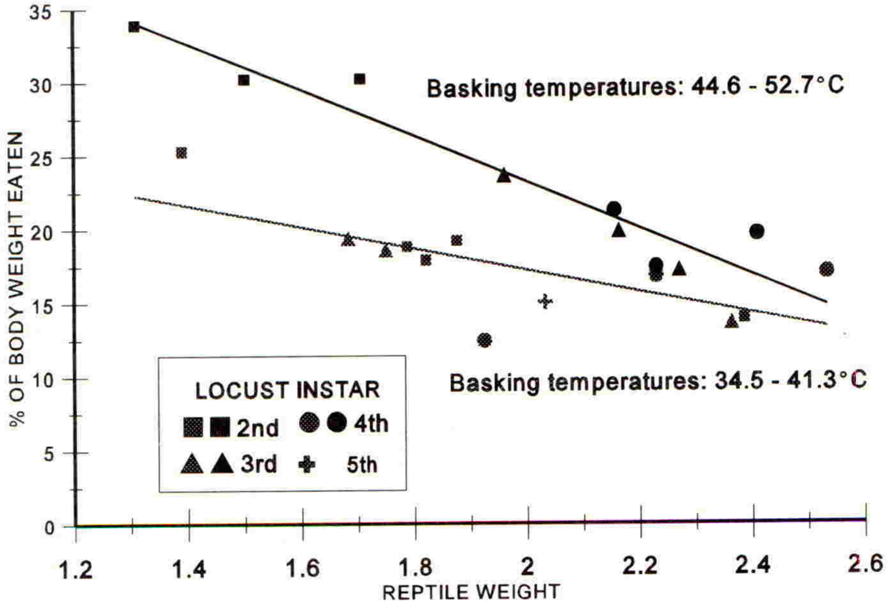

Figure 3. Relative food intake in relation to basking temperature and body weight of two *Pedioplanis* lizards.

DISCUSSION AND CONCLUSIONS

Due to the small size of treated areas during locust control operations, grasshoppers recovered fairly rapidly from the surrounding unsprayed areas especially once deltamethrin had degraded. However, the apterous bushhoppers took longer to recover because of their low vagility. These species could only recover after a full season once rainfall had stimulated new hatching. The timing of spraying relative to rainfall may, therefore, be an important factor in determining the time these species take to recover. Immature or newly emerged populations of apterous bushhoppers sprayed immediately after rainfall, may take longer to recover than more mature reproductive populations sprayed immediately before rainfall stimulates new hatching. The difference in abundance between treated and untreated plots at 362 d post application is unlikely to be a treatment effect since species richness and composition were very similar.

Preliminary laboratory studies show that lizards can potentially eat sprayed hoppers, alive or dead, in the field. Subadults can consume more weight of hoppers per unit body weight than adults and are therefore likely to ingest higher concentrations of chemical in proportion to their body weight by feeding on sprayed hoppers. Since lizards can eat more early instars than late instars, they have the potential to ingest relatively higher concentrations of chemical by feeding on early instar hoppers. However, the dose that lizards ingest may also depend on the relative chemical deposits found on the different locust instars. Therefore, to assess the highest risk to reptiles during locust control operations, the focus should be on subadult reptiles especially those eating early instar locusts. However, most control in the Karoo is directed at 4-5th instars because nymphal bands generally reach 4th and 5th instar stage before control campaigns are fully operational.

Experiments to verify the risk to lizards from ingestion of the max. calculated Decis concentration are currently underway and drift and deposition concentrations will also be used to assess the risk to selected birds and mammals.

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REFERENCES

Dirsh, V M (1965) *The African genera of Acridoidea*. The University Press, Cambridge.

Everts, J W; Kortenhoff B A; Hoogland H; Vlug H J; Jocque R; Koeman J H (1985) Effects on non-target terrestrial arthropods of synthetic pyrethroids used for the control of the tsetse fly (*Glossina spp.*) in settlement areas of the southern Ivory Coast, Africa. *Archives of Environmental Contamination and Toxicology* **14**, 641-650.

Greig-Smith, P W (1993) Killing with care - can pesticides be environmentally friendly? *Biologist* **3**, 132-136.

Kremen, C (1992) Assessing the indicator properties of species assemblages for natural areas monitoring. *Ecological Applications* **2**, 203-217.

Mullie, W C; Keith, J O (1993) The effects of aerially applied fenitrothion and chlorpyrifos on birds in the savannah of northern Senegal. *Journal of Applied Ecology* **30**, 536-550.

Samways, M J; Moore S D (1991) Influence of exotic conifer patches on grasshopper (Orthoptera) assemblages in a grassland matrix at a recreational resort, Natal, South Africa. *Biological conservation* **57**, 117-137.

EFFECTS OF DIMETHOATE ON GROUND BEETLES IN SEMI-FIELD ENCLOSURES: A MARK-RECAPTURE STUDY

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ABSTRACT

The feasibility of using mark-recapture techniques to assess the effects of dimethoate on the density and mobility of the carabid beetles, *Harpalus rufipes, Pterostichus madidus* and *P. melanarius,* was investigated in semi-field enclosures within a spring wheat crop. The distribution and probability of recaptures of individually-marked beetles were used to estimate survival, recruitment, and rate of displacement. The technique provides a useful semi-field method to study acute toxicity and sub-lethal effects of pesticides on mobile, medium-to-large sized epigeal arthropods.

INTRODUCTION

To promote natural pest control and to minimize the impact of agricultural practices on the environment, pesticide registration processes now take account of side-effects of pesticides on beneficial and other non-target arthropods but standard methods to assess these effects in the field are still in their infancy. Any quantitative assessment of the impact of pesticides on the population dynamics of these arthropods needs to be based on reliable estimates of population density and dispersal.

Field studies of ground beetles, which form part of the natural enemy complex suppressing pest outbreaks, are usually based on data from pitfall trap catches. Pitfall traps provide a relatively cheap and efficient means for catching mobile and cryptic epigeal arthropods, but their catch is influenced by the beetles' density, catchability and mobility, and can only provide a relative measure of abundance. Sublethal effects of pesticides on the mobility of beneficial arthropods may influence the subsequent pitfall trap catch as well as the long-term fitness of populations surviving pesticide applications. For a clear understanding of the impact of pesticides on population processes there is, therefore, a need to distinguish between induced changes in density and changes in mobility.

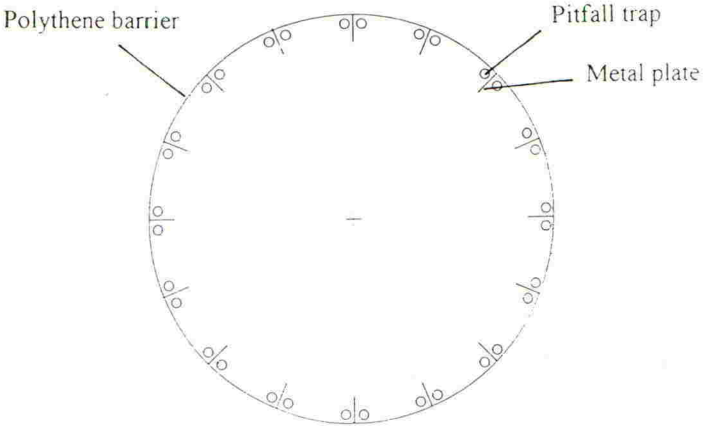
Mark-recapture methods can be used to estimate both population densities and mobility. The ratio of marked to unmarked individuals caught in traps, after release of known numbers of marked individuals into a population, can be used to estimate population size and, if the sampling area can be defined, population density. Mark-recapture studies performed within enclosures, over relatively short periods, are both geographically and demographically defined. This simplifies the estimation of population density and permits the use of relatively robust mark-recapture models. In addition, the number of recaptures over a period of time and their distance from a release site can be used to calculate a probability of recapture and be used as an indicator of displacement rate.

This paper describes a mark-recapture study performed within circular enclosures to investigate lethal and sub-lethal effects of the organophosphorus insecticide dimethoate on several medium-to-large carabid species, at natural population densities. The study was intended as a preliminary investigation to demonstrate the feasibility of the technique to determine pesticide-induced changes in population density (survival and recruitment) and displacement (Kennedy & Randall, in press).

MATERIALS AND METHODS

The mark-recapture study was conducted in June and July 1995, within two circular enclosures in a 5.1 ha field of spring wheat at Rothamsted. Each enclosure was at least 30 m from the field edge, 10 m in diameter and, between mid-May to August, had a boundary formed by a polythene barrier extending 0.3 m both below and above the soil surface. A total of 32 pitfall traps were placed in pairs along the inside of each barrier at equidistant intervals (Fig. 1). Each pitfall trap consisted of a 60 mm diameter plastic beaker sunk into the ground, inside a section of drainpipe, with its upper rim flush with the soil surface and covered by a raincover made from an inverted flower-pot saucer. Metal plates, 75 mm high and 500 mm long, radiating from the barrier towards the centre of the enclosure, were pushed into the ground between the two traps of each pair to facilitate the capture of ground beetles.

Fig. 1. Diagram of a circular enclosure illustrating the positions of pitfall traps relative to the polythene barrier.



Pitfall traps were opened on 5 June and checked daily until 28 July 1995. All medium-to-large ground beetles caught were given an individual-based mark by scratching their elytra with coded values, highlighted with enamel paint, similar to the method described by Thomas (1995). Marked beetles were released in the centre of the enclosures within which they were caught, on the same morning that they were collected. No additional beetles were added to the enclosures, nor were beetles 'stock-piled' for release before the study. This avoided changes in natural population densities which could lead to subsequent changes in the behaviour of individuals. Recaptures were similarly re-released within each enclosure and all recapture data (single and multiple recaptures) were considered in the analyses. Only data for the three most abundant ground beetles, *Harpalus rufipes, Pterostichus madidus* and *P. melanarius*, are presented in this paper.

On 5 July 1995, enclosures were sprayed with either water (enclosure A) or dimethoate (enclosure B). Dimethoate was applied at the manufacturer's recommended field rate (840 ml in 200 l water/ha; 336 g a.i./ha) and water was applied at the same rate (200 l/ha). No other insecticides were applied to the enclosures or to a 20 m surround. All other agrochemical inputs to the field and the enclosed plots followed normal farm practice.

Densities, and their standard errors, were estimated using a weighted mean Petersen estimate (Begon, 1979). Separate population estimates were derived for the four-week pre-treatment and the four-week post-treatment periods. In addition, for the post-treatment period, separate estimates were calculated for the subpopulation known to have been present before treatments were applied (marked before 5 July; 'survivors') and the subpopulation marked since treatments were applied ('recruits'). The significance of a difference between density estimates was calculated using Bartlett's pooled estimate of variance and Student's t-test.

Mean individual daily recapture rates were determined assuming that the probability of recapture of an individual on any given day follows a geometric distribution. The following were found to be adequate estimates of the mean daily probability of recapture and its standard error:

$$P(r) = \frac{R}{D} \qquad\qquad SE_{P(r)} = \sqrt{\frac{R(D-R)}{D^3}}$$

where $P(r)$ is the mean individual daily recapture rate, $SE_{P(r)}$ is its standard error, R is the total number of recaptures within a sampling period and D is the total number of days available for recapture after initial release of individuals within a sampling period. Differences in recapture rates were tested for statistical significance using Bartlett's pooled estimate of variance and Student's t-test.

RESULTS

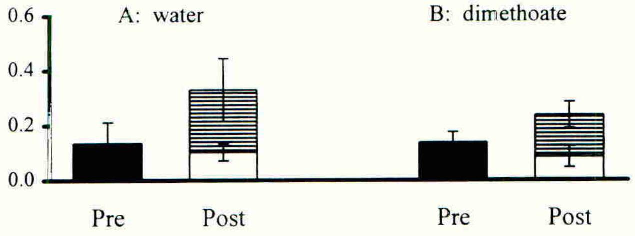
A total of 142 individuals of the three species were marked and released during the eight week duration of the study. *Pterostichus melanarius* dominated, forming 46 % of individuals marked, followed by *Harpalus rufipes* (29 %) and *P. madidus* (20 %). Nearly all individuals (at least 73%) estimated to have been present, either pre-treatment or post-treatment, were marked and released within each four-week sampling period.

Densities, survival and recruitment

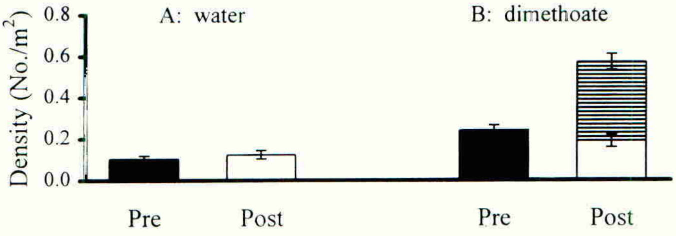
Density estimates varied greatly between species, enclosures and sampling periods (Fig. 2). Significant ($p < 0.05$) pre-treatment differences between enclosures were observed in density estimates of both *P. melanarius* and *P. madidus*. Post-treatment 'survivor' density estimates were, with one exception, lower than pre-treatment estimates and the ratio between the two was used as an index of survival between the two sampling periods (Table 1). All species had a greater survival index in the water-treated enclosure A than in the dimethoate-treated enclosure B, but comparisons of pre-treatment and post-treatment 'survivor' population densities revealed no significant differences within enclosures and no significant interaction between enclosures and sampling periods. Recaptures of ground beetles marked after treatments were applied were used to estimate recruitment. Substantial recruitment of *P. melanarius* was estimated in the dimethoate-treated enclosure B but no recruits were found in the water -treated enclosure A. No significant differences in recruitment between enclosures were determined for either *H. rufipes* or *P. madidus*.

Fig. 2. Estimated densities, and their standard errors, of pre-treatment (filled), post-treatment 'survivor' (open) and post-treatment 'recruit' (hatched) populations of three carabid species in circular enclosures.

(a) *Harpalus rufipes*



(b) *Pterostichus melanarius*



(c) *Pterostichus madidus*

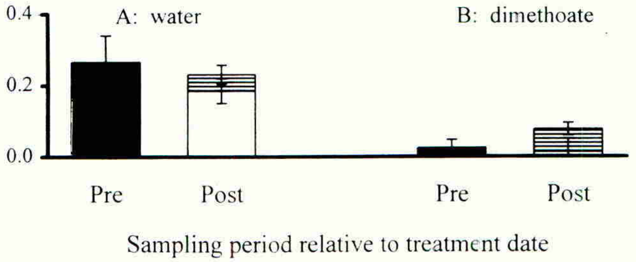


Table 1. Survival indices (post-treatment "survivor" density/pre-treatment density; ± SE) of three marked species in water- (A) and dimethoate-treated (B) enclosures.

	A water	B dimethoate
H. rufipes	0.762 ± 0.493	0.624 ± 0.326
P. melanarius	1.206 ± 0.263	0.787 ± 0.151
P. madidus	0.693 ± 0.230	0.500 ± 1.563

Recapture rates

Pre-treatment recapture rates were generally consistent across enclosures but varied greatly between species (Table 2). No significant differences could be determined between sexes and data were pooled for subsequent analyses. *Pterostichus melanarius* were recaught the most frequently, and *H. rufipes* and *P. madidus* the least frequently.

Table 2. Mean daily recapture rates (± SE) of individuals of three marked species in water- (A) and dimethoate-treated (B) enclosures during pre- and post-treatment sampling periods.

		A water	B dimethoate
H. rufipes	pre-treatment	0.049 ± 0.013	0.070 ± 0.018
	post-treatment		
	"survivors"	0.097 ± 0.033	0.073 ± 0.036
	"recruits"	0.075 ± 0.032	0.122 ± 0.035
P. melanarius	pre-treatment	0.227 ± 0.030	0.214 ± 0.020
	post-treatment		
	"survivors"	0.216 ± 0.033	0.160 ± 0.029
	"recruits"	–	0.261 ± 0.023
P. madidus	pre-treatment	0.046 ± 0.013	0.043 ± 0.043
	post-treatment		
	"survivors"	0.140 ± 0.027	0.000
	"recruits"	0.075 ± 0.036	0.165 ± 0.040

"Survivors" of all species were recaught less frequently in enclosure B than in enclosure A, but only significantly so for *P. madidus*. Recapture rates of "recruits" were generally greater in enclosure B than enclosure A and, again, significantly so only for *P. madidus*.

DISCUSSION

This preliminary study demonstrates the feasibility of using mark-recapture techniques within enclosures to estimate simultaneously changes in carabid population densities and displacement rates following pesticide applications. In addition, the distinction between 'survivors' and 'recruits' during the post-treatment sampling period permitted levels of survival and recruitment to be estimated. Without this distinction, changes in density due to recruitment result in underestimates of mortality. Lack of replication in this study, other than replication through time and by individuals, prevented the separation of treatment effects from effects of enclosure location but, nevertheless, demonstrated the suitability of the methodology.

Density estimates made using a weighted mean Petersen index are based on a number of assumptions (Begon, 1979) including the assumption that there are no births (or immigration) and no deaths (or emigration) within the population. Enclosing populations using physical barriers reduces immigration and emigration, and conducting mark-recapture studies over short periods of time ensures that the effects of mortality remain negligible. Further, by determining separate and independent density estimates for pre- and post-treatment sampling periods, any bias caused by acute mortality following pesticide applications is avoided.

Significant pre-treatment differences in population densities between enclosures highlighted high spatial variability in ground beetle abundance and emphasised the importance of measuring treatment effects relative to pre-treatment populations. Spatial variability in recruitment may further confound interpretation emphasising the need for suitable replication.

Sublethal effects of pesticides can lead to alterations in behaviour of beneficial arthropods, disrupting mate location, foraging behaviour, dispersal and predator avoidance, and can therefore influence their long-term population dynamics. Sub-lethal effects can be measured quantitatively soon after exposure through detailed analysis of locomotory behaviour. In this study, the probability of recapture was used as a crude estimate of displacement rate. Displacement rate is influenced by both the speed and pattern of movement and, consequently, provides a useful summary statistic of mobility.

Mark-recapture techniques employed within enclosures provide a useful means of determining the side-effects of pesticides on mortality, recruitment and displacement, and so provide an insight into the likelihood of subsequent population recovery. Such studies, combined with laboratory and field studies as well as data on the population dynamics of individual species, permit a greater understanding of the impact of chemical pest control on non-target arthropods.

ACKNOWLEDGEMENTS

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REFERENCES

Begon, M (1979) *Investigating animal abundance: capture-recapture for biologists.* London: Edward Arnold.

Thomas, C F G (1995) A rapid method for handling and marking carabids in the field. *Acta Jutlandica* **70**, 57-59.

Kennedy, P J; Randall, N P (in press) A semi-field method to assess the effect of dimethoate on the density and mobility of ground beetles (Carabidae). *Acta Jutlandica.*

SESSION 10

PRECISION FARMING – II. MAKING DECISIONS ON INPUTS

Chairman	Mr J R Finney *British Crop Protection Council, Farnham*
Session Organiser	Dr S Parkin *Silsoe College, Bedford*

AN INFORMATION SYSTEM FOR PRECISION FARMING

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ABSTRACT

The management of variability lies at the heart of precision farming. Three forms of variability have become apparent, spatial, temporal and predictive. Spatial variability can be seen as changes across the field, temporal variability shows up as changes from year to year, and predictive variability is the discrepancy between the predicted and actual values. Firstly the variability must be measured, then understood before management becomes practical. Furthermore, the development and adoption of coherent strategies and practices (some of which are presented) are seen as fundamental to the success of Precision Farming. To support this process accurate and timely information is needed as well as a new generation of arable software.

INTRODUCTION

The management of variability is the keystone to effective use of Precision Farming technology. Three forms of variability have been identified; spatial, temporal and predictive. Spatial variability is the variation seen across the field. It can be easily seen in any yield or soil map. Whether the spatial variability is significant, is something the manager must decide, but nearly all yield maps have a characteristic low yielding boundary around the edge of the field. Temporal variability can be seen when comparing yield maps from year to year, again significance must be deduced, but trend maps can be developed to show underlying features. Predictive variability, is where assumptions in the future are made but not realized. To be able to choose the appropriate levels of inputs, assumptions must be made as to the expected crop yield. If that yield is not reached then those assumptions could perhaps have been improved.

To be able to manage these types of variability, we first need to understand them and before we can understand them we need to measure them. Each phase has different information needs.

As Precision Farming is more complex than traditional management, a systems approach must be taken to allow the full potential use of the different technology adoption levels (Blackmore et al. 1994). This leads to an integrated, coherent set of management options, right from the purpose of running the farm, down to the actual field operations.

MEASURING VARIABILITY

Spatial variability can be measured by recording factors at precise locations. Yield maps are produced by fitting a yield monitor to a combine harvester to know the amount of grain harvested at any particular time. A Differential Global Positioning System (DGPS) is used to record the actual position in Eastings and Northings. A similar system is adopted for soil sampling, except that the samples are collected manually and sent away to the laboratory for analysis. This triplet data can then be filtered, converted and presented as a contour map, showing the spatial variability (Blackmore 1996). See Fig. 1

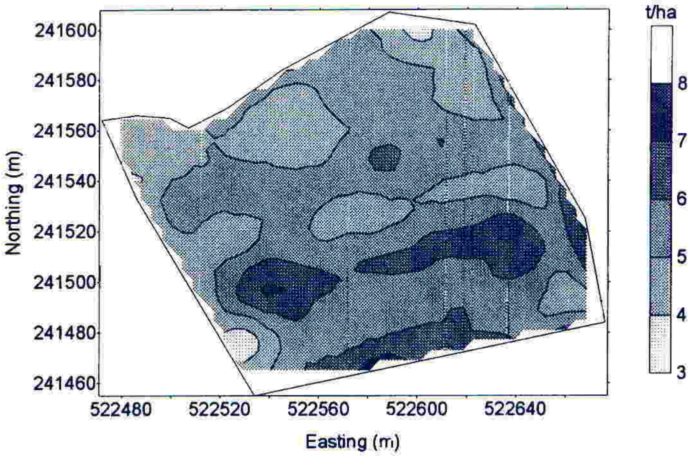

Figure 1. Yield map of Farhighlands field, Shuttleworth Farms 1992

Temporal variability can be seen by comparing a number of maps that have been recorded over time. Fig. 2 shows such a series from 1992 to 1995. Note that the crop is winter wheat except for 1994 which is beans

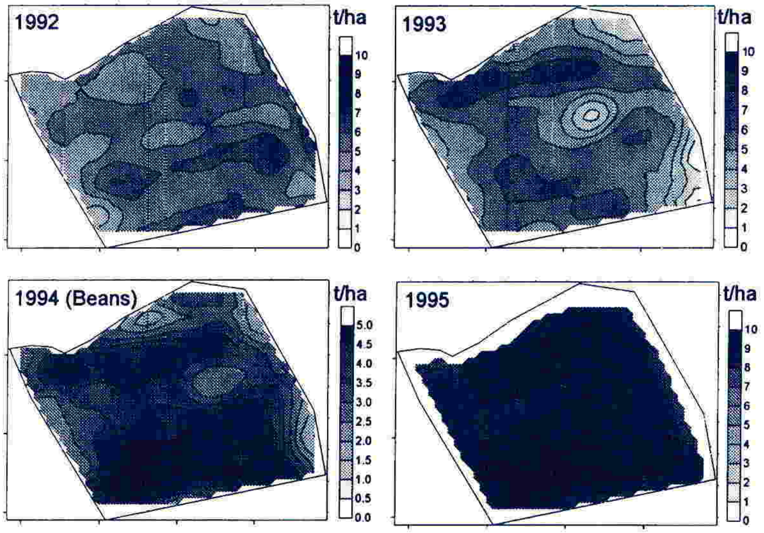

Figure 2. Yield maps of the same field from 1992 to 1995

Predictive variability can be assessed by measuring the difference between the expected values from the crop and the actual values achieved. The most common values are productive area, yield and quality. The over-estimation of the drilled area of crop leads to expected margins that are significantly different from actual ones, as does the over-prediction of yield based on only the best areas. Yield quality is difficult to assess until the later growth stages, but crop quality factors can be measured as shown in the chlorophyll map in Fig. 3.

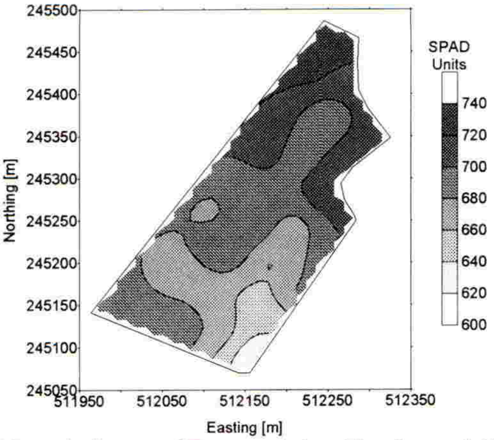

Figure 3. Chlorophyll map of Farsweetbrier, Shuttleworth Farms 1996

UNDERSTANDING VARIABILITY

Variability within the harvest is quantified by the yield map and causal factors are sought to explain the reasons why certain areas only produce a low yield. To help understand the reasons for the variability, methodologies are being developed and within those methodologies certain software tools are also being developed.

Understanding spatial variability

To be able to understand some of the spatial aspects the temporal trend must be removed to show the underlying or stable characteristics of the field. Figure 4 has been produced from the data set of Fig. 2. (Larscheid and Blackmore 1996) This shows that throughout the years of 1992 to 1995 area marked 'Low' has been yielding consistently very low, while area 'High' has been yielding consistently very high.

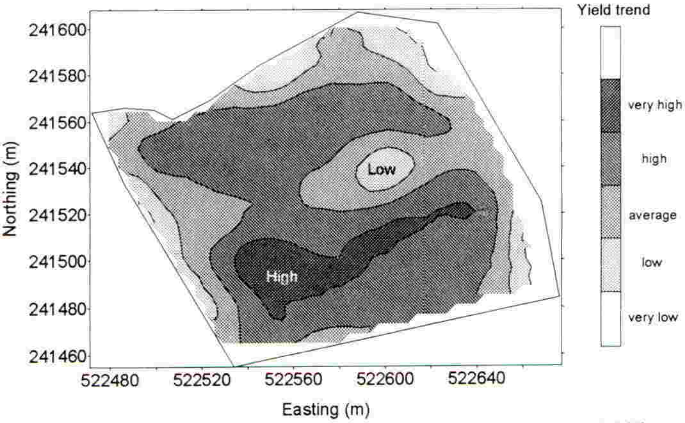

Figure 4. Yield trend map showing consistent spatial variability

When variability of a yield map is noted, the question arises as to the cause of the variation. As the fields are usually treated uniformly, a limiting factor is sought. This is the precept of Von Liebig's principle. ('The yield of a crop is limited by the nutrient in shortest supply')

There are two main types of spatial variability, local maxima and minima within the field (Low and High Fig 4.) and the decreased yield usually found round the edges of the field, which can be attributed to different edge effects.

Anecdotal evidence suggests that major edge effects can be attributed to pests (such as rabbits or deer), large trees (shading and moisture deficit) and compaction (turning on the headlands). The localized highs and lows can be attributed to many other factors such as brows and dips, reduced soil depth, blocked drains, etc. In essence, physical factors should be considered first followed by chemical factors. Sampling of these points can give an indication of absolute values that can be compared with expert guidelines. A better technique would be to take a transect between points Low and High with regular samples that can be used comparatively as the high yielding area by definition has minimized the constraints. This can be compared with the low yielding area and it may be possible to identify the limiting factors.

Understanding temporal variability

Temporal variability compounds the complexity of spatial variability as each area within the field can change from year to year. If data is collected over a number of years, they can be amalgamated into a trend map (shown in Figure 4), which removes the temporal variability. Alternatively a temporal trend map can be created that identifies those areas that that have consistently increased or decreased over the time period. (Fig 5.)

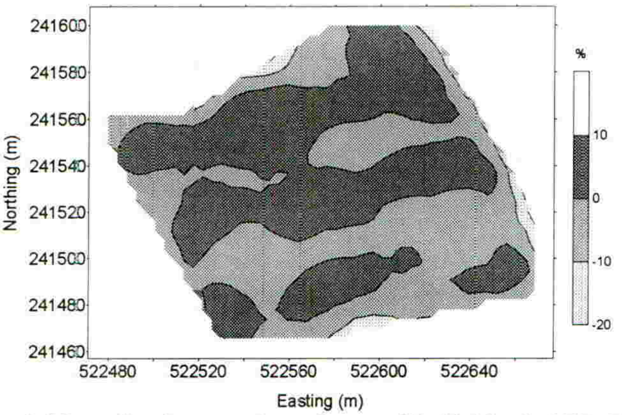

Figure 5. Normalized temporal trend map of Farhighlands 1992-1995

Understanding predictive variability

Predictive variability describes the differences between what was predicted and what actually happened. This can take many forms such as the weather, the expected yield and the prices for the coming year. Over-estimation of future yield is one of the biggest errors in this category (Anon 1994). The use of assessment techniques during the growing season may well give the information required to understand why predictive variability is so prevalent. The major factors can be accounted for by more accurate measurement and record keeping. Remote sensing may be able to also shed some light on problems at an early growth stage.

MANAGING VARIABILITY

There are three levels of decision that can be taken on the farm; Strategic, Practice and Operational. Strategic decision making will only occur occasionally from year to year and will affect the whole purpose of the farm enterprise and is likely to be personal to an individual manager. Three identified strategies are; (Blackmore et al. 1994)

- Yield protection with high physical inputs,
- Reduced inputs with optimal return and low environmental concern
- Reduced inputs with high environmental concern

Many farmers will say that their main purpose is to make money, but that is too simplistic, sustainability and environmental issues are becoming more important. Practices are the management options that apply to a particular sector. Operational elements describe the particular field operations.

To be able to manage variability, an understanding of the cause of the variability is needed. Hence the need for personal strategies, farm practices and field operations.

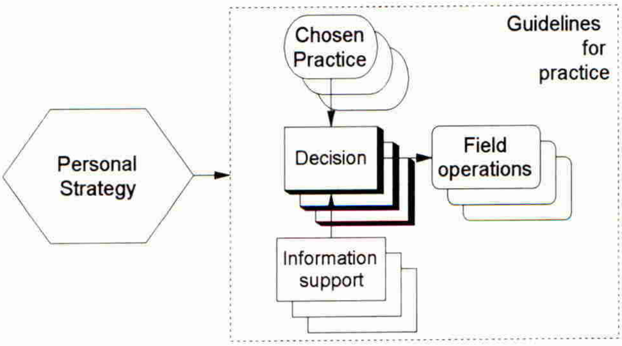

Figure 6. Relationships between Strategy, Practice and Operation.

Personal strategies

There are many different factors that must be taken into account when formulating a strategic approach, including balancing the economic returns with the environmental impact and amount of risk envisaged.

Strategies could include such concepts as, Best Management Practices, Integrated Crop Management and Integrated Pest Management, Minimal Crop Risk, Minimal Financial Risk and Environmental Protection.

Spatially variable farm practices

Four spatially variable groups have been explored. They are; Fertiliser, Spray, Cultivation and Seeding. Within those groups individual practices have been identified. No value judgment is expressed as to the adoption of any particular practice - that is reliant solely on the manager.

Five fertiliser practices have been identified so far; Maximize Yield, Maximize Return, Replenishment, Nutrient Balance and Organic.

1. Maximize Yield is perhaps the first practice identified by most farmers, but this infers just that - maximize the yield without regard to other constraints. This practice would then try to maximize the yield on all parts of the field according to the predicted yield requirements. The information support for this practice would probably be based on an established yield model.

2. Maximized Return will try to optimize inputs based on their relative costs for the expected returns. This is a more sensible approach as it takes into account the causal factors for the variability and the remedial costs. Consider the problem of a low yielding area within a field. Under the Maximize Yield practice more fertiliser should be applied to attempt to bring up the yield. This will tend to work as long as the yield in this area is being limited by the available nutrients. If it is not limited by fertiliser (waterlogging for example) then that extra fertiliser would be wasted. Under Maximized Return fertiliser would be reduced on these low yielding areas that have unmanageable causal factors. This approach improves the overall efficiency and hence the economic returns and environmental impact. The information support would be based on the yield model as well as the economic model

3. Replenishment is where fertiliser is applied to the parts of the field in direct proportion the crop taken in that area. This can be assessed from the previous years yield maps. The application map then tends to be the same shape as the yield map. The information support would take the form of yield maps and established recommendations.

4. Nutrient Balance is the practice adopted by many farmers in North America and has recently been introduced by some companies in the UK. Nutrient Balance is where soil samples are taken across the field and assessed for their nutrient levels (usually as maps). They are then compared with the established recommended levels for the predicted yield. The difference between the two gives the fundamental application map, which can then be modified before application by a spatially variable spreader. This practice is quite simplistic and requires information support from soil sampling and established recommendations.

5. Organic practices may also be adopted as it is likely that the same spatial variability will be encountered. Information support will come from traditional practices and field histories.

The best use of spatially variable spraying is likely to come from the application of herbicides and not fungicides as they tend to be too temporally volatile for adequate management.

Five spray practices have been identified. Maximized Yield and Maximized Return have the same justifications as in the fertiliser practices, but have different connotations and information requirements here. As sprays tend to be used to reduce crop loss (as opposed to increasing crop yield, as with fertiliser) the risk of crop (and hence financial) failure becomes more pronounced when reducing the overall input. Therefore, risk management plays an important part in most of the spraying practices.

1. Maximized Yield implies the use of techniques to minimise the risk of crop failure and will utilize blanket prophylactic treatment of the field. Information support comes from historical trends.

2. Maximized Return tries to optimize the input for best returns but has a more defined procedure for assessing and managing the potential risk. Information support will use various models and a risk assessment process.

3. Crop Protection is similar to Maximized Yield but tries to ensure that the maximum survival of the crop or minimized competition from weeds, occur. Little information support is needed as blanket over application would be used to minimise risk to the crop.

4. Minimum Operations prioritizes the number of field operations to such an extent that the number of spray operations are reduced to a minimum. Information support could take the form of a linear programmed economic model that included the tractor costs.

5. Minimum Input would use the least amount of spray but may incur the maximum risk. These decisions would rely on a sound forecasting methodology.

Four cultivation practices have been identified; Minimum Tillage, Selective Cultivations, Conventional Cultivations and Soil Protection.

1. Minimum Tillage will tend to minimise the number of operations. Models would be used that incorporate machine costs.

2. Selective Cultivations uses combinations of machines to give a required seedbed. Machine characteristics and a knowledge of the soil would be needed to make these decisions.

3. Conventional Cultivations take the form of primary and secondary tillage, often with little regard to the actual resulting tilth. Again knowledge of the machine properties and soil characteristics are required.

4. Soil Protection addresses the problems encountered from erosion and tries to minimise this impact. Knowledge of the soil type, climate and field topography are needed.

Four Seeding practices have been identified; Maximized Return and Maximized Yield are the same options as before, as is Soil Protection.

There may be an opportunity to use Varietal Mix that can utilize the spatial micro-climates to their full extent by changing seed varieties in different parts of the field. A knowledge of the varietal characteristics and field conditions are needed.

<u>Spatially variable field operations</u>

Spatially variable operations require equipment that can vary treatment spatially. Equipment for spraying, cultivating and seeding are all available in prototype form, although fertiliser application is currently available as equipment or as a service.

All of the spatially variable operations are defined by treatment maps that show the segmented areas of the field and the treatment type or rate of application. The field equipment controller can then implement the managerial decision based on the desired treatment map. A record should be kept by the controller of what actually happened in the field (as an actual treatment map) as this may be different from what was desired. This in itself can be a very useful piece of information.

CONCLUSIONS

Precision farming is the process of managing variability, which in turn, improves the overall efficiency of the agronomic process. This improved efficiency is beneficial to the farm both economically and environmentally. Many new information technologies are becoming available to assist in this process but without the adoption of coherent strategies and practices, the full benefit cannot be realized. A systems approach is needed to develop the methodology for adopting and using these new technologies into a recognized best management practice for precision farming.

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REFERENCES

Blackmore, B S; Wheeler P N; Morris R M; Morris J; Graham J (1994) Information Technology in Arable Farming. *Report for Scottish Natural Heritage; TIBRE Project.*

Blackmore, B S; Marshall, C J (1996) Yield Mapping; Errors and Algorithms. *Presented at: 3rd Internation Conf. on Precision Agriculture.* June 23-26 1996 Minneapolis USA. Sponsored by ASA, CSSA, SSSA, ASAE, ASPRS & Univ. of Minnesota.

Anon (1994) *Farmers and Farming; Business strategies, Budgeting and cash-flow,* p15, Midland Agriculture.

Larscheid, G; Blackmore B S (1996) Interactions Between Farm Managers and Information Systems with Respect to Yield Mapping. *Presented at: 3rd Internation Conf. on Precision Agriculture.* June 23-26 1996 Minneapolis USA. Sponsored by ASA, CSSA, SSSA, ASAE, ASPRS & Univ. of Minnesota.

TOWARDS THE INTERPRETATION OF YIELD MAPS

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ABSTRACT

Yield mapping systems can provide detailed retrospective information on crop performance, but without some interpretation this is of little practical use. Interpretation, however, is a complex problem since many factors - pests, diseases, weeds, nutrients, soil physical conditions and management - may limit crop yield. It is shown that complex information on yield variation contained in yield maps for successive seasons can often be generalised to a few simple patterns of between-season variation (including consistent high yield) which occur in reasonably well-defined regions of the field. Automated pattern recognition procedures are used for this purpose. It is likely that one or a few related factors limit crop yield within such regions. Such regions may form the basis for defining distinct management units within the field. They may also be used for stratification to reduce the costs of diagnostic sampling to detect specific problems.

INTRODUCTION

Yield mapping has attracted considerable interest in the farming industry with the development of commercial systems for combine harvesters incorporating a sensor to measure grain mass flow and satellite positioning technology (eg. Stafford *et al*, 1996). However, the practical usefulness of data on yield variation within fields remains to be fully established. It is the contention of this paper that yield maps will be useful in so far as they can be interpreted. A possible framework for interpretation is proposed.

Two important facts about yield maps are taken as axiomatic, and some implications of these are considered.

The variation shown in a yield map represents combined effects of many factors

Many factors can determine crop yield, and many of these are spatially variable (notably soil conditions and the distribution of pests, diseases and weeds). Spatial variation of these factors results in yield variability, but also has the more subtle consequence that the factor(s) limiting yield differs from point to point. Thus, for example, soil pH is possibly limiting on yield, and is also spatially variable. However, variation in pH will not be important in those parts of the field where yield ultimately is limited by the effects of late-season drought. This has important consequences. Consider a particular input, currently applied uniformly across the field, which corresponds to a factor (possibly) limiting on yield. Certain low-yielding regions of a field may be limited by this factor and require a higher rate of the input. Other low-yielding regions may be limited by other, intrinsic factors (eg. poor soil structure) and so the rational response would be to reduce the input. Certain high-yielding regions of the field may still be limited by the factor in question so merit a higher rate. Other high-yielding regions may be limited by a different factor (eg. available water) and would not be affected by some reduction of the rate of input. In summary, the ideal treatment map for a given input does not necessarily correspond simply to the yield map or map of potential yield under uniform application. Understanding of the causes of observed variation is needed if an appropriate treatment is to be specified. This is true, of course, of any other source of information on crop performance (such as remote sensor measurements made during the season to aid management).

Yield maps are retrospective information

The discussion above shows that it is difficult to determine how a farmer could have achieved optimum use of inputs during a season given the variations expressed in the resulting yield map. It is still more difficult to use one or more yield maps to determine a management strategy for the following season with different (and unknown) weather, a different (and unknown) burden of pests, diseases and weeds and, possibly, a different crop variety or even species.

Stafford *et al* (1996) report weak correlation between yields at sites within a field in successive years for a single crop species. This implies that the yield map (under uniform treatment) for one season is not a very good indication of expected yield variation for the following season (under uniform treatment). This casts doubt on the possibility of using one or more past yield maps to derive a simple map of yield potential.

Implications

In summary, yield maps will only be useful in so far as they can be interpreted to produce more general information on limiting factors within a field. This information will form a background to the interpretation of data on the development of the particular crop being managed.

An interpretative framework is now proposed. It was suggested above that spatial variation of environmental factors within a field means that the factor or factors limiting yield differ from place to place. It is proposed, as a hypothesis, that crop yields will show similar variation between seasons (due to seasonal differences in weather and management) within regions where the same factor or factors are generally limiting on yield. If this hypothesis is true, then even though simple correlations between yield maps of a field are weak, it will be possible to identify sets of sites in the field within which yield variation between the seasons is similar, and these sets of sites will correspond to location where the same factor or factors are generally limiting.

This paper presents a preliminary study to investigate the hypothesis above. A computerised method of pattern recognition was applied to a set of yield maps of an experimental field in order to identify any regions within which similar between-season patterns of variation could be identified. The resulting regions were then compared to a mapped pattern of soil series in the field to see if they correspond to underlying causes of yield variation.

MATERIALS AND METHODS

Yield maps were used from three successive harvests (on Cashmore field, Silsoe Research Institute) in which the crop was winter barley managed conventionally with uniform application of inputs (see Stafford *et al*, 1996). In addition local weather records (precipitation and Class A pan evaporation) and a soil series map were available.

The data set for each harvest comprised estimates of yield for areas 10 m long (in the direction of the combine pass) and 4 m wide, with associated co-ordinates. The data sets were searched to identify all sets of spatially corresponding yield estimates for all three years (allowing a tolerance of 5 m). Yield values for each season were standardised to zero mean and unit variance. Cluster analysis was then carried out using the FCM algorithm of Bezdek *et al* (1984).

A map showing the class of maximum membership was generated from these data. The map of classes of maximum membership was overlaid on the map of soil series. The class of maximum membership and the soil map unit were then recorded for 500 randomly located sites in a contingency table. The association between these categories and between clusters and soil parent material was tested by a chi-squared approximation.

This produces a "fuzzy" classification of the data. A number of distinct patterns (here, of between-season variation in yield) are recognised among the observations. These patterns are termed "class centres". The degree of resemblance of any one observation to a class centre is measured by its "membership" in that class. An observation may therefore have a membership greater than zero in more than one class, but most closely resembles the class in which it has greatest membership.

RESULTS

The class centres are shown in Figure 1. The standardised yield values corresponding to the centre of each class are shown for each year. Figure 2 shows a map of the cluster of maximum membership at points across the field. Figure 3 shows the cumulative deficit of pan evaporation over precipitation at the ends of successive months in each of the three years.

In one class (3) the centre elements correspond to above average yields in all three years (and the highest of all clusters in 1995). Another class (1) has centre values corresponding to the highest yields in 1993 and 1994 but the lowest in 1995. The behaviour of this class might be tentatively related to the seasonal differences in evaporation/precipitation balances, suggesting that class 1 represents the limiting effect of dry conditions in Spring and Summer 1995.

Table 1 shows the contingency table for soil series (as mapped) and the cluster of maximum membership at 500 locations. The top figure in each cell is the number of locations corresponding to it and the lower figure is the standardised residual from the expectation under a null hypothesis of no association (Minitab, 1988). A positive residual indicates an association.

Table 2 shows the χ^2 statistic for the full table (sum of squared standardised residuals) and the p value for the null hypothesis assuming an approximation to χ^2. The same statistics are shown for the cluster/soil parent material table. χ^2 for this statistic is a component of that for Table 1.

There is strong evidence that the cluster of maximum membership is significantly associated

Figure 1. Centres of four fuzzy classes.

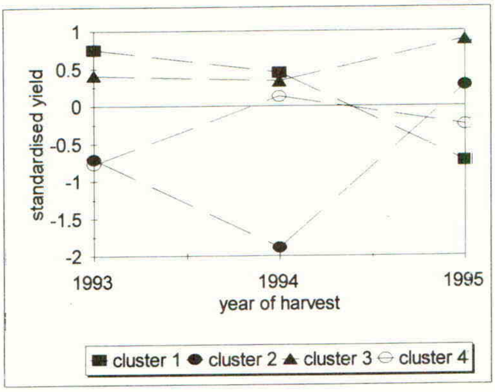


Figure 2. Map showing cluster of maximum membership.

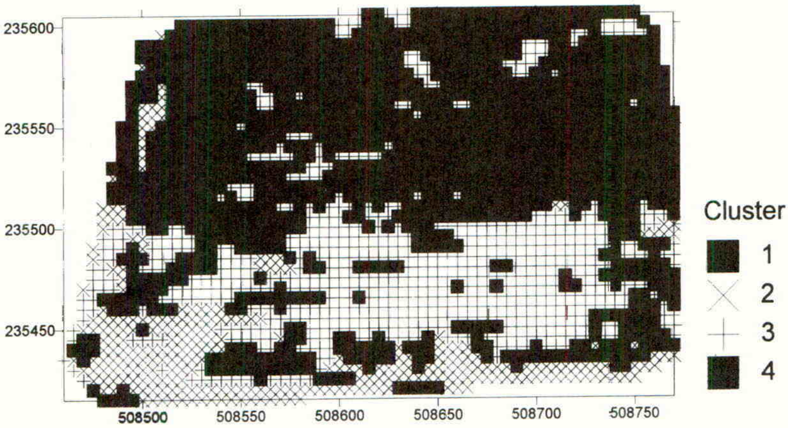
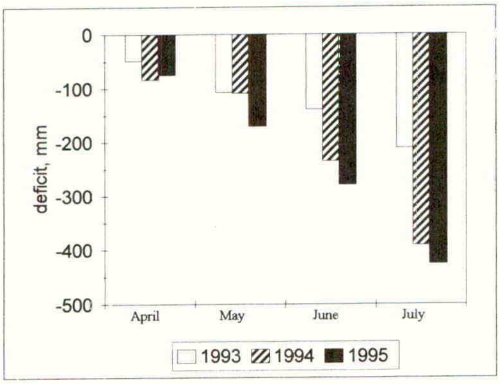


Figure 3. Cumulative evaporation/rain deficit at month end



with soil series and that this is primarily explained by the association with soil parent material (χ^2 for the combined table is 90% that of the full table). Having rejected the null hypothesis for clusters/parent material, association of clusters and series *within* each parent material was tested (see Table 2). A null hypothesis of no association is accepted for series over alluvium and over Lower Greensand but rejected for series over Gault Clay.

The tables for parent material and series within parent material are not shown. However, the former indicates an association of clusters 1 and 4 with series primarily over the Lower Greensand and 2 and 3 with the series over the other materials. Within Gault Clay, clusters 2 and 4 are associated with the Evesham map unit and cluster 3 with the Bardsey unit.

Table 1. Cashmore field. Contingency Table of Soil series and Cluster of maximum membership for 500 random locations.

Figures in italics are standardised residuals under a null hypothesis of no association. Positive residuals indicate a positive association.

		Parent Material						
		Lower Greensand			**Gault Clay**		**Alluvium**	
		Soil series						
		Lowlands	**Hallsworth**	**Nercwys**	**Evesham**	**Bardsey**	**Enborne**	**Fladbury**
Cluster of maximum membership	**1**	97	9	33	4	10	3	0
		4.1	*0.6*	*2.7*	*-2.7*	*-3.2*	*-3.9*	*-1.5*
	2	3	1	0	9	8	26	5
		-4.0	*-1.0*	*-2.6*	2.0	*-0.3*	*7.2*	*5.0*
	3	30	1	10	17	54	28	2
		-3.7	*-2.2*	*-2.1*	*1.2*	*6.1*	*2.1*	*0*
	4	75	13	24	15	13	10	0
		1.7	*2.2*	*0.9*	*0.4*	*-2.5*	*-2.3*	*-1.5*

Table 2. Results of χ^2 analysis on Table 1 and combined and sub-tables.

Null hypothesis:	**χ^2**	**degrees of freedom**	**P**
No association of cluster of maximum membership with:			
soil map unit	251.4	18	<0.001
map units grouped by parent material	226.4	6	<0.001
Soil map units over:			
Lower Greensand	6.5	6	0.17
Gault Clay	10.8	3	0.01
Alluvium	3.2	3	0.16

on fuel and maintenance. Clearly, if the current system is inefficient, spending money on a precision farming system will not correct those inefficiencies.

Precision farming influences the costs of production rather than the responses to those inputs. The breakdown of those costs for winter wheat and potatoes is as follows:-

Table 1. Crop production costs (Murphy 1996)

		Wheat		Potatoes	
		£/ha	%	£/ha	%
Variable Costs					
	Seed	51.8	6.99	501.4	18.16
	Fertiliser	67.1	9.05	176.9	6.41
	Sprays	118.8	16.03	366.3	13.27
Sub Total		237.7	32.07	1,044.6	37.84
Fixed Costs					
	Labour	95	12.82	418	15.14
	Machinery	202	27.25	415	15.03
	Rent	121	16.32	117	4.24
	Sundries	85.5	11.54	765.7	27.74
Sub Total		503.5	67.93	1,715.7	62.16
Total Costs		741.2	100.00	2,760.3	100.00

From the above, it would appear that of the costs associated with crop production, precision farming has the potential to reduce the variable costs. In the case of wheat, these represent 32.07% of the total and for potatoes 37.84%. If it were possible to make an overall saving of 15% of variable costs, in wheat this would mean £35/ha and in potatoes, £156/ha.

Fixed costs will increase substantially as follows:-

Table 2 Costs of equipping a 320 hectare farm for precision farming

	£	£
Soil Mapping	10,500	
GPS on combine	7,000	
GPS data reader	1,500	
Differential correction	1,200	
Crop software	2,000	
Smart controls for sprayer, spreader, and drill	2,500	
Total		24,700
Annual cost of depreciation		7,950
Cost per ha		24.84

The above assumes that soil nutrient mapping is carried out every three years and the machinery is depreciated over five years using a straight line method. The costs of the sprayer, spreader and drill are the add-on costs of the spatially variable technology. No allowance has been included for repairs and maintenance of the equipment.

Clearly, on a 320 hectare arable farm at £24.84 per hectare, the savings look to be within the bounds of achievement whether there are potatoes or not. This compares well with the suggested target of a 15% saving in variable costs.

If in time, the initial costs of the equipment fall by 25%, the comparable figure would be an annual cost of £22.31 per hectare and a requirement to save 9.39% of variable costs for an all wheat farm and 6.59% for the same farm with 40 ha of potatoes. Assuming a 15% variable cost saving on the same basis, the break even farm size would be 288 hectares for an all wheat farm.

RISK MANAGEMENT FACTORS IN PRECISION FARMING

In precision farming, the risks are as follows:-

1). How do yields vary, if at all, with spatial variation of inputs?
2). How much is it possible to save on inputs?
3). Will earlier savings incur added costs later?
4). What are the effects of seasonal changes in weather patterns?
5). What yield penalties can be avoided by saving on inappropriate pesticide applications?
6). How much influence has the inherent variation of the farm.

Many successful farmers are those who in managing their businesses have minimised their risk. In the past, this has been achieved by applying insurance sprays, using generous amounts of nitrogen fertiliser and being over supplied with labour and machinery. With the technical, economic and social trends outlined earlier, it is questionable whether risk minimisation will continue to be viable and we must substitute these physical inputs with better management.

As farming becomes more and more complicated with increased demands from external influences, for example planning, health and safety and highways legislation, there will be further demands made on managers. In order to be able to fulfil the decision-making processes associated with producing the crops, there has to be some way of reconciling these competing demands.

It is for these reasons that we need to develop robust management decision tools referred to above and to know whether financial benefits are consistent in unpredictable weather within and between seasons.

The above figures appear to be a salesman's dream. However, they assume that the targeted cost reductions have no effect on yield. We do not yet know whether spatially varied inputs result in the same yield as the crop would have produced if the inputs had not been varied. The calculations only concern themselves with costs and benefits in the form of cost savings. If in fact the yields were to vary due to input variation, then output factors would need to be brought into the equation. For example, it has been suggested by a number of sources that reducing inputs to low output areas will make savings, but what if those low output areas produce even lower outputs as a result of reduced inputs or vice versa for areas of higher potential?

A further factor is that when more closely matching crop inputs to perceived requirements, unforeseen variations in climate increase the risk to the crop when compared with current commercial practice. For example changes in disease status when weather patterns vary within the normal range.

Similarly, when a precision farming path is being followed through a season, there are management questions in dealing with the effects of significant changes to weather patterns on crop development. Earlier decisions on crop inputs such as nitrogen may turn out to be inappropriate after the opportunity to make changes has long passed. So far, most of the experience is from the recent relatively favourable seasons in the last few years. It will be important to know what to do if there is a sudden increase in pest or disease pressure or a sudden flush of weeds when suitable growth stages for spraying had been passed or adverse weather prevents pesticide applications.

On the positive side, there may have been many occasions when sub-clinical damage to the crop has occurred by the application of a spray in unsuitable weather conditions or because it was a ‘hot’ chemical and precision farming methods may enable savings to be made here once these situations can be identified.

CONCLUSION

Although farming is now increasingly competitive, the interests of farmers, consumers and the environment have converged, with the demand for consistent, quality products, grown in an environmentally sensitive manner. Precision farming may help to achieve this, but to be consistent it needs robust decision making tools. The economics of precision farming look encouraging with the costs of the system being less than the possible savings at current prices and assuming a 25% fall in capital costs.

Risk management in precision farming is a matter of whether it works, whether it can save costs and whether it can stand up to the effects of an unpredictable climate.

REFERENCES

Murphy, M C *Report on Farming in the Eastern Counties of England 1993/94* Cambridge University 1995, pp 56 & 87.

Pooley, J C (1996) Rural Stress - Growing your business in an adverse climate *Agricultural Progress* **71**, 1-6.

Barry, P *Risk Management in Agriculture*, Iowa State University Press 1984, pp. 97-100

RESPONDING TO INTER- AND INTRA-FIELD VARIATION TO OPTIMISE FOLIAR DISEASE MANAGEMENT IN WHEAT

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ABSTRACT

The development of techniques to allow pesticide application to be spatially varied on an intra-field scale should enable a logical progression from the current practice of varying inputs according to the requirements of individual crops. The success of precision farming will depend partly on the extent to which the development of techniques to monitor crops and convert crop measurements into improved treatment decisions are guided by biological understanding of the causes of variation in input optima. Quantification of the potential benefits from spatial adjustment of fungicide treatments is currently limited by shortage of objective data on the extent of variation in representative wheat crops. There is some evidence that intra-field variation in epidemic development and the sensitivity of the crop to disease might justify spatially varied treatment, but this would require the development of complex, automated monitoring techniques. The poor relationships between past yield variation and yield variation in the current crop, and yield potential and yield response, limit the value of yield maps as tools to optimise disease control inputs.

INTRODUCTION

Precision farming is currently technology led. The development of yield mapping (Stafford *et al.*, 1996) has largely preceded understanding about how spatial information should be interpreted into management action. This gap between potential and practice has led to a healthy degree of scepticism within the industry, about the practical value of intra-field measurements. Understanding of the biology of cropping systems should be used to aid the exploitation of existing precision farming technology and guide the development of new crop monitoring and management techniques - otherwise the sceptics may be proved right.

Measurements of intra-field variation will only be widely used to improve crop management if the benefits of improved production efficiency substantially outweigh the costs of increased crop monitoring. Such an outcome is more likely where what is measured varies substantially within fields, influences the optimum input, and is either quick and cheap to monitor or has some temporal stability or broad utility (so that the monitoring cost can be spread over several crops or crop inputs). The relationship between the variable and the optimum input must also be properly understood, to allow spatial information about the crop to be converted into improved treatment decisions.

The application of precision farming techniques to disease control has been largely neglected, possibly because disease epidemics are dynamic (and hence, temporally unstable) and the technology to map their spatial variation is poorly developed. This paper focuses on winter wheat foliar disease control and uses understanding derived from studies of the effects of inter-field variation on optimum fungicide inputs, to help define the variables most (and least) likely to justify intra-field monitoring.

THE OPTIMUM FUNGICIDE INPUT

Yield response curves have long been used to calculate economic optima for crop nutrients, but are only now being used to help optimise fungicide inputs for disease control (Sylvester-Bradley *et al.*, 1995). Fig. 1 shows a typical fungicide dose response curve for winter wheat. Each total dose point on the curve represents the mean of a range of dose/timing combinations for one-, two- and three- spray programmes applied between GS 32 and GS 59 (Tottman, 1987). Clearly, within any total dose the efficiency of disease control can be optimised by adjusting the timing and dose of individual applications, but for simplicity only the mean values will be considered here.

The fungicide dose economic optima (F_{opt}) can be calculated as the point on the response curve beyond which the financial gain from the increased yield is less than the cost of the fungicide needed to obtain the increase in yield. Adjusting fungicide applications spatially on an intra-field scale will only be worthwhile if there is substantial intra-field variation in F_{opt}, and if that variation can be predicted at the time of the fungicide treatment decisions from spatial measurements available at reasonable cost.

F_{opt} is influenced by the *magnitude* of the response (Y_{res}) between the untreated yield (Y_{unt}) and the maximum yield (Y_{max}), and the *curvature* of the response between the Y_{unt} and Y_{max} points. *Magnitude* of response being controlled predominantly by disease severity and the sensitivity of the crop to that disease. *Curvature* being influenced predominantly by the innate activity of the fungicide(s) against the predominant pathogen(s) at a site (hence more active fungicides tend to have lower dose optima).

Ultimately, it may be possible to spatially adjust the active ingredients applied, but it is probably more realistic to first consider only the adjustment of dose of a chosen fungicide or mixture, so the rest of this paper concerns variables that might influence Y_{res}.

SPATIAL VARIATION IN YIELD POTENTIAL

Yield maps are now becoming more widely available. Intuitively, most growers and consultants feel more confident in applying higher inputs to crops with high yield potential, so the question arises: should fungicide inputs be adjusted according to the yield potential of different parts of a field ? The answer is yes, only if: (i) past measures of intra-field yield variation explain a useful proportion of the variation in yield of the current crop, (ii) disease was effectively controlled in the crops from which the past measures of yield were taken (so they can be considered as measures of Y_{max}), and (iii) variation in Y_{max} explains a useful proportion of the variation in Y_{res} (and hence F_{opt}).

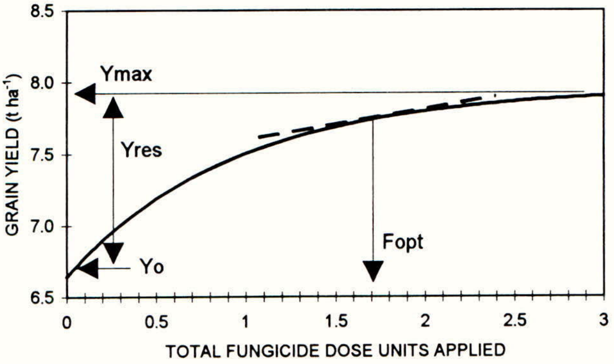

Figure 1. Fungicide dose response curve for cv. Riband at ADAS Rosemaund in 1994. Dotted line represents the gradient at which increase in yield equals increase in fungicide cost.

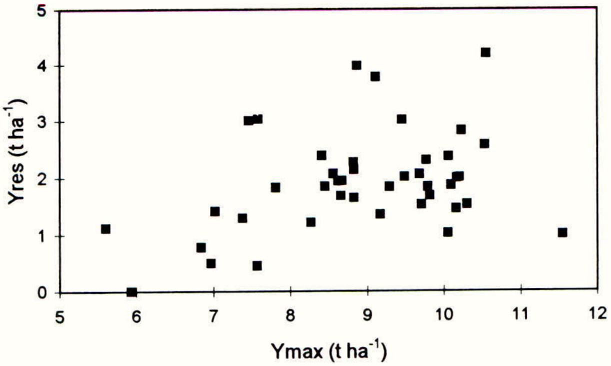

Figure 2. Relationship between maximum yield (Y max) and yield response (Yres) to fungicide treatment, for 42 experiments on cv.Riband.

Clarke *et al.* (in press) reported, that approximately 40% of the spatial variation in yield of a crop can be explained by variation in the yield of previous crops. The remainder of the variation having no temporal stability from season to season.

Fig. 2 shows data from 42 experiments on cv. Riband where Y_{res} could be calculated and plotted against Y_{max} for the same site.

Whilst there is some evidence that large responses are rare from low yield potential crops, the relationship between Y_{max} and Y_{res} is poor, with 13% of variance accounted for by linear regression ($Y_{res} = -0.239 + 0.242\ Y_{max}$; $P < 0.05$; 40 degrees of freedom).

SPATIAL VARIATION IN DISEASE

Final disease severity is a key determinant of Y_{res} and hence F_{opt}. Host resistance and weather have a strong influence on disease severity (hence, F_{opt} will tend to be low on more resistant cvs. and during seasons when the weather is not conducive to disease development) but, apart from local micro-climatic effects, are generally constant across a field. So host resistance and weather would remain key determinants of the need for treatment, but need not be considered in spatially adjusting the treatment.

Some diseases, such as yellow rust (*Puccinia striiformis*), develop initially from discrete foci which, although visually striking, occupy only a small proportion of the field area - 4% in the example of image analysis from an aerial photograph shown in Fig. 3 (note: reprographic errors increase this to 7% in the image shown). Practical experience suggests that others, such as powdery mildew (*Erysiphe graminis*), sometimes exhibit gradients across fields. Theoretically, cost savings could be made by 'patch spraying', or adjusting the dose applied according to disease severity. However, the situation is not analogous to patch spraying of weeds, where a patch mapped in one season will not move substantially by the following season. Also, applying fungicides after an epidemic has developed is ineffective, so treatment decisions need to be based on indicators of future disease risk. One such indicator is the current level of disease in the crop, which acts as a source of inoculum for future epidemic development.

Regular mapping of disease by eye would be tedious and uneconomic. The development and operational costs of automated disease sensors might be justified to detect inter-field variation of the main economic diseases of cereals. Their adaptation to allow spatial mapping might be justified for those diseases which express significant intra-field variation. To be of value, the sensitivity of detection would need to allow quantification of disease within the range of severities where variation in current inoculum influences future disease severity (between zero and 0.1% leaf area affected for yellow rust (Paveley *et al.*, in press)), rather than in the range where inoculum is no longer limiting epidemic development. Epidemiological theory suggests that similarly sensitive detection would be required to guide fungicide applications to control other foliar diseases capable of high rates of epidemic growth. Hence, the levels of disease that might be detected by remote sensing techniques would probably be too high, and would only serve to indicate that a fungicide should have been applied some time ago. Machine mounted sensors based on immunoassay (Dewey, 1996) or nucleic acid technology (Beck *et al.*, 1996),

Figure 3. Image analysis from aerial photograph of yellow rust foci occupying 4%* of field area (increased in image shown due to reprographic errors).

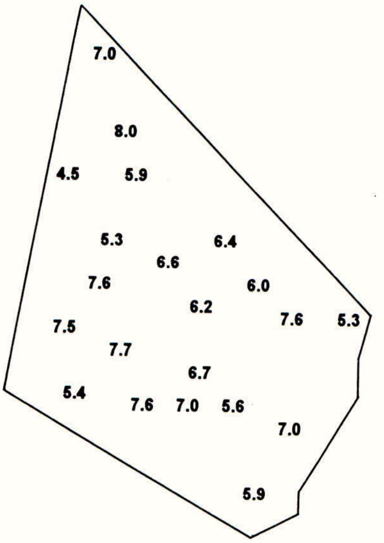

Figure 4. Calculated green area index (GAI) values from sampling points within a wheat crop.

could achieve suitable levels of sensitivity, and might sample airborne spores within/above the crop canopy (Schmechal *et al.*, 1996). Widespread uptake would be required to reduce the unit cost of such complex technology to an acceptable level.

SPATIAL VARIATION IN CANOPY SIZE

The effect of a given amount of disease on yield has been shown to vary substantially depending on the physiological state of the crop, and in particular, depending on the amount of green leaf area in the crop canopy (Bryson *et al.*, 1995).

Data quantifying spatial variation in canopy size are rare. Fig. 4 shows data from a field of winter wheat cv. Hereward from ADAS Boxworth in 1995, from which 21 spatially referenced samples were taken and peak green area index (GAI, the number of units of planar area of green leaves, stem and ears per unit ground area that they occupy) values calculated, via nitrogen uptake (Sylvester-Bradley *et al.*, 1990), from $4m^2$ sample areas. The locations of the values in the figure represent the sampling locations. Calculated peak GAI values between 4.5 and 8.0 were recorded at different sampling points. Work is ongoing to assess the extent to which such variation is typical of winter wheat crops. However, even allowing for sampling error adding to the variation, it seems reasonable to conclude that intra-field variation in canopy size can be significant. Indeed it is likely that many of the factors causing intra-field yield variation are expressed through variation in green canopy size and duration.

In a 1994 experiment using yellow rust as a model disease, described by Bryson *et al.* (1995), in which replicated plots of peak GAI 4.2 and 6.6 were created by manipulating available nitrogen, substantial effects on epidemic development were found. Calculations using the Beer's Law analogy, assuming a constant conversion efficiency of intercepted solar radiation post-anthesis to grain dry matter, indicated that the contributions of leaf layers to grain yield were also markedly affected. Where yellow rust was excluded by fungicide treatment, the contributions to yield of the upper leaves were greater in the GAI 6.6 canopy. The contributions of the lower leaves were relatively unaffected by canopy size. The growth rate of the epidemic on the larger canopy was approximately double that on the small, and the combination of increased disease development and increased contribution, caused the calculated yield response to control of disease on the flag leaf to be approximately 2 t ha^{-1} higher (Fig. 5.). Returning to the effect of changes in Y_{res} on F_{opt}; the larger response to disease control should indicate an increased optimum fungicide input; at least for flag leaf sprays around GS 39

CONCLUSIONS

Research to determine the relationships between variation in crop and disease, and variation in optimal fungicide inputs at an inter-field scale, should provide a logical basis for progression to the intra-field scale.

There is some evidence that intra-field variation in the state of the crop and the state of disease epidemics could cause intra-field variation in the optimum fungicide input. Quantification of the potential benefits from spatial adjustment of treatments is hampered by shortage of

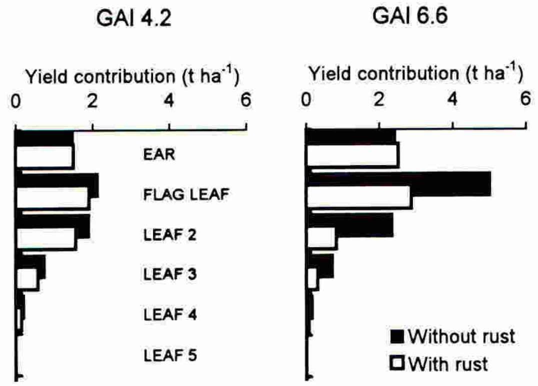

Figure 5. Effect of green area index (GAI) on contribution to yield from different leaves down the canopy and on loss of contribution caused by yellow rust.

objective data on the extent of the variation in representative wheat crops. One exception is yield, where substantial data sets are now being accumulated. However, the poor relationships between past yield variation and yield variation in the current crop, and yield potential and yield response, limit the value of yield maps as tools to optimise disease control inputs.

Significant spatial variation in disease severity is apparent for yellow rust and mildew. To be fully effective, fungicides have to be applied early in an epidemic. Hence, disease detection systems will only be of value as decision aids if they are able to differentiate between the low levels of disease which determine future epidemic progress. The development of automated disease detection systems can probably be justified on economic grounds to improve the efficiency of measurement of inter-field variation. Further development to allow intra-field disease mapping may be justified for some diseases.

There is limited evidence for intra-field variation in the physiological state of wheat crops. The extent of such variation is not well quantified but, if common, may have significant effects on both the rate of epidemic development and the effect of disease on yield. Variation in canopy size may prove amenable to automated monitoring (Hinzman *et al.*, 1986) and has implications for a number of crop protection and nutritional inputs, so monitoring costs might be effectively shared across potential savings in a range of input costs. However, care will be required in converting such information into treatment decisions. It seems likely that variation observed in the rate of epidemic development in canopies of different size is due to differences in nitrogen uptake. Pathogen species are known to respond differently to the nutritional state of the host so theoretically, differences in canopy size could indicate changes in the optimal fungicide input in opposite senses for different diseases. A neater solution might be to spatially adjust nitrogen inputs to ensure uniformly optimal canopy size, improving nutritional efficiency and removing the need to adjust fungicide inputs spatially to cope with the variation.

In general, while the research and technology is being put in place to gather and interpret intra-field data, there is much that can be done to improve disease management decisions at an inter-field scale.

ACKNOWLEDGEMENTS

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REFERENCES

Beck, J J; Ligon, J J; Etienne, L; Binder, A (1996) Detection of crop fungal pathogens by polymerase chain reaction technology. *BCPC Symposium Proceedings* No.65: *Diagnostics in Crop Production*, 111-117.

Bryson, R J; Sylvester-Bradley, R; Scott, R K; Paveley, N D (1995) Reconciling the effects of yellow rust on yield of winter wheat through measurements of green leaf area and radiation interception. *Aspects of Applied Biology* 42, *Physiological Responses of Plants to Pathogens*, 9-18.

Clarke, J H; Froment, M A; Dampney P M R; Goodlass, G; Stafford, J V; Lark R M (in press) An investigation into the relationship between yield maps, soil variation and crop development in the UK. *Proceedings 3rd International Conference on Precision Agriculture*, University of Minnesota.

Dewey, F M (1996) Production and use of monoclonal antibodies for the detection of fungi. *BCPC Symposium Proceedings* No.65: *Diagnostics in Crop Production*, 85-91.

Hinzman, L D; Bauer, M E; Daughtry, C S T (1986) Effects of nitrogen fertilization on growth and reflectance characteristics of winter wheat. *Remote Sensing of Environment*, **19**, 47-61.

Paveley, N D; Lockley, K D; Sylvester-Bradley, R; Thomas, J (in press) Determinants of fungicide spray decisions for wheat. *Pesticide Science*.

Schmechal, D; McCartney, H A; Magan, N (1996) A novel approach for immunomonitoring airborne fungal pathogens. *BCPC Symposium Proceedings* No.65: *Diagnostics in Crop Production*, 93-98.

Stafford, J V; Ambler, B; Lark, R M; Catt, J (1996) Mapping and interpreting yield variation in cereal crops. *Computers and Electronics in Agriculture*, **14**, 101-119.

Sylvester-Bradley, R; Scott, R K; Stokes, D T (1990) A physiological analysis of the diminishing responses of winter wheat to applied nitrogen. No.1. Theory. *Aspects of Applied Biology*, **25**, *Cereal Quality III*, 277-287.

Sylvester-Bradley, R; Goodlass, G; Paveley, N D; Clare, R W; Scott, R K (1995) Optimising the use of fertiliser N on cereals and parallels for the development of fungicide use. In: *A Vital Role for Fungicides in Cereal Production*, H G Hewitt *et al.* (eds), Oxford: Bios, pp. 43-56.

Tottman, D R (1987) The decimal code for the growth stages of cereals, with illustrations. *Annals of Applied Biology*, **110**, 441-454.

BENEFITS AND LIMITATIONS OF PRECISION FARMING

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ABSTRACT

The concept of precision farming has been made possible by the use of satellite location systems to produce maps of the distribution of data within individual fields on farms. This was first introduced on a practical scale with a yield measurement system fitted to a combine harvester. It is now possible to map fertility levels in the soil and using field maps, apply fertiliser on a variable basis according to the different levels shown on the map. Sampling of pests, diseases and weeds can be carried out using Differential Global Positioning System (DGPS) which may in time be linked to variable spray application in order to rationalise pesticide application. A need is identified for simple sensors for in-field use by agronomists in order to record the location of pests and weeds for use as an agronomy management tool.

INTRODUCTION

Precision farming can be defined as a management practice that operates on the basis of in-field analysis of profit as against a whole field system of analysis. Arable farming is based on a combination of combinable crops, root crops, field vegetables and some specialised horticultural crops. They are farmed on a rotational basis but management is determined on a field by field decision making process in which inputs are normally applied to whole, or at best, part fields as a blanket treatment.

The economics of arable farming are related to this approach. Profit is determined using gross margin analysis. This consists of relating outputs to the fixed and variable costs of the farming system. A typical winter wheat production of 7.4 tonnes/ha sold for £112 /tonne would give the following:

Table 1 Typical production costs for winter wheat production in the UK

INCOME	£/ha
Yield	829
Area payment	274
TOTAL	1103
EXPENDITURE	
Variable costs	278
Fixed Costs	450
TOTAL	728
GROSS MARGIN	375

Yield is key to the financial success of the arable operation. The price of wheat will vary, as will the subsidy but the yield is the variable that a grower must strive to increase at all times. The profit a grower makes is dependent on his yield and his costs. Profit can be increased by increasing yield and/or reducing costs. This system of management has been in place for more than twenty years. It is currently coming under some scrutiny as profits have plateaued as costs have risen. Whilst the UK grower has been cushioned by the area aid payments and the world price of grain this cannot be relied upon to continue. It must be a realistic proposition that precision farming may give the grower the way to significantly increase his profitability by allowing him access to a much higher level of crop management that he has had hitherto.

SYSTEMS OF PRECISION FARMING

The origins of precision farming go back over a decade when it became apparent that we might be able to locate areas of differing yield potential in existing fields and selectively treat them. This has become ever more apparent as fields become larger by engulfing other fields with different geological, edaphatic and agronomic origins. Every farmer is well aware of the bad areas in his fields and is also well aware of the lower yields from headlands, compacted areas and poorly draining areas and patches.

The term precision farming can be taken to mean the careful monitoring of soil and crop agronomy to fit the different conditions found in different parts of each field. Precision farming has also been called 'Prescription Farming', 'Site Specific Farming' and 'Variable Rate Technology'(Johannsen 1994).

Inherent in the means of precision farming is the ability to be able to locate different areas of a field down to units of land small enough to make measurements meaningful and subsequent treatments practically possible. Location of variations in fields has been undertaken by remote sensing, Geographic Information Systems (GIS) and Global Positioning Systems (GPS).

Some of the earlier approaches to precision farming was using satellite remote sensing. Satellite images from Landsat and SPOT have been used to distinguish crop species and locate stress and disease conditions. It was this system that was initially considered for monitoring of EEC crop areas for subsidy grants, until politics interfered and on the grounds of "spying" the programme was never followed through. Cost is also a problem with satellite sensing. The cost of satellite pictures of a farm of 1,000 ha is around £2,000. Other means of sensing is the use of aerial photographs taken by small aircraft, often pilot-less miniature monoplanes. Unfortunately the costs are not much less than for satellite sensing but it provides more detail and a higher definition and allows small areas to be enlarged as needed. Whilst this form of monitoring allows good location to field boundaries and prominent land marks it still requires location on the ground by survey to locate particular parts of a field. This can be linked to the crop tramlines to give a grid system for sampling but requires either optical location to standard points or measuring distances along tramlines using a marking wheel or radar speed sensor system (Miller et al 1995). All these types of location system are prone to cumulative error and also need high manual input.

The use of Global Positioning Systems (GPS) is now well established as a method of location determination. It was originally developed for military purposes and has proved highly reliable in the fields of nautical and aeronautical navigation. It is in these areas that high usage has resulted in affordable and easy to handle hard and software that we are now able to adapt for use in agriculture. Using a cluster of military satellites GPS can be used to link any kind of data to a precisely determined position. This is referred to as 'Geocoding' and enjoys the advantage of being reproducible at any time. It also requires no need to measure sampling or assessment points in the field. The equipment will locate your position and map it at any chosen point.

Accuracy with GPS is relatively high and accurate within 50 m. In order to achieve higher orders of accuracy needed for agricultural purposes additional satellite navigation equipment based on a known position allows the user to distinguish the deviation between the results of GPS location to its actual position. This 'Differential GPS' (DGPS) increases the location resolution to as high as plus or minus 5 m (Schroeder & Schnug 1995). Higher resolutions are possible but are not likely to be of benefit in agriculture since the machines on farm are themselves operating on working widths of 10 m or more.

YIELD MAPPING

Attempts to gain better information on yield coming off combine harvesters have been made over the last fifteen years. In the main these have consisted of various types of flow-meters measuring volumetric flow of grain over the output auger. They lack the crucial aspect of location of results to fixed points in the field.

The monitoring of yield in relation to field position using DGPS has been developed over the last five years by Massey Ferguson amongst others. A monitoring system is marketed under the brand name of 'Datavision' (Anon 1995) which is a comprehensive maintenance and performance monitoring system with an in-cab display. The yield component is measured by determining the mass of grain flowing over the main grain elevator. Using the grain mass avoids the need to monitor hectolitre weights. Every 1.2 seconds the machine records yield; latitude and longitude. This information is recorded and transferred to a computer. The many yield points are converted into regularly spaced data and put into a grid of 10 m x 10 m squares within the field boundary. From the grid a contour yield map can be drawn. An example is shown in Figure 1.

This graphic presentation of data is very impressive but is it useful? All good farmers will already know from walking their fields that some areas are poor grain producers. What is useful is the distribution of yield shown in Figure 2.

Fig.1. Hawnes End Yield Map from 1992 - Courtesy Massey Ferguson

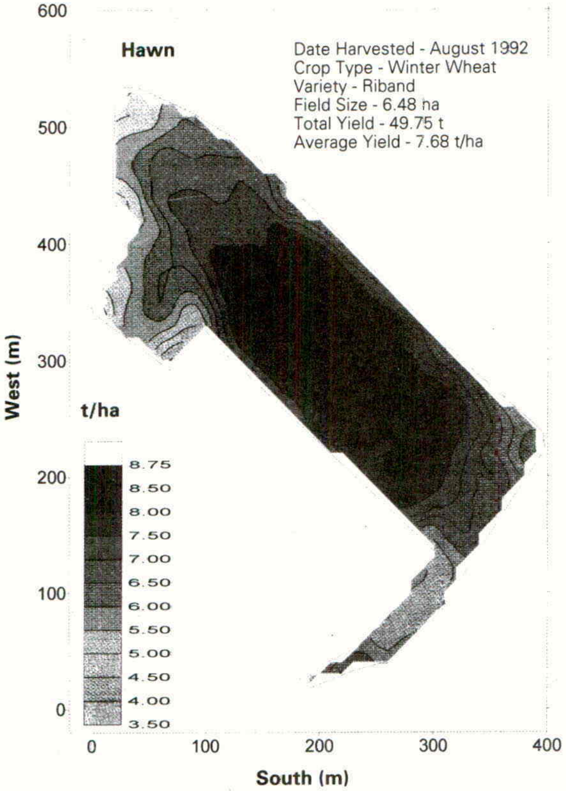
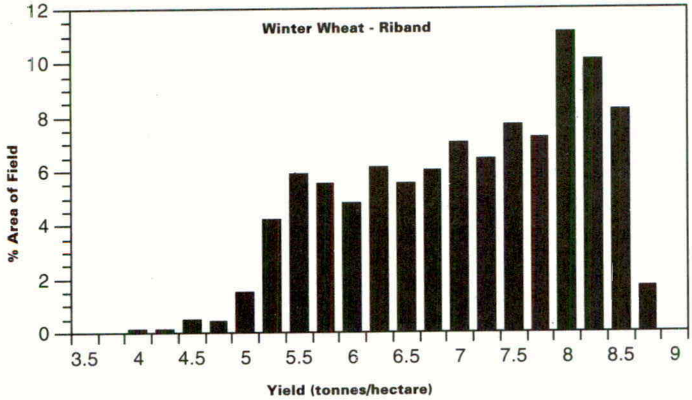


Fig.2. Yield Distribution histogram from Hawnes End 1992 - Courtesy Massey Ferguson



What can be done with this information? Firstly using the example of gross margin in the introduction the break-even yield is 6.9 tonnes/ha. The histogram shows that nearly 25% of this field is loosing money and the map tells us where.

Most of the yield mapping carried out has been on combinable crops. Development of the system for root crops is under way and in 1995 a field of sugar beet was harvested and the continuously monitored using a modified version of the Datavision system (Anon 1996). The weighing system was incorporated in an eight tonne MF700 series tandem axle trailer. It utilises commercially available weighing cells mounted on a sub-frame fitted beneath the trailer body. The resultant map showed yield variations of from nil to 35 tonnes/ha and indications of poor yield on old cereal tram lines and on light drought prone soils. It is anticipated that the system will be developed for potatoes, forage grass and maize.

FERTILISER MAPPING

Soil sampling has been a feature of fertiliser management for many years and there is considerable data already available as a base for producing maps of deficiencies related to DGPS location. It is agreed that a higher number of sampling points will be required in order to produce a detailed map.

Once the data is recorded it can be used to regulate fertiliser application rates as spreaders move across a field. This is already available a service to growers through the SOYL company from Hambledon, Portsmouth (Millar 1996). Mapping of soil sample results normally takes one month. The data is then retained centrally and transmitted to the Soyl-Opti unit on the fertiliser distributor using digital mobile data transfer. When in operation the driver follows his desired path and leaves the Soyl-Opti to apply varying amounts of nutrient according to the required levels determined by the soil map. At present the system is confined to P, K, Mg and pH application but it will shortly be adapted to apply nitrogen and other fertilisers.

Research on appropriate methods of sampling and interpreting the data is being carried out at Reading University by Dr M. Oliver (Salter 1996). There is still need to establish the reliability of the maps and sampling for different nutrients. It is envisaged that individual nutrients will vary in availability independently of other nutrients.

CROP PROTECTION

The need to rationalise crop protection is very important. Consumer resistance to the use of spray chemicals is high but their use is unavoidable if yields and quality are to be maintained. Pressure to reduce the quantity of pesticides in crops is politically motivated In Denmark, Holland and Germany there are positive targets set for the reduction of pesticides over time. The use of DGPS generated pest and weed maps will allow variable pesticide doses to be sprayed. This will have the political benefit of reducing total pesticide use and the economic benefit of reducing pesticide costs on farm.

The systems described above use DGPS for mapping data once collected. There is interest in using DGPS for sampling location. Haydock & Evans (1995) describe work being carried out using DGPS to locate sampling points for the determination of the presence of potato cyst nematode populations. They propose an automatic sampling system in which the presence of the eelworm pests concerned would be determined by ELISA technique using the reaction to monoclonal antibodies. From this information nematicides would be spot applied only where they would be justified.

A similar approach to the use of DGPS has been reported (Penny 1996) where it is being used to pin point brassica pests and make threshold spraying possible. This system works using a mobile transmitter that enables the operator to record the presence or absence of the pest which can be related to the threshold for that pest and spraying would be carried out accordingly. At present the system is being developed for the control of Cabbage Aphid (*Brevicoryne brassicae*)

The use of variable dose sprayers is now a realistic possibility and work with automated patch spraying of weeds has been described (Miller et al 1995). This technique does not necessarily depend on the automatic spraying of weeds. So far experiments with automated crop/weed identification have not been encouraging (Bull 1995).

The current system of monitoring crop protection is by field walking. This is very effective and from such inspections agronomists give field recommendations to the grower which involve the type and name of spray to be used, the rates of use, timing, spray quality and any other conditions considered necessary to the operation of the sprayer. Many agronomists use quad-bikes to cover the ground. These machines would be an ideal platform for DGPS transmitters so that data on pest occurrence and distribution can be collected for processing as fields maps. It could also be used to record and transmit the spray recommendations so avoiding the need to hand record recommendation sheets. From this it is only a small step to calculate the order for the quantity of pesticides required. What is of great promise is the use of small hand held transmitters so that agronomists can record the incidence of troublesome weeds and pests and map their occurrence without the need of fixed transmitters on “quad-bikes”.

The DGPS system would be used for weed and pest problems that are irregularly spread over a field and which persist throughout a rotation. The analysis of some characters of weed patches are described by Rew and Cussans (1995). The value of this technique is the ability to record the presence of pests for use at other times in the rotation when treatment is carried out in the absence of the pest or weed e.g. pre-drilling. Certain weeds come to mind in this context e.g. Common Couch (*Elymus repens*), Wild Oat (*Avena fatua*), Blackgrass (*Alopecurus myosuroides*), Creeping Thistle (*Circium arvense*) and Docks (*Rumex spp.*). Diseases such as Barley Yellow Dwarf virus and Barley Yellow Mosaic virus. Take-all disease (*Gaeumannomyces graminis*) and Brown Foot rot (*Fusarium culmorum*) also lend themselves to mapping. Certain soil born pests such as nematodes clearly lend themselves to mapping using DGPS. There are many other examples that could be added to these lists.

Whilst the variable sprayer is being developed we still need a simple, robust, reliable and cheap location transmitter for the agronomist or adviser to record the occurrence of the pests he is interested in. This may come from existing equipment adapted from other uses. There is a in-car navigation system based on a PSION palmtop computer - Series 3a. This uses GPS to give a location to an accuracy of +/- 50 m. The manufacturers indicate that DGPS can easily be added to the system to give us the accuracy we would need for in-field location of pests, diseases and weeds.

OTHER USES

If it is possible to map the distribution of soil, fertility and yield it is only a matter of time before we will also be able to map the amounts of micro-nutrients in the soil. By the same means that allow variable amounts of fertiliser to be applied the grower will apply variable doses of critical micro-nutrients. This would clearly apply to the use of manganese in arable crops. Whether there would be any benefit in applying this system to tissue analysis must be doubtful. The levels of nutrients in crop tissues is transient and very weather dependent.

Recording of agronomic characteristics would be of value if the maps produced had a long term value. One could consider several characteristics in this area. Seed rates, plant populations, tiller numbers, dates of critical growth stages could all be recorded and mapped if suitable equipment were available that made the recording straight forward and simple. Time might be a serious constraint as in order to gather sufficient data the whole farm would need comprehensive sampling to give sufficient points for a map to be drawn. If mapping was to be based on a grid of 100m x 100m the time involved would become acceptable.

DISCUSSION AND CONCLUSIONS

Yield is the ultimate determinant of the success or failure of an agricultural operation. Without yield maps there is no point in considering precision farming. The difficulty will arise in using this data. A yield map tells us only the results of the cropping programme in the year it is produced. It is dependant on the weather occurring during the growing season and is restricted to the soil cultivation, fertiliser use, variety and crop protection followed in that particular year. The data will need to viewed over a long time period in order to iron out rotational and weather effects.

The production of soil maps, nutrient maps and pest maps will enable comparisons to be made with the yield maps. A strong correlation of yield with a particular variable will enable the grower or advisor to try to remedy low yields where they occur by altering the level of input concerned. It will still however require considerable skill to understand why there are high and low yielding parts of a field. This question is not easily answered as yield is the result of the interaction of a large number of complex variables, some fixed e.g. soil types and others ephemeral e.g. weather. If, for example, low yielding areas correspond mainly to headlands how can this be remedied? It may be decided that there is a need for more intensive sub-soiling and deeper ploughing than higher yielding areas of the field. This will add costs to yield production in these areas which must be paid for by increases in yield in these poorer areas as a result of the changed cultivation's. Would it not be more cost-effective to keep low yielding areas as headlands/traffic areas and put higher inputs into the better yielding parts of the field in the form of higher fertiliser application, seed rates and sprays? If we have the means to apply our inputs on a variable basis it will not take long to see at the next harvest which decision was correct and whether it has raised or lowered yield in the same parts of a field compared to previous years. It will also enable growers to compare alternative inputs in pre-determined parts of a field so that he can analyse which choice was correct.

It is too early to predict the value of precision farming using DGPS based mapping but the indications are clear that it could rationalise fertiliser and pesticide use. If it could also be used as an agronomic tool to raise the level of management in arable farming it will become an essential process on many farms. All farms now have some form of computer based management system. Provided that DGPS mapping is kept simple to use through farm computers and can be interpreted within existing management procedures it will be welcomed by competent growers and agronomists. If the maps are used in conjunction with automated variable application machinery the benefits should outweigh the cost within four years of purchase. If, however, DGPS mapping requires complicated, time consuming or expensive additional specialist equipment neither the grower nor the agronomist will have time to use it. It is clear that mapping will involve high cost levels of initial inputs both in man hours and analytical costs. This will need to be backed up by a long term commitment to use the system otherwise there will be insufficient data to make the maps effective nor the change in inputs profitable.

REFERENCES

Anon (1995) Datavision Yield Mapping System. *Massey Ferguson Group Ltd.* pp.1-10.

Anon (1996) Silsoe Maps it all Out. *British Sugar Beet Review* **64**, 2, 58.

Bull,C R; Zwiggelaar, R; Stafford, J V (1995) Imaging as a technique for assessment and control in the field. *Aspects of Applied Biology* **43**, 197-204.

Haydock, P P J; Evans, K (1995) The potential use of global positioning satellite (GPS) technology in the mapping and management of potato cyst nematode populations. *Aspects of Applied Biology* **43**, 125-128.

Johannsen, CJ (1994) Precision Farming: Farming by the Inch, *The Earth Observer* **6**, 6-8.

Millar, D (1996) the Sky is the Limit. *CROPS* **14**, 11, 52.

Miller, P C H; Tuck, C R; Stafford, J V; Bolam, H C (1995) Engineering systems for the design of plot sprayers and to aid field sampling approaches. Aspects of Applied Biology **43**, 109-116.

Miller, P C H; Stafford, J V; Paice, M E R (1995) The Patch Spraying of Herbicides in Arable Crops. *Proceedings Brighton Crop Protection Conference - Weeds* **3**, 1077-1086.

Penny, E (1996) Targeted Pesticide Use. *CROPS*, **14**, 14. 19. 9.

Rew, L J; Cussans, G W (1995) Patch Ecology and Dynamics - How Much Do We know. *Proceedings Brighton Crop Protection Conference - Weeds* **3**, 1059-1068

Salter, J C (1996) Precision Farming *Fertiliser Review 1996, Fertiliser Manufacturers Association*, pp. 6.