INSECTICIDE RESISTANCE IN POPULATIONS OF *ORYZAEPHILUS SURINAMENSIS* AND *CRYPTOLESTES FERRUGINEUS* FROM GRAIN STORES IN ENGLAND AND WALES.

A.J. PRICKETT, J. MUGGLETON, J.A. LLEWELLIN

ADAS Central Science Laboratory, London Road, Slough, Berks, SL3 7HJ

ABSTRACT

Discriminating doses have been set to enable the detection of resistance in the stored product beetle pests *Oryzaephilus surinamensis and Cryptolestes ferrugineus* to all those organophosphorus insecticides currently available in the UK for use in association with stored grain. These tests were then used on strains of *O. surinamensis* and *C. ferrugineus* collected by random sampling of farm grain stores, and of grain stored in bulk, off farms in England and Wales, between 1987 and 1989. In *O. surinamensis* resistance to malathion, fenitrothion, pirimiphos-methyl, chlorpyrifos-methyl, etrimfos and methacrifos was found. Resistance in *C. ferrugineus* was limited to malathion, fenitrothion and etrimfos. Comparison of these results to data on pesticide usage, collected at the same time, shows the difficulty of relating the results of laboratory resistance tests to pesticide usage in individual grain stores.

INTRODUCTION

Resistance in stored product beetles has been recognised since the early 1970s when a worldwide FAO survey investigated the resistance of eight species to malathion, lindane, and the fumigants phosphine and methyl bromide (Champ & Dyte, 1976). In Great Britain, malathion resistance was found to be present in *Rhyzopertha dominica*, *Sitophilus granarius*, *S. oryzae*, *Tribolium castaneum* and *T. confusum*, but absent in *Oryzaephilus surinamensis*, *O. mercator* and *Sitophilus zeamais*. Lindane resistance was found in all eight species. Subsequently resistance in these beetles to organophosphorus insecticides appears to have increased worldwide (Champ, 1986). In Britain data for the years after the FAO survey (Muggleton, 1987) show that the frequency of malathion resistance increased in the decade following the early 1970s, but remained at, or about, the 1979-1982 level for the period 1983-1986. Data for 1984-1986 showed that for *O. surinamensis*, nearly 30% of the populations tested were resistant to pirimiphos-methyl and malathion, a few (6%) were resistant to fenitrothion, but that nearly all (92%) were resistant to chlorpyrifos-methyl.

The disadvantages of these earlier data are that they are not a random sample, coming from premises with infestation problems and thus where resistance is more likely to be found, and that for most species it was possible to test for resistance to only one organophosphorus compound, malathion. The present paper gives the results from a random sample of farm grain stores in England, and for nearly all the commercial grain stores in England and Wales, and so should present a more accurate picture of the frequency of resistant populations in these stores. In addition, we have addressed the problem of a lack of resistance tests for compounds other than malathion, by developing new discriminating dose tests for both *O. surinamensis* and *C. ferrugineus*.

RESISTANCE - A DEFINITION

For the purpose of this paper, resistance has been defined as occurring where insects have inherited the ability to survive a discriminating dose of insecticide, designed to kill all normal or susceptible insects in a population.

METHODS

Collection of beetles and data

In 1987 pre-harvest visits were made to 742 farms in England that grew cereal grain. Farms were stratified into three size groups by the area of cereal grain grown, and a further stratification was made into each of the five MAFF Regions, the aim being to visit 50 farms in each size category in each region. A random sample of farms in each category was supplied by the Agricultural Census Branch of MAFF. Data on storage practice was collected during the visits and baitbags and, where appropriate, other trapping methods were used to collect samples of beetles. Between October 1988 and March 1989 similar data were collected from commercial grain stores in England and Wales. This second exercise was limited to off-farm stores with over 1000 tonnes capacity, and excluded port sites. 182 sites with such stores were identified, and of these it proved possible to visit 171 sites.

Determination of discriminating doses

Dose-response data were obtained for each of eight strains of *O. surinamensis* and two strains of *C. ferrugineus* known to be susceptible to malathion, and for a further two strains of *C. ferrugineus* known to be resistant to malathion but not to other organophosphorus insecticides. The test method is described below. Two of the *O. surinamensis* strains had been cultured in the Laboratory since before the use of organophosphorus insecticides. The remaining strains of both species were collected, from the field, between 1964 and 1983. The discriminating dose was set by taking the ED99.9 which typified those strains least tolerant of the insecticide (Muggleton, 1987). Once a dose had been identified, suspected resistant strains were exposed to it, and the progeny of any survivors bred-up and tested at the putative dose. A significant increase in survivors among these progeny, compared to their parents, was taken as confirmation that the ability to survive the dose was inherited.

Adult beetles were exposed to discriminating doses of insecticide following the general procedures set out in FAO Method No. 15 (Anon., 1974), in which beetles are confined on insecticide impregnated filter papers by glass rings coated with 'Fluon' (an aqueous suspension of polytetrafluoroethylene). With the exception of methacrifos, the doses were applied to 'Whatman No. 1' filter papers in a mixture of 'Shell Risella' oil, petroleum ether and acetone in a ratio of 1:3:1 by volume. 0.5 ml of this mixture was applied to each filter paper which was then left to dry for 18 hours. Methacrifos was applied in a mixture of polyethylene glycol (molecular weight 300) and acetone in a ratio of 1:4 by volume. Technical grade insecticides were used throughout. The discriminating doses used to detect resistance are shown in Table 1.

TABLE 1. The discriminating doses used to detect resistance. A five hour exposure period was used.

Insecticide	*O. surinamensis* % concn in oil	*O. surinamensis* deposit (mg/m^2)	*C. ferrugineus* % concn in oil	*C. ferrugineus* deposit (mg/m^2)
Malathion	0.3	78	1.0	260
Fenitrothion	0.5	130	0.2	52
Pirimiphos-methyl	0.6	156	0.5	130
Chlorpyrifos-methyl	1.0	260	0.5	130
Methacrifos	0.4*	104	-	-
Etrimfos	0.2	52	0.15	39

* in polyethylene glycol

RESULTS

Trapping for beetles was carried out at all 742 farms included in the exercise. Trapping was possible at 157 of the commercial grain store sites, and 283 individual storage structures were sampled at these sites. All the results below refer to these 283 stores, and not to the sites. *O. surinamensis* occurred in 4.8% of the farm stores and in 14.5% of the commercial stores. *C. ferrugineus* occurred in 4.6% of the farm stores and 10.6% of the commercial stores. Occurrence indicates the presence of at least one live adult and does not, therefore, necessarily suggest the presence of an infestation.

The percentage and number of populations of *O. surinamensis* and *C. ferrugineus*, from the farm and commercial grain stores, that were resistant to the six organophosphorous insecticides are shown in Tables 2 and 3 respectively. Details of the percentage of farm and commercial stores using each of the organophophorus insecticides available for use in grain stores in the United Kingdom (UK) are given in Table 4. In compiling these data no differentiation has been made between use on the grain and use on the store fabric. The information is based on data collected from all 742 farms and from 281 out of the 283 commercial stores. It is estimated that insecticide was used in 53.4% of the farm stores, and in 85.4% of the commercial stores.

TABLE 2. The percentage and number (in parenthesis) of populations of *O. surinamensis* from farm and commercial grain stores resistant to organophosphorus insecticides.

	% and number resistant: farm stores		% and number resistant: commercial stores	
Malathion	13.0	(4)	25.0	(7)
Fenitrothion	3.0	(1)	18.0	(5)
Pirimiphos-methyl	27.0	(8)	82.0	(23)
Chlorpyrifos-methyl	100.0	(30)	100.0	(28)
Etrimfos	60.0	(18)	100.0	(28)
Methacrifos	77.0	(23)	29.0	(8)
Total tested		30		28

TABLE 3. The percentage and number (in parenthesis) of populations of *C. ferrugineus* from farm and commercial grain stores resistant to organophosphorus insecticides

	% and number resistant	
	farm stores	commercial stores
Malathion	9.1 (2)	14.3 (3)
Fenitrothion	0 (0)	4.8 (1)
Pirimiphos-methyl	0 (0)	0 (0)
Chlorpyrifos-methyl	0 (0)	0 (0)
Etrimphos	4.5 (1)	9.5 (2)
Total tested	22	21

TABLE 4. The percentage and number of farm and commercial grain stores using each of six organophosphorus insecticides. The non-organophosphorus category includes some fenitrothion/pyrethrin mixtures. The percentages for the farm stores are weighted, see text.

	% and number using insecticide	
Insecticide	farm stores	commercial stores
Malathion	0.7 (8)	0 (0)
Fenitrothion	0.8 (6)	1.1 (3)
Pirimiphos-methyl	39.6 (332)	69.4 (195)
Chlorpyrifos-methyl	1.9 (15)	13.5 (38)
Methacrifos	0.7 (8)	3.2 (9)
Etrimfos	2.1 (18)	10.0 (28)
Non-organophosphorus	11.8 (83)	9.6 (27)
None	46.6 (310)	14.6 (41)

DISCUSSION

The results confirm the findings of earlier work, that there is little evidence of resistance to organophosphorus insecticides in *C. ferrugineus* in the UK, but that resistance to organophosphorus compounds is widespread in *O. surinamensis*. For the farm stores, the frequency of resistance in *O. surinamensis* to pirimiphos-methyl, chlorpyrifos-methyl and fenitrothion is similar to that found in inland premises between 1984 and 1986 (Muggleton, 1987). Resistance to malathion appears, however, to be less frequent (13% compared to 29.5%), but the difference is not significant (X^2= 3.119). In contrast there are some striking differences between the resistance found in farm stores and that in the commercial stores. In general these relate to the fact that resistance was detected more frequently in the commercial store *O. surinamensis* populations than in those from the farm stores. The notable exception to this is methacrifos resistance which was much less frequent in the commercial stores than in the farm stores.

The high frequency of detection of resistance in the commercial stores compared with the farm stores probably has two causes, the more extensive use of insecticides in commercial stores and the concentration in commercial stores of grain from many different sources. The lower detection rate of methacrifos resistance in commercial stores is puzzling. It would seem to suggest that methacrifos resistance can be inherited separately from resistances to other organophosphorus compounds. There is a possibility, of course, that methacrifos resistance was mis-scored in one or other of the exercises. However, retesting the farm populations, using the same operator and methacrifos stock solution as for the commercial stores, did not alter the result.

One aspect of these results that requires further investigation is the high number of populations of *O. surinamensis* resistant to chlorpyrifos-methyl, methacrifos and etrimfos, in spite of the low usage of these compounds in both types of store. It is possible that there is cross-resistance between these insecticides and those used frequently in the past, like malathion, or that used most frequently at present, pirimiphos-methyl. For chlorpyrifos-methyl there is evidence, however, that in one strain, at least, chlorpyrifos-methyl resistance is inherited separately from that for most of the other organophosphorus compounds. The discovery, during this work, of three strains resistant only to chlorpyrifos-methyl supports this idea. A study of six grain stores in Minnesota, USA has shown the existence of chlorpyrifos-methyl resistance in *O. surinamensis*, with low knockdown frequencies at four stores in the absence of chlorpyrifos-methyl usage (Subramanyam et al; 1989). This, together with the widespread existence of chlorpyrifos-methyl resistance in the UK, points to the possibility that some individuals of *O. surinamensis* have a natural tolerance to chlorpyrifos-methyl (Muggleton, 1987). It is possible that other such mechanisms exist in *O. surinamensis* but, presumably, not in *C. ferrugineus*.

Using the present data, a comparison can be made between the usage of pirimiphos-methyl in stores, and the presence of resistance in those stores to that compound. Table 5 shows, separately, the number of farm and commercial stores which had, or had not, used pirimiphos-methyl in the twelve months prior to collection of the beetles, and the number of those stores with resistant or susceptible populations of *O. surinamenis*. There is no significant difference between the proportion of resistant populations from stores using pirimiphos-methyl and that from stores not using pirimiphos-methyl (For both farm and commercial store comparisons, Fisher's Exact Test gives a probability >0.9). A similar lack of correspondence between pesticide use and resistance is found for the other insecticides for which this comparison can be made. Thus it would appear that even when considering the most widely used insecticide there is, from these data, no evidence that the use of insecticide in the individual stores is directly related to the presence of resistance. This does not mean, of course, that such a relationship does not exist; it may be that our data are insufficient to show it. The resistance shown by any population will be the result of its exposure to insecticides over a number of generations. Using our data we can only consider insecticide usage in the previous twelve months. To make a proper comparison it would be necessary to know the exposure history of a population over many generations, and it is unlikely that such data will ever be available. An added problem is that with grain moving between stores the population in any one store is unlikely to remain constant with respect to its genetic make-up, and may also reflect exposure to insecticides at distant sites or, indeed, outside the UK. Thus it can be argued that what we are seeing in these data is a reflection of the general incidence of resistance in the UK, and that we should not attempt to relate it to pesticide usage at any one site. The value of the data collected is in showing the current situation regarding resistance in this country. It must be stressed, however, that what is being discussed here are laboratory defined resistances and that they may not yet lead to control problems in the field. What they do undoubtedly indicate is that populations of beetles are present in the field with individuals that are able to survive higher doses of insecticide than are the normal individuals. They may be controlled by properly applied field treatments at the recommended dose but their presence greatly reduces the safety margin between control success and failure. There is an urgent need, therefore, to discover the origins of these resistant strains.

TABLE 5. The number of pirimiphos-methyl (p-m) resistant and susceptible populations of *O. surinamensis* found in stores which had, or had not, used pirimiphos-methyl in the previous twelve months.

		Number of populations that were	
		p-m resistant	p-m susceptible
farm stores	using p-m	4	9
	not using p-m	3	11
commercial stores	using p-m	16	3
	not using p-m	6	2

ACKNOWLEDGEMENTS

Part of this work was supported by a research grant from the Home-Grown Cereals Authority. We should also like to thank Cheminova, Ciba-Geigy, Dow, ICI, Sandoz and Sumitomo for their gifts of technical grade insecticides; Mrs J. Eade, Miss L.M. Farmer, Mrs M.J. O'Donnell, Miss L.A. Sharrock and Dr. J. Waller for their work developing the discriminating doses, and Miss S. Blades, Miss L. Nair, Mr J.C. Starzewski and Miss I.T. Taylor for applying them and recording the results.

REFERENCES

Anon. (1974) Recommended methods for the detection and measurement of resistance of agricultural pests to pesticides. Tentative method for adults of some major beetle pests of stored cereals with malathion or lindane. FAO Mehod No. 15. *Plant Protection Bulletin*, FAO, 22, 127-137.

Champ, B.R. (1986) Occurrence of resistance to pesticides in grain storage pests. In: *Pesticides and Humid Tropical Grain Storage Systems*, B.R. Champ and E. Highley (Eds), Canberra: ACIAR.

Champ, B.R.; Dyte,C.E. (1976) *Report of the FAO Global Survey of pesticide susceptibility of stored grain pests*, Rome: FAO.

Muggleton, J. (1987) Insecticide resistance in stored product beetles and its consequences for their control. In: *Stored Products Pest Control, T.J. Lawson (Ed), BCPC Monograph No. 37*, Thornton Heath: BCPC Publications, pp. 177-186.

Subramanyam, Bh.; Harein, P.K.; Cutkomp, L.K. (1989) Organophosphate resistance in adults of Red Flour Beetle (Coleoptera: Tenebrionidae) and Sawtoothed Grain Beetle (Coleoptera: Cucujidae) infesting barley stored on farms in Minnesota. *Journal of Economic Entomology*, **82**, 989-995.

THE COTTON-WHITEFLY FIELD CONTROL SIMULATOR: LABORATORY APPARATUS FOR EVALUATING INSECTICIDES AND RESISTANCE MANAGEMENT STRATEGIES UNDER SIMULATED FIELD CONDITIONS

M.W. ROWLAND, B.HACKETT, M.F. STRIBLEY, R.M. SAWICKI

A.F.R.C., Institute of Arable Crops Research, Department of Insecticides, Rothamsted Experimental Station, Harpenden, Herts, AL5 2JQ

ABSTRACT

Laboratory apparatus and techniques are described for rearing whitefly (*Bemisia tabaci*) populations on cotton and treating them with insecticide under simulated field conditions. The effects of these treatments can be observed and monitored without interfering with insects or plants. Simulator experiments with cypermethrin and profenofos against resistant and susceptible whiteflies gave results that were unexpected on the basis of standard bioassay data, but which were likely to be a much better indication of field response. As well as being a powerful screening tool, the simulators are well-suited for evaluating resistance management strategies.

INTRODUCTION

The evolution of resistance to insecticides has led to considerable interest in strategies for delaying its selection in pest populations (Green *et al.*, 1990). An equally pressing concern, however, is how to control populations that are already resistant to a wide range of chemicals. The common response is to screen new insecticides, combinations of insecticides, or synergists against resistant insects, using standard topical or residual bioassays, in the hope that some compounds remain effective. Unfortunately, standard bioassays may be poor predictors of insecticide efficacy in the field, where deposition is usually non-uniform and some life-stages may avoid exposure or inhabit parts of a plant not reached by insecticide. On the other hand, field trials incorporating these factors may be difficult to conduct, expensive, and subject to vagaries of climate, predators and disease.

To address these problems, we are developing laboratory techniques for evaluating pesticide performance under conditions that mimic the ecology and control of pests in the field. This 'field simulator' technology is suitable for screening insecticides more realistically against standard strains or contemporary field populations, and for evaluating both preventative and curative resistance management strategies. We describe here the application of this approach to the whitefly *Bemisia tabaci* on cotton.

MATERIALS AND METHODS

Cotton field simulators

Cotton field simulators for *B.tabaci* consist of three units: a sprayer in its housing unit at the front, a central cage holding plants and insects, and a plenum chamber with an exhaust fan at the rear (Figure 1). The main mechanical components of the sprayer are a drive unit, two spinning-disc controlled droplet applicators (CDAs), and a peristaltic pump to transfer insecticide solution from a reservoir to the CDAs. Caterpillar tracks propel the sprayer along overhead rails forward into the cage and back into its housing unit. Droplet size and delivery volume can be altered as required (Rowland *et al.*, 1990).

The cage itself (170 x 120 x 100 cm) is framed with square steel tubing. It is glazed but has fine steel mesh at each end to provide ventilation. Above the cage are banks of fluorescent and tungsten lights. The plenum chamber contains a 32 cm diameter variable-speed fan to draw air uniformly through the cage, simulating a light breeze (0.2 m/s).

Simulators are kept at 26 $\pm$ 2 °C with a 16 h photoperiod. Cotton plants can be kept in the simulators for 10 weeks, during which they support three whitefly generations. Adults present on leaves are counted *in situ* using rigid endoscopes inserted through brush borders on the sides of the cage.

Insects and insecticides

Resistant (R) and susceptible (S) strains of *B.tabaci*, initially collected from cotton in the Sudan (Dittrich *et al.*, 1985), were supplied by Ciba-Geigy, Basle. Formulated insecticides, also supplied by Ciba-Geigy, were cypermethrin ('Polytrin' 20% a.i. E.C.), profenofos ('Curacron' 50% a.i. E.C.) and a 1:10 mixture of cypermethrin and profenofos ('Polytrin C' 44% a.i. E.C.).

Dip tests against larvae and adults

Following standard bioassay protocols, cotton leaves infested with known numbers of resistant or susceptible 2nd-instar larvae were immersed into serial dilutions of insecticide for 10s. Survivors were counted at the pupal stage 9 days later. For tests against adults, cotton leaf discs immersed in insecticide solution were laid on agar gel inside plastic petri dishes and infested with 50 adults of mixed age and sex. Mortality was scored after 2 days. Results of both assays were subjected to probit analysis.

Experiments using field simulators

To measure the short-term effect of insecticides on adults in the simulators, approximately 500 resistant or susceptible newly-emerged whiteflies released onto 8 cotton plants (cv. "Delta Pine") inside each cage were given 24 h to settle, and then counted with an endoscope. Each simulator was then sprayed with a different dose of insecticide, and the number of adults remaining on plants after 2 days was recorded. Data were subjected to probit analysis for comparison with standard bioassay results.

Longer term effects of various treatment regimes against age-structured resistant populations were initiated by infesting cages containing 8 plants with 600 adults of the R strain. Adult numbers were monitored at 2-3 day intervals over the following three generations. The four regimes evaluated in this way were (i) cypermethrin alone (50g/ha), (ii) profenofos alone (500g/ha) with the exhaust fan on to dissipate profenofos vapour, (iii) profenofos alone with the fan off, and (iv) a temporal alternation of cypermethrin and profenofos with the fan on. Plants were sprayed twice per generation; the first treatment being timed to coincide with maximum adult emergence, and the second to concide with high densities of immatures. Treatment schedules are shown in more detail in Figure 2.

RESULTS AND DISCUSSION

Resistance levels in standard bioassays and simulator tests

Dip tests on both adults and larvae indicated moderate to strong resistance of the R strain to cypermethrin and profenofos alone, but little or no resistance to the cypermethrin and profenofos mixture (Table 1). Simulator tests on adults also disclosed resistance to profenofos, but unlike in dip tests there was no clear difference in the response of S and R adults to cypermethrin. Conversely, the simulator tests did show resistance to the mixture, at a level comparable to that obtained for profenofos alone.

TABLE 1. Comparison of LC_{50}s[1] and resistance ratios[2] (in parentheses) for a resistant (R) and susceptible (S) strain in standard bioassays and short-term simulator tests.

	Dip tests				Simulators	
	larvae		adults		adults	
	S	R	S	R	S	R
Cypermethrin	0.08	1.81 (23)	0.21	17.4 (83)	42.7	67 (1.6)
Profenofos	0.12	1.71 (14)	0.73	21.0 (29)	9.8	217 (22)
Mixture	0.16	0.19 (1.2)	1.49	3.8 (2.6)	6.2	158 (25)

[1]Expressed in mg/l for dip tests, g/ha for simulator tests
[2]LC_{50} for R strain/LC_{50} for S strain

These discrepancies between standard bioassays and simulators tests reinforce other findings (eg. Dennehy *et al.*, 1983) that the former can greatly misjudge how resistance is expressed under more realistic exposure conditions. Recent experiments indicate that the discrepancies are partly due to shorter contact with cypermethrin in the simulator than in the dip tests. This would in turn influence the expression of toxicological synergism between pyrethroids and organophosphorus compounds (Ishaaya *et al.*, 1987) applied as mixtures. Such effects are precluded in artificial, forced-contact bioassays.

Longer-term effects of control regimes

Cypermethrin alone was unsuccessful in controlling the R strain (Figure 2). Although applications of this compound did substantially reduce adult numbers, they failed to stem a progressive build-up of the adult population from generation to generation. Profenofos alone was ineffective with the exhaust fan on, but with the fan switched off this compound gave excellent and sustained control. Similarly, an alternation of cypermethrin and profenofos timed to coincide with adult and larval peaks respectively proved very successful in keeping the population at low density (Figure 2).

These very marked differences in control efficacy illustrate other aspects of pesticide performance whose implications can be explored most precisely using field simulator technology. Cypermethrin alone acts primarily as an adulticide, killing adults exposed to residues on the upper leaf surfaces. Lacking any detectable translaminar or vapour action (M.Rowland *et al.*, unpublished data), this compound is unlikely to affect immatures congregated on the under-surfaces of leaves. Hence although cypermethrin treatments killed *c*. 50% of R adults/day, this did not constrain the egg production of survivors (*c*. 6 eggs/female/day; M.Rowland, unpublished data) sufficiently to forestall population growth. Lack of success with cypermethrin was due not to resistance (which was not expressed in the simulators; Table 1), but to its lack of translaminar larvicidal activity.

In contrast, profenofos kills whiteflies through translaminar and vapour action as well as by direct contact with residues (M.Rowland *et al.*, unpublished data). With the fans switched off, vapour build-up achieved satisfactory control (Figure 2), despite resistance being expressed in the simulators (Table 1). This chemical was much less effective with the fans dissipating vapour rapidly after spraying.

Even with the fans on, however, profenofos can contribute to controlling some resistant populations. The effectiveness of the cypermethrin/profenofos alternation demonstrates the potential for exploiting a knowledge of pest ecology to maximise the efficacy of pesticides against different life-stages, and indicates a key role for field simulators when devising such strategies.

Figure 1. Exploded view of field simulator with insecticide sprayer.

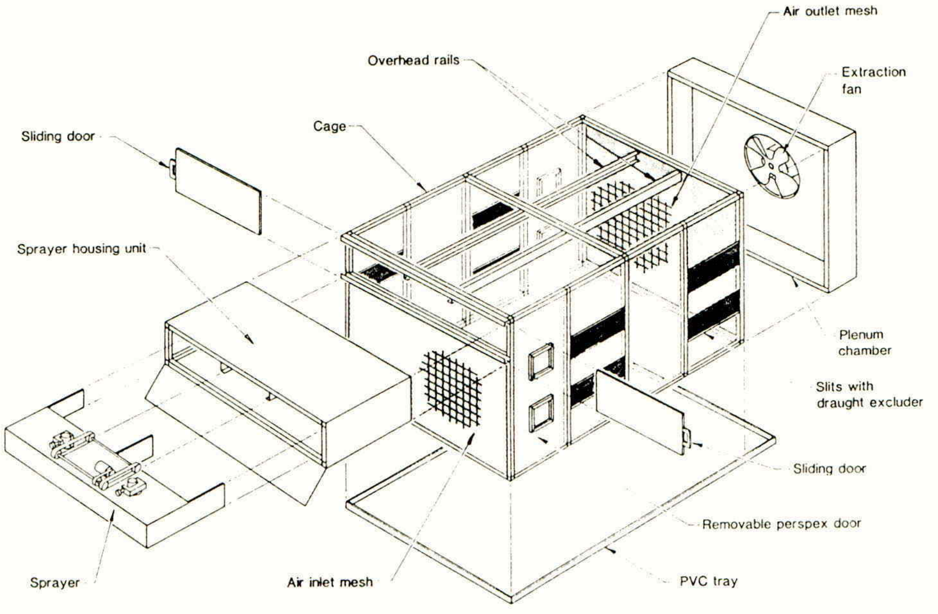
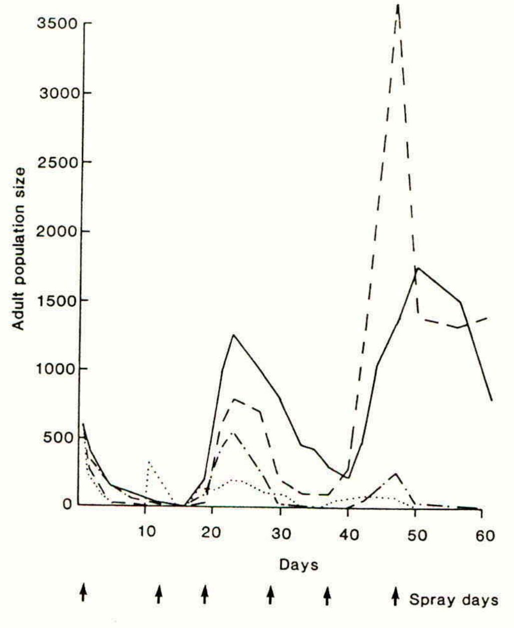


Figure 2. Effect of different treatment regimes on populations of whiteflies in the simulators (— — — profenofos with the fan on, ... profenofos with the fan off, ——— cypermethrin, —·—·—· cypermethrin alternated with profenofos).



CONCLUSIONS

Conventional bioassays are indispensible for large-scale, initial screening of insecticidal activity, and for routine documentation of changes in resistance levels. But for a more accurate and realistic appraisal of promising chemicals, and for evaluating how best to use insecticides to delay or combat resistance, field simulators provide a new and potentially very versatile approach.

ACKNOWLEDGEMENTS

The project was funded by Ciba-Geigy, Basle, and we thank Drs V. Dittrich and G. Voss of the company for their interest and support.

REFERENCES

Dennehy,T.J.; Granett,J.; Leigh,T.F. (1983) Relevance of slide-dip and residual bioassay comparisons to detection of resistance in spider mites. Journal of Economic Entomology **76**, 1225-1230.

Dittrich, V.; Hassan, S.O.; Ernst, G.H. (1985) Sudanese cotton and the whitefly: a case study of the emergence of a new primary pest. Crop Protection, **4**, 161-176.

Green, M.B.; LeBaron, H.M.; Moberg, W.K. (1990) Managing resistance to agrochemicals - from fundamental research to practical strategies. American Chemical Society, Washington.

Ishaaya, I.; Mendelson, Z.; Ascher,K.R.S.; Casida, J.E. (1987) Cypermethrin synergism by pyrethroid esterase inhibitors in adults of *Bemisia tabaci*. Pesticide Biochemistry and Physiology, **28**, 155-162.

Rowland, M.; Pye, B.; Stribley, M.; Hackett, B.; Denholm, I.; Sawicki, R.M. (1990) Laboratory apparatus and techniques for the rearing and insecticidal treatment of whitefly *Bemisia tabaci* (Homoptera: Aleyrodidae) under simulated field conditions. Bulletin of Entomological Research, **80**, 209-216.

A COMPARISON OF THE IN VITRO METABOLISM OF *CIS*-CYPERMETHRIN IN A RESISTANT AND SUSCEPTIBLE STRAIN OF *HELIOTHIS VIRESCENS*

S.E. CLARKE, C.H. WALKER, A.R. McCAFFERY

School of Animal and Microbial Sciences, University of Reading, Whiteknights, PO Box 228, Reading, RG6 2AJ

ABSTRACT

The PEG87 strain of *Heliothis virescens* exhibited a powerful monooxygenase based resistance to *cis*-cypermethrin. This metabolic resistance was reflected in the elevated levels of cytochrome P-450 (the terminal component of the monooxygenase system) in the resistant strain.The microsomal fraction from 4th instar PEG87 had a cytochrome P-450 specific content of 0.78 nmoles/mg of protein compared to 0.13 nmoles/mg for the susceptible strain (BRC). This six-fold increase in cytochrome P-450 was accompanied by a four-fold increase in the specific content of the cytochrome P-450 reductase. The *in vitro* rate of metabolism of *cis*-cypermethrin by PEG87 preparations was far higher than that observed in BRC. This difference was most significant for the products of oxidative metabolism which were NADPH dependent and suppressible by piperonyl butoxide. This increased cytochrome P-450 dependent oxidative attack of the *cis*-cypermethrin molecule is the basis of the metabolic resistance in the PEG87 strain.

INTRODUCTION

The tobacco budworm, *Heliothis virescens*, is a major pest of cotton in the United States, Central and South America. Control of *H.virescens*, especially in the late season, is primarily achieved by use of the synthetic pyrethroids.

Resistance to pyrethroids in *H.virescens* involves a number of processes but the major mechanisms appear to include target site insensitivity (Nicholson & Miller, 1985; Payne *et al.*, 1988) and metabolism. Metabolism of pyrethroids in *H.virescens* has been reported to occur by both oxidative (Nicholson & Miller, 1985) and hydrolytic attack (Dowd *et al.*, 1987).

The monooxygenases have been implicated in this metabolic resistance in studies on the in vivo fate of cypermethrin in *H.virescens* (Little *et al.*, 1989; Lee *et al.*, 1989). In order to more clearly establish and define the role for cytochrome P-450 in this resistance the fate of *cis*-cypermethrin *in vitro* using subcellular fractions from resistant and susceptible insects was investigated.

This study forms part of a wider programme investigating the major mechanisms of pyrethroid resistance in field strains of the insect, leading to the development of a comprehensive management strategy.

MATERIALS AND METHODS

Insects

Resistant (PEG87) and susceptible (BRC) strains of *Heliothis virescens* were supplied by ICI Americas Incorporated, Goldsboro, N. Carolina, USA and ICI Agrochemicals, Jealott's Hill, UK., respectively. These were reared in the laboratory in a similar manner to that detailed by Ahmad & McCaffery (1988). The PEG87 strain displayed a 5000-fold resistance to cis-cypermethrin as compared to the BRC strain after treatment by topical application.

Chemicals

The 3-phenoxybenzoic acid and the corresponding aldehyde and alcohol were purchased from Sigma Chemical Co., Poole, UK. The other reference compounds were supplied by Shell Research Ltd, Sittingbourne, UK., as was the *cis*-[^{14}C-cyclopropyl]cypermethrin (48 μCi/mg). Piperonyl butoxide was supplied by Wellcome Research Laboratories, Berkhamsted, UK.

Reverse phase hplc

A SpectraPhysics solvent delivery system was used. The eluate was monitored for u.v. absorbance at a wavelength of 254nm with a SpectraPhysics SP8773XR detector. Fractions for radioassay were collected in a Pharmacia fraction collector and quantified using a Packard Tricarb 2250CA scintillation counter employing Ecoscint scintillation fluid. The column was of 250 mm x 4.9 mm containing 5μm Spherisorb-ODS stationary phase (Hichrom) eluted with water-acetonitrile containing 0.5% (*V/V*) acetic acid with a linear gradient from 5% to 100% acetonitrile over 25 minutes at a flow rate of 1ml/min. The elution times of the reference compounds by this system are described in Table 1.

TABLE 1. Liquid chromatography of *cis*-cypermethrin and its principal metabolites.

Compound and Code	Elution time (min)
cis-cypermethrin (*c*-cyper)	27.9
4'-Hydroxy-*c*-cyper (4'HO-*c*-cyper)[a]	24.3
trans-Hydroxy-*c*-cyper (*t*HO-*c*-cyper)[b]	24.3
3-phenoxybenzoic aldehyde (PBald)	21.9
cis-3-(2,2-Dichlorovinyl)-2,2-dimethyl-cyclopropanecarboxylic acid (*c*-Cl2CA)	20.0
cis-3-(2,2-Dichlorovinyl)-*cis*-2-hydroxymethyl-2-methylcyclopropanecarboxylic acid lactone (*c*-Cl2CA-lac)[b]	19.5
3-phenoxybenzoic acid (PBacid)	18.8
cis-3-(2,2-Dichlorovinyl)-*trans*-2-hydroxymethyl-2-methyl cyclopropane carboxylic acid (*t*HO-*c*-Cl2CA)[b]	14.8

[a] 4'-Hydroxy refers to the 4-position of the 3-phenoxy group.

[b] *trans*-Hydroxy and *cis*-Hydroxy refer, respectively, to one of the two 2,2-dimethyl groups which has been hydroxylated. The stereochemical descriptor defines the orientation of the hydroxymethyl group relative to the carboxyl group of the cyclopropanecarboxylic acid.

Microsome preparation

Microsomes were prepared from 4th instar larvae by differential centrifugation, at a temperature of 4°C where possible. After removal of heads and the contents of the gut the insects were washed and scissor minced in 50mM Tris-HCl buffer (pH 7.5) containing 20% (*V/V*) glycerol, 1mM ethylenediaminetetraacetic acid (EDTA), 400μM phenylmethylsulphonyl fluoride (PMSF) and 100μM phenylthiourea. This mixture was homogenised in this buffer with two 30 second bursts in a liquid shear homogeniser. This brei was filtered through two layers of muslin and centrifuged at 10,000g for 20 minutes. The supernatant was decanted and respun at 100,000g for 90 minutes. The resulting pellet was gently rinsed with 50mM Tris-HCl buffer (pH 7.5) containing 20% (*V/V*) glycerol, 1mM EDTA and 400μM PMSF then resuspended in this buffer and centrifuged again at 100,000g for 60 minutes. The final microsomal pellet was resuspended in a small volume of the same buffer to an approximate concentration of 4mg/ml and stored at -80°C until needed. No loss of activity was seen in samples stored in this way for up to six months.

In vitro assays

Microsomal suspensions (1mg/ml) were incubated with 30μg/ml *cis*-cypermethrin (10μl of a 3mg/ml solution in acetone) and 10mM NADPH at 25°C for 5 minutes before the reaction was terminated by the addition of 0.5ml of 1M HCl. The *cis*-cypermethrin and its metabolites were extracted by 3 x 5ml of acidified diethylether which was evaporated to dryness under a stream of nitrogen. These samples were resuspended in 100μl of acetonitrile for analysis by hplc. Alternative incubations without NADPH were also performed in the same manner, as were those containing the monooxygenase inhibitor piperonyl butoxide at a concentration of 100μM (10μl of a 10mM solution in acetone).

Enzyme assays

Cytochrome P-450 was determined spectrally by the method of Omura & Sato (1964). Microsomes were diluted two-fold with distilled water. Reduction to the ferrous form of the haemoprotein was achieved by the addition of several grains of sodium dithionite and the sample cuvette gassed with carbon monoxide and the ensuing difference spectrum recorded between 400 and 500nm. Cytochrome P-450 was quantified using the extinction coefficient (450-490nm) of 91mM-1cm-1. The activity of the flavoprotein cytochrome P-450 reductase was determined by the method of French & Coon (1979) according to its ability to reduce cytochrome c. The sample was diluted with 100mM Tris-HCl buffer (pH 7.5) and 0.2ml of this and 1.0ml of cytochrome c (0.46mg/ml) was added to each cuvette. The volume was made up to 2.9ml and after the establishment of a baseline at 550nm 0.1ml of NADPH (20mg/ml) was added to the sample and the initial velocity measured. The activity was calculated using the extinction coefficient for reduced cytochrome c of 18.5mM-1cm-1.Protein was determined by the method of Lowry *et al.* (1951) using bovine serum albumin as standard.

RESULTS

The resistant PEG87 strain of *H.virescens* demonstrated elevated levels of the components of the monooxygenase system compared to the susceptible BRC strain (Table 2). Both cytochrome P-450 and its reductase were higher in PEG87 insects.

TABLE 2. Comparison of the specific content of the monooxygenase components in PEG87 and BRC microsomal fractions.

Strain	Cytochrome P-450 (nmol/mg)	Cytochrome P-450 reductase (Units/mg)
BRC	0.13 ± 0.02	0.006 ± 0.001
PEG87	0.78 ± 0.16	0.026 ± 0.005

The production of the monohydroxylated products of *c*-cyper (4'HO-*c*-cyper and *t*HO-*c*-cyper) was NADPH dependent and ocurred at a higher rate in PEG87 than BRC microsomes (Table 3). These metabolites also underwent esteratic cleavage to give *c*-Cl2CA-lac and tHO-*c*-Cl2CA the appearance of which displayed the same dependence and strain specific pattern. The production of the ester cleaved product of *c*-cyper (*c*-Cl_2CA) was stimulated by the addition of NADPH, but in the absence of NADPH was little higher in PEG87 than BRC. The 3-phenoxy benzoic metabolites could not be accurately quantified as the radiolabel was only available at the cyclopropyl ring. However the production of PBald was apparent from the u.v. trace and in the presence of NADPH this was succeeded by the formation of PBalc and PBacid.The addition of piperonyl butoxide to the incubation mixture resulted in a suppression of the formation of oxidative products (Table 3) such that many metabolites were no longer detectable. This inhibitor also removed the stimulatory effect of NADPH on the formation of *c*-Cl_2CA.

TABLE 3. Metabolism of *cis*-cypermethrin by microsomal preparations from PEG87 and BRC insects.

Metabolite	Rate of Formation (nmol/min/mg protein) BRC		PEG87	
-	NADPH	+NADPH	-NADPH	+NADPH
4'HO-*c*-cyper/*t*HO-*c*-cyper	nda	0.23	nda	2.62
	(nda)	(nda)	(nda)	(0.31)
c-Cl_2CA-lac	nda	0.08	nda	1.36
	(nda)	(nda)	(nda)	(0.59)
*t*HO-*c*-Cl_2CA	nda	0.01	nda	0.38
	(nda)	(nda)	(nda)	(nda)
c-Cl_2CA	0.38	0.50	0.71	1.25
	(0.35)	(0.40)	(0.62)	(0.70)

nda - no detectable activity.
All values are the average of two determinations that did not vary by more than 10%. Values in bracket are those for incubations containing 100µM piperonyl butoxide.

DISCUSSION

This study demonstrates that the metabolic resistance displayed by the PEG87 strain of *H.virescens* is a consequence of its elevated monooxygenase system, in particular the higher specific content of cytochrome P-450. Cytochrome P-450 has been established to be a superfamily of related enzymes with broad and overlapping substrate specificities (Nebert *et al.*, 1989). Such a structure is likely to exist for insect cytochromes P-450 and the six-fold increase in specific content may represent an elevation of one or more isoenzymes with related capabilities for metabolising pyrethroids.

The metabolism of *c*-cyper by the microsomal preparations demonstrate that it is the rate of the cytochrome P-450 dependent oxidative reactions that represents the major metabolic difference between the resistant PEG87 strain and the susceptible BRC strain. The esteratic cleavage is of microsomal origin and may be due to the presence of a carboxylesterase analogous to those found in rat liver microsomes (Mentlein *et al.*, 1987). However a soluble esteratic activity is also apparent in both BRC and PEG87 and *in vivo* this would also contribute to the clearance of cypermethrin. Quantitatively the NADPH dependent metabolites are still the most important in PEG87 *H.virescens*.

The NADPH dependent increase in formation of *c*-Cl2CA in PEG87 microsomes would appear to be related to the increase in cytochrome P-450 levels. This could be a result of the 4'HO-*c*-cyper being a better substrate for esteratic attack or as a result of a cytochrome P-450 oxidative attack leading to an apparent ester cleavage. Hydroxylation of the a-carbon would lead to an unstable metabolite that could break down in this way (Edwards *et al.*, 1987).

The involvement of the cytochrome P-450 monooxygenase system in pyrethroid resistance in *H.virescens* has been suggested previously (Nicholson & Miller, 1985; Lee *et al.*, 1989). This study clearly demonstrates that the pyrethroid resistant PEG87 insects possess greatly elevated levels of cytochrome P-450 which is reflected in a far greater rate of metabolism of the cypermethrin compared to susceptible insects. The NADPH dependence and the sensitivity to inhibition by piperonyl butoxide in these *in vitro* assays accurately establishes cytochrome P-450 as a major factor in the resistance of this strain of *H.virescens* to pyrethroids.

ACKNOWLEDGEMENTS

The authors are grateful to the Pyrethroids Efficacy Group for financial support. Our thanks are also due to J.N. Perry for technical assistance.

REFERENCES

Ahmad, M.; McCaffery, A.R. (1988) Resistance to insecticides in a Thailand strain of *Heliothis armigera* (Hubner) (Lepidoptera:Noctuidae) *Journal of Economic Entomology* **81**,45-48.

Dowd, P.F.; Gagne, C.C.; Sparkes, T.C. (1987) Enhanced pyrethroid hydrolysis in pyrethroid resistant larvae of the tobacco budworm *Heliothis virescens* (F) *Pesticide Biochemistry and Physiology* **28**, 9-16.

Edwards, R.; Millburn, P.; Hutson, D.H. (1987) Factors influencing the selective toxicity of *cis*- and *trans*-cypermethrin in rainbow trout, frog, mouse and quail:

biotransformation in liver, plasma, brain and intestine. *Pesticide Science* **21**, 1-21.

French, J.S.; Coon, M.J. (1979) Properties of NADPH-cytochrome P-450 reductase purified from rabbit liver microsomes. *Archives of Biochemistry and Biophysics* **195**, 565-573.

Lee, K.S.; Walker, C.H.; McCaffery, A.R.; Ahmad, M.; Little, E. (1989) Metabolism of *t rans*-cypermethrin by *Heliothis armigera* and *H.virescens*. *Pesticide Biochemistry and Physiology* **34**, 49-57.

Little, E.J.; McCaffery, A.R.; Walker, C.H.; Parker, T. (1989) Evidence for an enhanced metabolism of cypermethrin by a monooxygenase in a pyrethroid resistant strain of the tobacco budworm (*Heliothis virescens* F.) *Pesticide Biochemistry and Physiology* **34**, 58-68.

Lowry, O.H.; Rosenbrough, N.J.; Farr, A.L.; Randall, R.J. (1951) Protein measurement with the folin phenol reagent. *Journal of Biological Chemistry* **193**, 265-272.

Mentlein, R.; Ronai, A.; Robbi, M.; Heymann, E.; Deimling, O.V. (1987) Genetic identification of rat liver carboxylesterases isolated in different laboratories. *Biochemica et Biophysica Acta* **913**, 27-38.

Nebert, D.W.; Nelson, D.R.; Adesnik, M.; Coon, M.J.; Estabrook, R.W.; Gonzalez, F.J.; Guengerich, F.P., Gunsalus, I.C.; Johnson, E.F.; Kemper, B.; Levin, W; Phillips, I.R.; Sato, R.; Waterman, M.R. (1989) The P-450 gene superfamily. Recommended nomenclature. *DNA* **8**, 1-12.

Nicholson, R.A.; Miller, T.A. (1985) Multifactorial resistance to transpermethrin in field collected strains of the tobacco budworm *Heliothis virescens* F. *Pesticide Science* **16**, 561-570.

Omura, T,; Sato, S. (1964) The carbon monoxide binding pigment of liver microsomes. II. solubilisation, purification and properties. *Journal of Biological Chemistry* **239**, 2379-2385.

Payne, G.T.; Blenk, R.G.; Brown, T.M. (1988) Inheritance of permethrin resistance in the tobacco budworm (Lepidoptera:Noctuidae) *Journal of Economic Entomology* **81**,65-73.

SEASONAL VARIATION OF SUSCEPTIBLE AND RESISTANT VARIANTS OF *MYZUS PERSICAE*

C. FURK, C. M. HINES

Central Science Laboratory, Ministry of Agriculture, Fisheries and Food, Hatching Green, Harpenden, Herts AL5 2BD

S. D. J. SMITH, A. L. DEVONSHIRE

AFRC Institute of Arable Crops Research, Rothamsted Experimental Station, Harpenden, Herts AL5 2JQ

ABSTRACT

The resistance freqencies of *Myzus persicae* populations from unsprayed oilseed rape sites in England were determined throughout the winters of 1988/89 and 1989/90. At all sites the proportions of the very resistant R_2 and R_3 aphids decreased through the winter and were virtually absent from January onwards even though susceptible (S) and R_1 aphids were still abundant. Results from the National survey of resistance further endorsed this seasonal fluctuation of resistant and susceptible variants.

INTRODUCTION

Over the last 25 years *Myzus persicae* has become increasingly difficult to control with pesticides as insecticide-resistant variants have become more abundant (Furk, 1986, ffrench-Constant & Devonshire, 1988; Smith & Furk, 1989). Resistance is conferred by elevated levels of an esterase enzyme (termed E4) (Devonshire, 1977) which can hydrolyse or sequester most insecticides. Aphids may be broadly classified as susceptible, moderately resistant (R_1), very resistant (R_2) or extremely resistant (R_3) according to the quantity of E4 present (Devonshire & Sawicki , 1979).

The National survey of resistance in the UK done by ADAS in conjunction with British Sugar field staff provides a broad regional picture of resistance frequencies (Smith & Furk, 1989). However, more detailed studies have indicated temporal and spatial variations some of which may be accounted for by the relative overwintering success of susceptible and resistant variants (Smith *et al.*, 1990).

Broadbent & Heathcote (1955) showed that the majority of alate *M.persicae* caught in the spring in the UK had migrated from a secondary host, confirming the importance of the anholocyclic part of the life cycle in determining the number of aphids which overwinter successfully.

This paper reports the results of the National survey of resistance done in 1989 and 1990 and of overwintering studies on susceptible and resistant variants of *M.persicae* from autumn-sown oilseed rape and suggests possible explanations of the patterns found.

MATERIALS AND METHODS

Three unsprayed oilseed rape sites at Southminster (Essex), Nocton (Lincolnshire) and Stoke Charity (Hampshire) were sampled monthly throughout the winter of 1988-89, and one site (Southminster) was further sampled through the winter of 1989-90, by taking between one and two hundred plants randomly from each site and removing adult *Myzus persicae*. A further six sites in Essex and six in Suffolk were sampled in October 1988 and February 1989, and three Suffolk sites again in 1989/90. All aphids were tested for insecticide resistance using an immunoassay technique (Devonshire *et al.*, 1986).

Results from all sites were pooled for September - November and January - March to represent autumn and spring populations for 1988/89 and 1989/90. Data for these time periods are presented as E4 activity distributions with the standard laboratory clones (S, R_1, R_2 and R_3), classified according to E4 quantity (Devonshire & Sawicki, 1979) as reference markers. However for convenience, aphids from the monthly samples from Southminster, Nocton and Stoke Charity and from the National survey have been classified as S, R_1, R_2 and R_3 according to their log esterase activity in the immunoassay i.e. S (< -0.7 using 0.08 of an aphid), R_1 (-1.0 to -0.25 using 0.02 of an aphid), R_2 (-0.25 to 0.4 using 0.02 of an aphid) and R_3 (> 0.4 using 0.02 of an aphid).

The National resistance survey consisted of aphid samples taken from sprayed and unsprayed sites throughout England in 1989 and 1990 from sugar beet, brassica, potato and oilseed rape crops by ADAS Regional Entomologists and British Sugar field staff and sent to either CSL, Harpenden or IACR, Rothamsted for testing.

RESULTS

E4 distributions for autumn and spring populations (Figure 1).

In autumn 1988 the majority of resistant aphids fell into the range of E4 activities corresponding to the R_1 to R_2 but with a small proportion in the R_3 (individual aphids sampled from oilseed rape at this time were very large resulting in a slight shift in activities towards higher values) (a). However samples from the same sites the following spring showed a shift towards E4 activity characteristic of R_1 or lower (b). The sample size was smaller in 1989/90 but similar seasonal changes in E4 distributions were found (c and d).

Monthly changes in resistance frequencies through the winter (Figure 2).

Very resistant R_2 and R_3 variants were found at all sites in decreasing frequencies until December or January, even at Stoke Charity which had the highest overall proportion of susceptible aphids. No very resistant aphids were found at any of the sites in February and March, 1989 (a - c). There was a similar trend at Southminster in 1989/90 (d).

National survey of resistance, 1989/90 (Figure 3).

Very few resistant R_2 and R_3 variants were found in the overall National survey until September when

Figure 1. Distribution of E4 activity in aphid samples (solid bars) in autumn and spring 1988/89 and 1989/90. The fitted distributions of four laboratory reference clones (broken curves) are given for comparison.

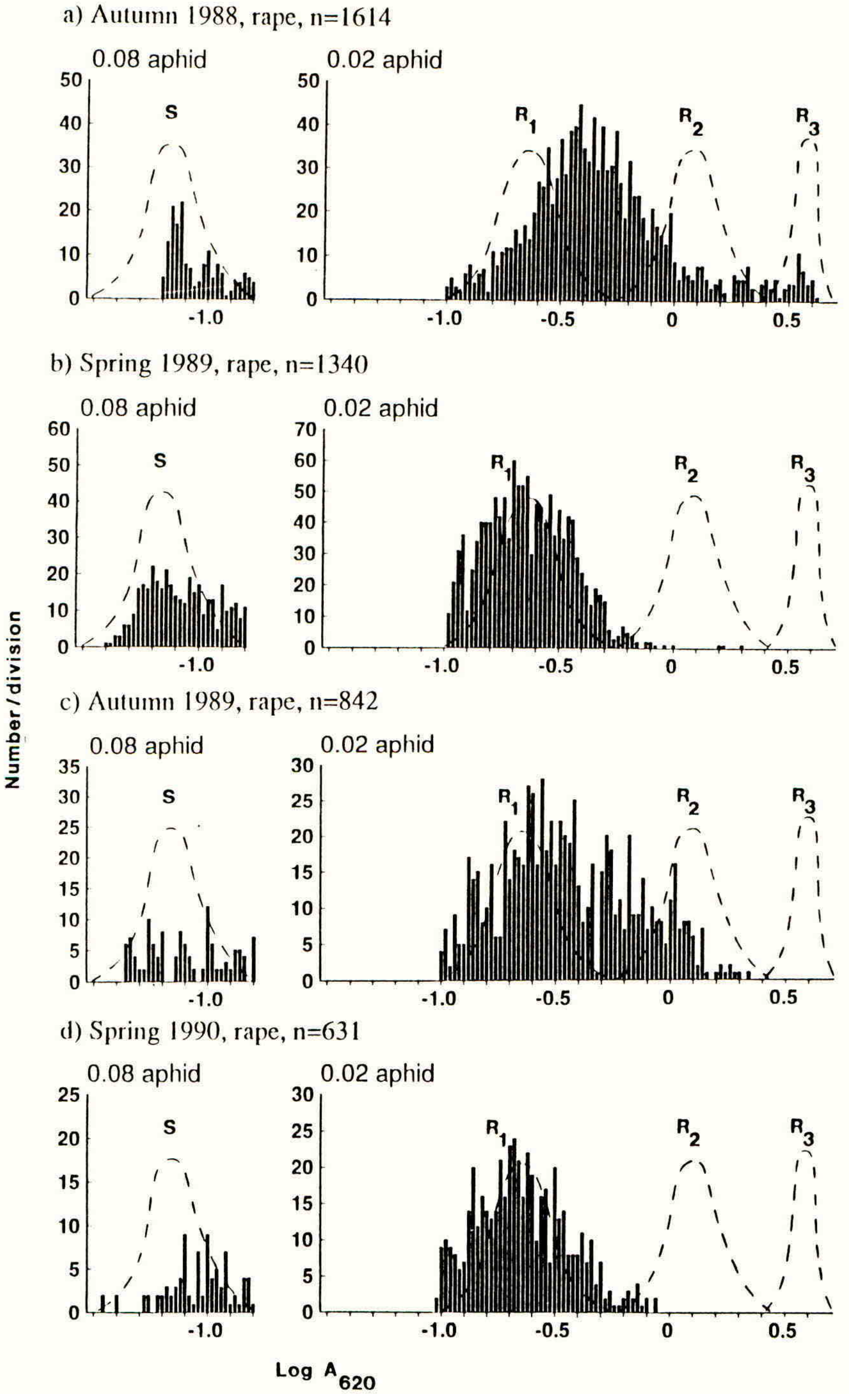
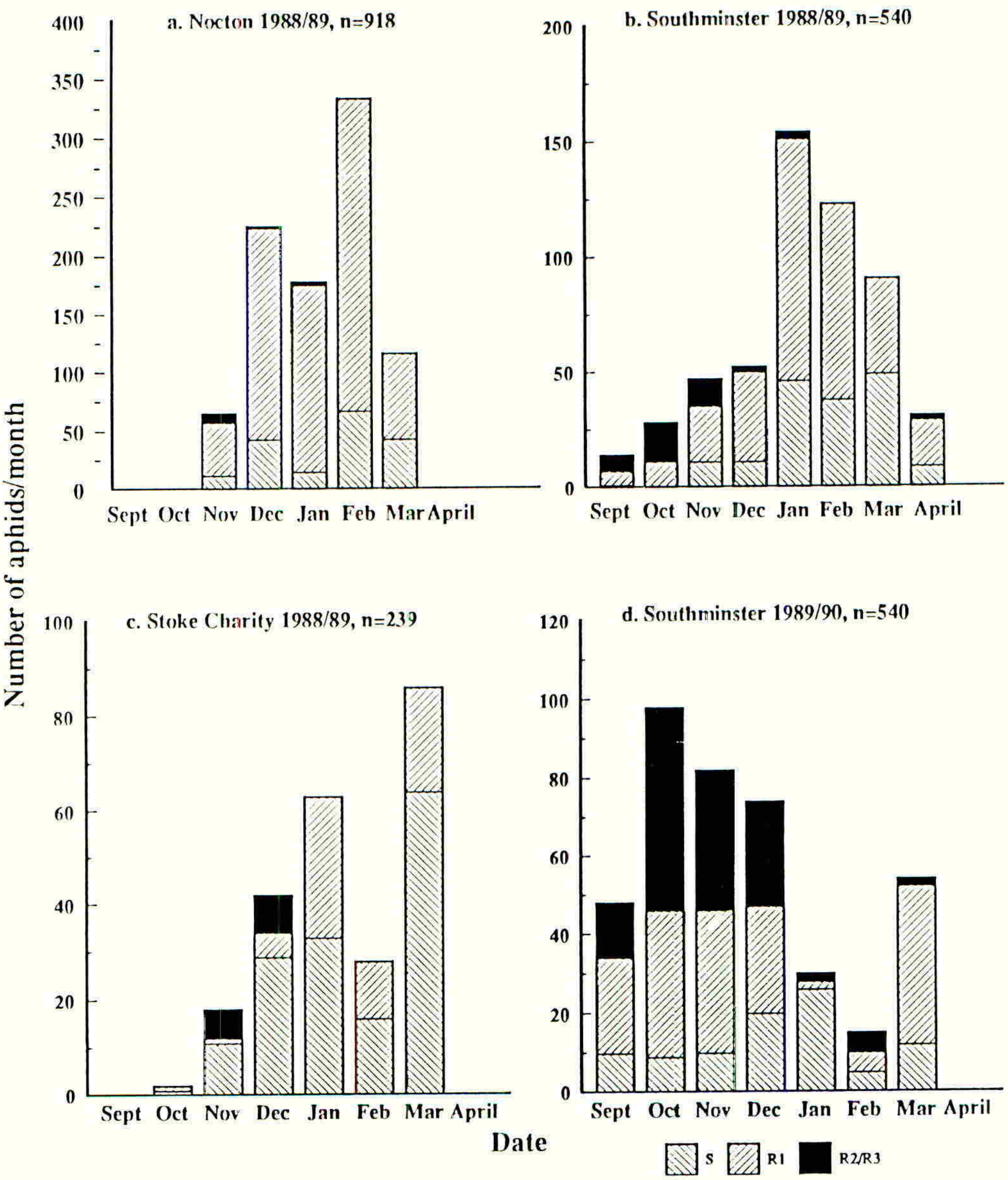
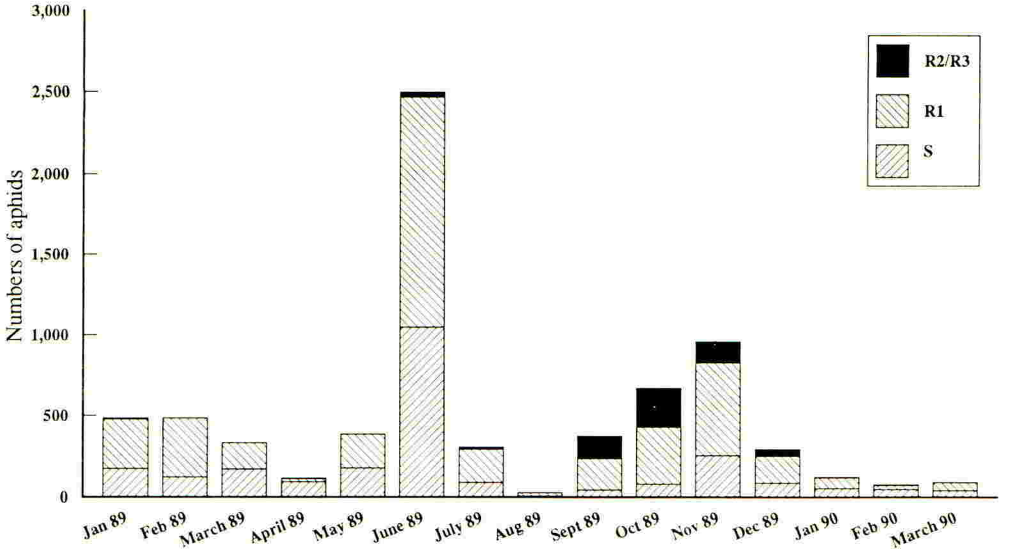


Figure 2. Numbers of susceptible and resistant *Myzus persicae* sampled at three unsprayed oilseed rape sites in England during winters of 1988/89 and 1989/90.



proportions reached 38 per cent of the total tested. Proportions then steadily declined reaching 14 per cent in November and December. During January to March 1990 only 10 out of 286 (3.5%) aphids collected were R_2/R_3.

Figure 3. Numbers of susceptible and resistant *Myzus persicae* collected from sprayed and unsprayed sites in England in 1989/1990.



DISCUSSION

Surveys in the late 1980s showed a trend towards increasing proportions of the highly resistant variants (Dewar *et al.*, 1988, ffrench-Constant & Devonshire, 1988). However where large numbers of R_2s were found they had generally been collected in the autumn. Our work has shown that the timing of the aphid sampling can significantly influence the overall results; late summer/autumn collections are more likely to have higher proportions of very resistant variants.

The change in E4 distributions on oilseed rape through the winters of 1988/89 and 1989/90 was reflected in the overall National survey, such that spring populations colonising crops in May-June, 1989 comprised mainly R_1 types. The build up of very resistant variants in the autumn samples may be accounted for by selection pressure from insecticides applied through the spring and summer.

It is uncertain what proportion of the total *M. persicae* population is found on crops rather than on weeds throughout the year and to what extent there is movement between the two (Taylor, 1977). There were 276,000 ha of autumn-sown oilseed rape grown in England in 1988/89 (MAFF unpublished figures) and therefore this crop is extremely significant as a source of overwintering aphids for colonising spring crops and hence the resistance frequencies of these populations are important. The apparent decline in the proportion of very resistant aphids through the winter may be accounted for by the differential overwintering success of the different variants. O' Doherty (1984) using supercooling techniques found that R_2 variants showed inferior coldhardiness after a period of acclimation compared with S and R_1 types.

The 1988-89 winter was extremely mild (the mean monthly temperature at Rothamsted was at least 1.7°C above the 30 year mean), allowing large numbers of *M. persicae* to overwinter successfully. Even though the temperatures in 1989/90 were also above average (at least 2.2°C above the 30 year mean, except for November), the rainfall was significantly above average (the mean monthly rainfall was 19.2 mm above the 30 year average), which may account for the relatively small aphid numbers overwintering. Nevertheless winter climatic conditions appear to affect significantly the resistance frequencies of overwintering populations and this may be crucial in regulating the proportions of very resistant variants in the population.

ACKNOWLEDGMENTS

This work was part supported by a grant from the Sugar Beet Research and Education Committee. The authors would like to thank all those colleagues who collected aphid samples.

REFERENCES

Broadbent, L. ; Heathcote, G. D. (1955) Sources of overwintering *Myzus persicae* in England. *Plant Pathology* **4**, 135-137.

Devonshire, A. L. (1977) The properties of a carboxylesterase from the peach-potato aphid, *Myzus persicae* (Sulz.), and its role in conferring insecticide resistance. *Biochemical Journal* **167**, 675-683.

Devonshire, A. L. ; Sawicki, R. M. (1979) Insecticide-resistant *Myzus persicae* as an example of evolution by gene duplication. *Nature* **280**, 140-141.

Devonshire, A. L. ; Moores, G. D. ; ffrench-Constant, R. H. (1986) Detection of insecticide resistance by immunological estimation of carboxylesterase activity in *Myzus persicae* (Sulzer) and cross reaction of the antiserum with *Phorodon humuli* (Schrank) (Hemiptera:Aphididae). *Bulletin of Entomological Research* **76**, 97-107.

Dewar, A. ; Devonshire, A. L. ; ffrench-Constant, R. H. (1988) The rise and rise of the resistant aphid. *British Sugar Beet Review* **56**, 40-43.

ffrench-Constant, R. H. ; Devonshire, A. L. (1988) Monitoring frequencies of insecticide-resistance in *Myzus persicae* (Sulzer) (Hemiptera:Aphididae) in England during 1985-86 by immunoassay. *Bulletin of Entomological Research* **78**, 163-171.

Furk, C. (1986) Incidence and distribution of insecticide resistant strains of *Myzus persicae* (Sulzer) (Hemiptera:Aphididae) in England and Wales in 1980-84. *Bulletin of Entomological Research* **76**, 53-58.

O'Doherty, R. (1984) Cold-hardiness of the peach-potato aphid resistant and susceptible to insecticides. In :*Crop Protection in Northern Britain 1984. Proceedings of a conference held at Dundee University 19-22 March 1984*. Dundee, Scottish Crop Research Institute, pp.148-153.

Smith, S. D. J. ; Dewar, A. M. ; Devonshire, A. L. (1990) Resistance of *Myzus persicae* to insecticides applied to sugar beet. *Proceedings of the 53rd IIRB Winter Congress*, 379-398.

Smith, S. D. J. ; Furk, C. (1989) The spread of the resistant aphid. *British Sugar Beet Review* **57**, 4-6.

Taylor L. R. (1977) Migration and the spatial dynamics of an aphid, *Myzus persicae*. *Journal of Animal Ecology* **46**, 411-423.

VARIATION IN RESISTANCE FREQUENCIES OF *MYZUS PERSICAE* ON SUGAR BEET - IMPLICATIONS FOR CONTROL.

SARA D J SMITH & ALAN L DEVONSHIRE

Department of Insecticides & Fungicides, AFRC Institute of Arable Crops Research, Rothamsted Experimental Station, Harpenden, Herts, AL5 2JQ.

ABSTRACT

Aphid populations sampled from sugar beet in 1988 and 1989 showed very different resistance frequencies. While moderately resistant, R_1, variants comprised the majority of the population in both years, there was a significantly greater proportion of R_2 aphids in 1988 than 1989. The consequences of applying different insecticidal sprays and granular treatments was assessed using populations with resistance frequencies similar to those above. The results are discussed in relation to temporal and spatial variations in susceptible and resistant variants, and the implications for future control.

INTRODUCTION

In the last 5 years the proportion of very resistant, R_2, aphids has substantially increased in the sugar beet growing region of the UK (Smith & Furk, 1989), highlighting the need to evaluate the consequences of different control strategies. Organophosphate and carbamate insecticides have been used extensively to control *Myzus persicae* on various crops including sugar beet, and more recently mixtures of pyrethroids with organophosphates or carbamates have been applied for virus control. However, pyrethroid mixtures select for resistant variants more rapidly than organophosphate or carbamate insecticides alone, leading to aphid resurgence and poor control (ffrench-Constant *et al*., 1987; Dewar *et al*., 1988). The initial resistance status of the colonising population is of primary importance to control. This paper reports the resistance status of aphid populations sampled from sugar beet in 1988 and 1989, and the results of field trials using different spray and granular treatments done in 1988 and 1989 on aphid populations with corresponding resistance frequencies.

METHODS

Resistance status of *M.persicae* on sugar beet in 1988 and 1989.

The resistance frequencies of random samples of adult *M.persicae* from unsprayed sugar beet from approximately twenty sites in Essex, Suffolk and Bedfordshire in 1988 and 1989 were determined by immunoassay (Devonshire *et al*., 1986). The data are presented as E4 activity distributions for each year, with standard laboratory clones classified according to E4 quantity (V1 or S; V4 or R_1; V16 or R_2; V64 or R_3) (Devonshire & Sawicki, 1979) as reference markers.

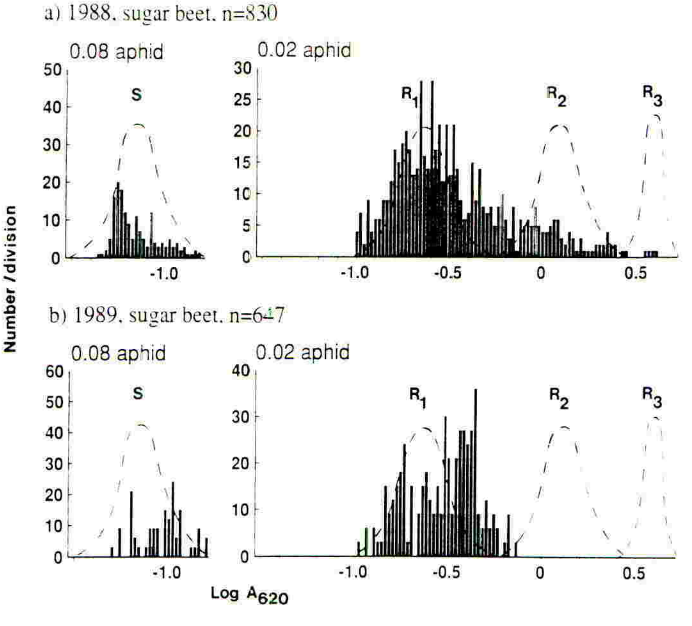
Field trial 1988 (artificial infestation).

Aphids from laboratory clones of known resistance status were introduced onto uncaged potted sugar beet plants in the field (approximately 20 aphids/plot of 30 plants), and allowed to settle and reproduce for two weeks before the first treatment was applied. Initial resistance frequencies were broadly typical of the indigenous population, R_1 (0.6), R_2 (0.3) and R_3 (0.05), but with a smaller proportion of susceptible aphids (0.05). Two insecticide treatments, pirimicarb (140g AI/ha) and deltamethrin+heptenophos (7.5+120g AI/ha) were applied twice with a 7 day interval. Five plants per plot were removed on each of five sampling occasions:- pre-treatment, 2 and 7 days after the first spray and 2 and 9 days after the second spray. Aphids were counted and adults taken for resistance testing.

Field trial 1989 (natural infestation).

Three spray treatments, pirimicarb (140g AI/ha), deltamethrin+heptenophos (7.5+120g AI/ha) and triazuron (100g AI/ha) (an experimental compound of a different insecticide class (Murray *et al.*, 1988)) were applied on one or two occasions to a natural infestation of *M.persicae* on sugar beet at Deepdale, Bedfordshire. A granule treatment, aldicarb (760g AI/ha), applied at sowing, was also assessed with and without a spray of pirimicarb (140g ai/ha). A similar sampling procedure to that of 1988 was adopted 3 and 12 days after each spray.

FIGURE 1. Distribution of E4 activity in aphid samples from sugar beet (solid bars) in 1988 and 1989. The fitted distributions of four laboratory reference clones (broken curves) are given for comparison.



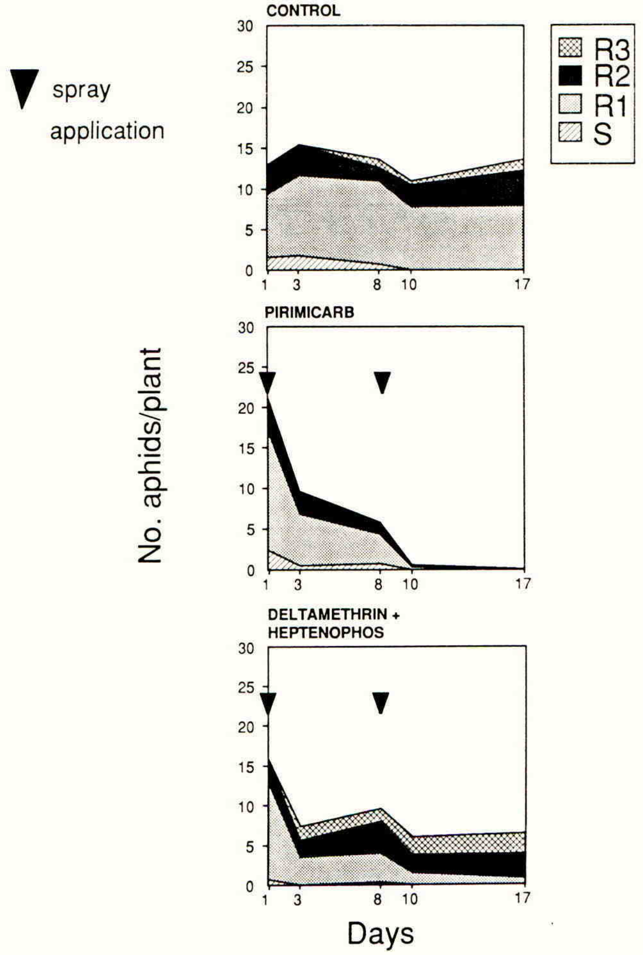
RESULTS

Resistance status of *M.persicae* on sugar beet in 1988 and 1989 (Figure 1).

The proportion of susceptible variants on unsprayed sugar beet was approximately similar in 1988 and 1989. The majority of resistant aphids in 1988 fell into the range of activities corresponding to R_1-R_2 and aphids equivalent to R_3 were detected at very low frequency (Figure 1 a.). However, in 1989 resistant aphids with R_1 activity only were found and very resistant variants, R_2-R_3, were almost absent (Figure 1 b.) compared with 1988 when they represented over 25% of the total.

Field trial 1988 (Figure 2).

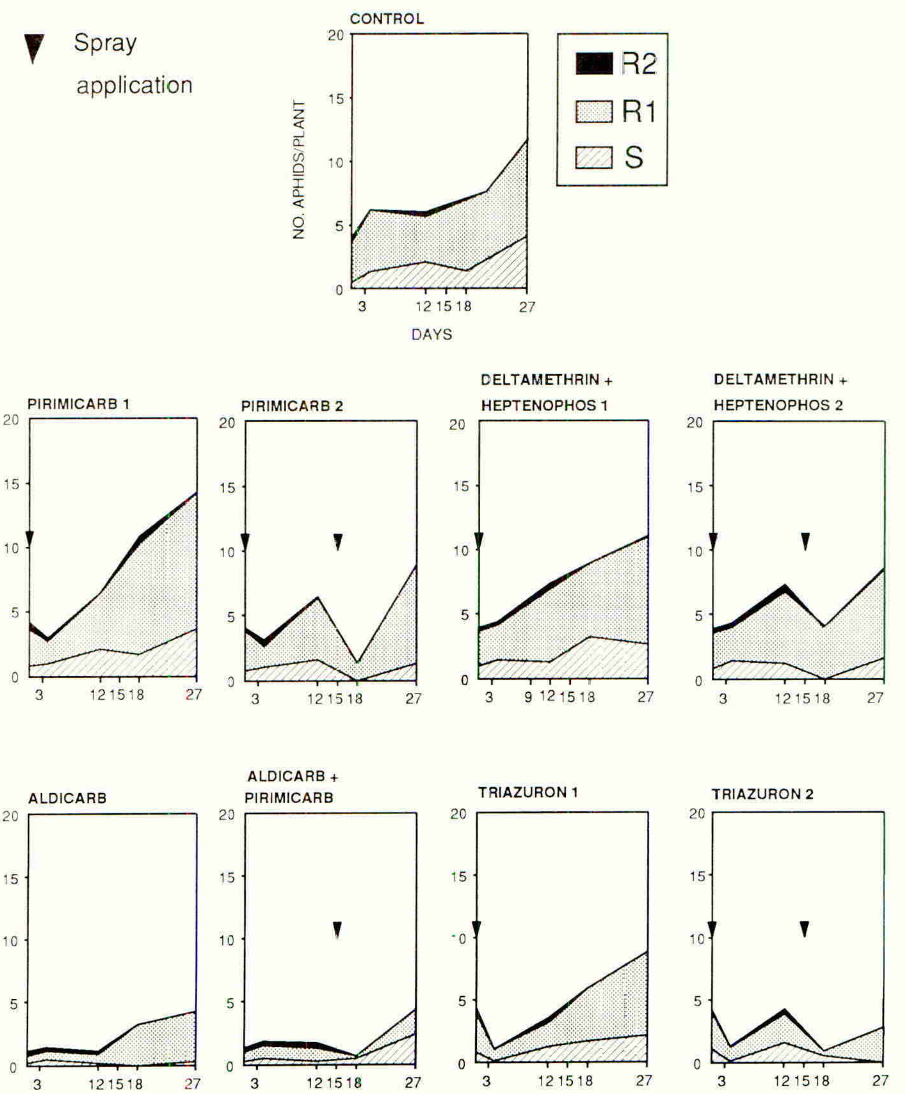
FIGURE 2. Survival of S, R_1, R_2 and R_3 aphids on unsprayed sugar beet, and after two sprays of pirimicarb or deltamethrin + heptenophos.



The first spray of deltamethrin+heptenophos gave a quicker initial control than pirimicarb, but after ten days their relative efficacies were reversed. After the second spray there were few survivors in the pirimicarb treated plots but in the deltamethrin+heptenophos plots the proportions of R_2s and R_3s had increased to over 90% of the total with only approximately 50% overall reduction in numbers compared with the untreated plots.

Field trial 1989 (Figure 3).

FIGURE 3. Relative efficacies of spray and granular insecticides against a natural infestation of *M.persicae* on sugar beet at Deepdale, Bedfordshire in 1989.



The indigenous population at Deepdale comprised mainly R_1 aphids with only a small proportion of very resistant R_2 types (less than 0.05). Aphid numbers in the aldicarb treated plots were initially lower than in the untreated plots and continued to remain relatively low for the duration of the trial. Three days after the first spray all treatments significantly reduced aphid numbers, with triazuron giving the best control of the mainly R_1 aphids and deltamethrin+heptenophos the poorest. Twelve days after the first spray only the aldicarb and triazuron plots had significantly fewer aphids than the untreated plots; numbers in other plots had risen significantly above those on the untreated plots. The resistance status of these aphids remained largely unchanged with very few R_2 aphids. After the second spray application, numbers were again significantly reduced to low levels. Pirimicarb and triazuron reduced numbers to 1 per plant or less while deltamethrin+heptenophos again gave the poorest control. By this time aphid numbers on plots which had received only one spray, except those treated with aldicarb (with or without pirimicarb) or triazuron, had risen significantly above those in untreated plots. There was little, if any, selection of very resistant variants by any of the treatments.

DISCUSSION

The reasons for the apparent absence of very resistant variants in the population in 1989 are unclear, although the very mild winter of 1988/89, which resulted in low aphid mortality, might have contributed; sugar beet crops were consequently colonised early by an exceptionally large migrant population (unpublished data from the Rothamsted Insect Survey), the majority of which corresponded to susceptible and moderately resistant (R_1) variants. Preferential overwintering success of susceptible aphids may explain the apparent loss of very resistant variants in the spring of 1989 (Smith *et al*., 1990; Furk *et al*., 1990).

The results of the 1988 trial confirmed the findings of previous trials (Dewar *et al*., 1988a) showing the adverse effects of pyrethroids, applied as mixture with an organophosphate, notably the selection of highly resistant aphids. However, prolonged colonisation of the trial at Deepdale in 1989 by predominantly S and R_1 aphids would have masked any selection of very resistant aphids. Consequently the trial served primarily to assess the persistence of each treatment in controlling these variants. Thus aldicarb gave good control combined with good persistence while the spray treatments gave poor persistence, although of these triazuron gave the best results. Triazuron also gave excellent control of R_2 and R_3 aphids in previous trials (Smith *et al*., 1990). The poor results for deltamethrin+heptenophos may reflect the lack of efficacy of the heptenophos component; organophosphorus compounds have proved the least effective against even R_1 aphids in other trials and pyrethroids have been implicated in the resurgence of very resistant variants (Dewar *et al*., 1988).

Thus not only variation in the resistance frequencies, but also the size of the indigenous population may significantly influence the control strategy adopted. Immigration of less resistant variants into treated areas, as occurred in 1989, may delay the build up of resistance (eg Comins, 1977; ffrench-Constant & Devonshire, 1986), but it cannot always be relied upon to dilute resistance frequencies. The persistence of a compound such as aldicarb when subjected to continual immigration by moderately resistant, R_1, aphids, may be more important in years such as 1989 than the ability to give good knockdown of very resistant, R_2 and R_3 aphids, as provided by pirimicarb for example.

ACKNOWLEDGEMENTS

This work was supported by a grant from the Sugar Beet Research and Education Committee.

REFERENCES

Comins, H.N. (1977) The development of insecticide resistance in the presence of migration. *Journal of Theoretical Biology*, **64**, 177-197.

Devonshire, A.L.; Sawicki, R.M. (1979) Insecticide-resistant *Myzus persicae* as an example of evolution by gene duplication. *Nature (London)*, **280**, 140-141.

Devonshire, A.L.; Moores, G.D.; ffrench-Constant, R.H. (1986) Detection of insecticide resistance by immunological estimation of carboxylesterase activity in *Myzus persicae* (Sulzer) and cross reaction of the antiserum with *Phorodon humuli* (Schrank) (Hemiptera:Aphididae). *Bulletin of Entomological Research*, **76**, 97-107.

Dewar, A.M.; Devonshire, A.L.; ffrench-Constant, R.H. (1988) The rise and rise of the resistant aphid. *British Sugar Beet Review*, **56**, 40-43.

ffrench-Constant, R.H.; Devonshire, A.L. (1986) The effect of aphid immigration on the rate of selection of insecticide resistance in *Myzus persicae* by different classes of insecticides. *Aspects of Applied Biology*, **13**, 115-125.

ffrench-Constant, R.H.; Devonshire, A.L.; Clark, S.J. (1987) Differential rate of selection for resistance by carbamate, organophosphorus and combined pyrethroid and organophosphorus insecticides in *Myzus persicae* (Sulzer) (Hemiptera:Aphididae). *Bulletin of Entomological Research*, **77**, 227-238.

Furk, C.; Hines, C.; Smith, S.D.J.; Devonshire, A.L. (1990) Seasonal variation of susceptible and resistant variants of *Myzus persicae* (Sulzer). *Proceedings of the British Crop Protection Conference*, this volume.

Murray, A.; Siddi, G.; Vietto, M. (1988) A new selective systemic aphicide. *Proceedings of the British Crop Protection Conference*, **1**, 73-80.

Smith, S.D.J.; Furk, C. (1989) The spread of the resistant aphid. *British Sugar Beet Review*, **57**, 4-6.

Smith, S.D.J.; Dewar, A.M.; Devonshire, A.L. (1990) Resistance of *Myzus persicae* to insecticides applied to sugar beet. *Proceedings of the 53rd IIRB Congress*, 379-398.

SESSION 10

CROP PROTECTION OPTIONS FOR REDUCED FARM INPUTS

CHAIRMAN DR J. P. G. WEBSTER

SESSION ORGANISER MR R. P. DAVIS

INVITED PAPERS 10-1 to 10-4

CONCEPTUAL RE-APPRAISAL OF UK ARABLE FARMING PRACTICES FOR INCREASED FLEXIBILITY IN CROP PROTECTION OPTIONS

V.W.L. JORDAN

Department of Agricultural Sciences, University of Bristol, AFRC Institute of Arable Crops Research, Long Ashton Research Station, Bristol BS18 9AF, UK

ABSTRACT

An arable farming system typically includes at least five important interacting components: rotation, cultivation, nutrition, protection and economics. It is not simply a sum of these components, but a complex with interactions which need to be fully understood. Crop protection is one quite complex component of this highly complex system and its needs are affected by changes in other parts of the system. It therefore needs to be treated as part of crop management - both planning and implementation - in order to ensure a reliable yield in terms of quantity, and feeding, milling or other properties, at reasonable cost with an acceptable profit margin for the practitioner. Thus, it is essential that expenditure on husbandry practices is regulated in the most efficient way to suit the crop grown. The following paper discusses opportunities for the integration of system components in the development of a lower input production system that will be sustainable in the long term.

INTRODUCTION

In the current situation in Europe of grain surpluses, increased production costs, falling grain prices and growing environmental concern, ways to rationalise and lower agrochemical inputs and reduce energy requirement, whilst maintaining quality production are being sought, and consideration given to their environmental consequences. This challenge provides an opportunity to re-appraise old concepts and methods alongside modern farming techniques, to devise systems to exploit natural regulatory mechanisms for preventing severe outbreaks of pests, diseases and weeds, and to justify their inclusion in integrated farming systems which are environmentally and economically sound as well as sustainable in the long term.

During the past decade, cereal crops in the UK have been grown under more intensive management regimes than ever before. New cultivars with high yield potential have been introduced, as have monocultures with minimum or reduced cultivation, early sowing and intensive use of fertilisers. These changes have markedly increased the risks of disease becoming severe, made plants more attractive and susceptible to pest attack, improved the growing conditions for some weeds, and necessitated new control strategies. Many changes in crop management have been introduced without a full understanding of their impact on pest, diseases and weeds.

Data from a survey in the early eighties (Sly, 1982) showed that in the UK, the average usage of herbicides, fungicides, insecticides and plant growth regulators in winter wheat and winter barley was 4.96 and 3.76 applications of pesticides/ha/year, respectively, with annual expenditure in the region of £270M. More recently, figures from the Arable Farm Crops Survey for 1988 (Davis *et al.*, 1990) showed that wheat was treated 6.7 times with 13 different active ingredients and winter barley 5.4 times with 10.9 different active ingredients. The conventional approach to crop production and pesticide use, has been via economically justified maximum yield responses, and has led to applications being either made routinely or targeted to specific risks, with a wide range in frequency of applications. Despite the range of control measures in the UK, annual losses from diseases of wheat and barley over the past decade are estimated to be over £125M.

Central to any farming enterprise is farm economics with production costs (seed, fertiliser, sprays - variable costs, + fixed costs) balanced against yield, for profitability. Data from the Report on Farming in the Eastern Counties of England, University of Cambridge, 1987/1988 show that in 1988, variable costs were *ca* £200/ha with fixed costs at £456/ha. Whilst it is difficult to reduce fixed costs, there may be greater opportunities to save expenditure by reduction in variable costs, especially the two most significant and costly inputs, nitrogen and pesticides. An examination of typical growing costs for winter wheat in north-west England (J. Hayes (ADAS): pers. comm), to identify areas where savings might be made, demonstrated the variability in expenditure for each agronomic input, and the estimated likely economic response, using data extrapolated from many field experiments (Table 1).

TABLE 1. Typical production costs for winter wheat in north west England.

Input	Costs (£/ha)		Likely Crop Response
	Average	Range	
Seed	42	24 - 62	low
Nitrogen	62	37 - 89	high
Phosphate/potash	24	0 - ?	low
Herbicide	24	10 - 86	medium
Fungicide	24	15 - 64	medium-high
Insecticide	5	0 - 12	medium
Growth regulator	7	0 - 27	low
Total	188		

Whilst agrochemicals are necessary to maintain food production at current levels, their intensive use is now considered by many people to be socially and environmentally damaging or even unacceptable. Organic farming, on the other hand, raises such questions as whether the methods are necessary to sustain the required food production level, and whether they are safe for humans and animals. Long Ashton has been given special responsibility within the AFRS to investigate aspects of lower-input arable farming and the environment (LIFE) and MAFF are also developing a project Towards A Lower Input System Minimising Agrochemicals and Nitrogen (TALISMAN). UK scientists are working together with those in other European Member States to develop moderating alternatives to the extremes of "Conventional Intensive" and "Organic" farming.

The objectives of this new programme are:

(i) to decrease the cost and improve the environmental safety of farming arable crops in the UK;

(ii) to provide basic information on the effects, interactions and ecological implications of a farming systems approach;

(iii) to investigate the opportunities to reduce crop protection and husbandry inputs selectively in experiments utilising the benefits of crop rotation and soil management, whilst sustaining cost-effective high-quality crop production.

Farming practices can sometimes be manipulated to reduce the impact of pests, diseases and weeds, thereby lowering the requirement for crop protection sprays. However, such modifications are only acceptable if profitable quality production is sustained. Therefore, research is needed to determine the best options in an integrated system for optimal response. Although interactions between various factors are inevitably complex in an integrated approach, this may be partially simplified by focusing on some key primary factors, for example to conserve nutrients, discourage pests, diseases and weeds and encourage beneficial elements.

Crop Rotation

Cropping sequences can play an important role in either encouraging or minimising pest, disease and weed attack.

Typical high energy-consuming systems are continuous winter wheats, with or without winter barley and oilseed rape in the rotation. These usually involve much nitrogen and pesticide use to achieve maximum yield. The yield performance of wheat is affected by many factors, but is much influenced by its postion in a cropping sequence. Mean yields in 1989 of ten cultivars grown in National Institute of Agricultural Botany winter wheat trials as either "first-wheats", "second-wheats" (Recommended List Trial Series) or continuous cereals, were 10.82, 8.42, and 5.84 t/ha, respectively (Furber, 1990). Therefore, "first wheats" offer the best yield potential, mainly as a consequence of the contribution of residual nutrients and of less pressure from trash-borne disease inoculum, which in turn offers options for reductions in pesticide use. Invariably, "first-wheats" are wheats grown for milling and breadmaking quality, and thus command a price premium; this must be an important consideration in devising a profitable lower-input cropping system.

Legumes have an important role in the development of a system to conserve nitrogen. They collect and store nutrients, particularly nitrogen, and crop residues add organic matter to the soil when incorporated. Other crop options need to be considered in the light of relative market prices and demands, support prices, the impact of the break crop on the yield of the subsequent "first wheat", and their position in the cropping sequence.

Winter oilseed rape is a profitable, competitive crop in which reductions in total amount of herbicide use can be made. Additionally, it seldom suffers from pest and disease constraints which are sufficiently damaging to justify routine pesticide applications. Winter oats and linseed may also be regarded as low-input option crops. Spring cereals, especially appropriate variety mixtures with different genes for resistance, can limit considerably the spread of disease, and be grown profitably without fungicides (Wolfe, 1985). If, however, spring crops are to be included in a cropping sequence with environmental protection in mind, then autumn catch crops need to be sown to reduce nitrogen volatisation to the atmosphere, and incorporated prior to spring sowing.

Consideration of these factors together has led to the design of a large field experiment at Long Ashton comprising a complete set of phases of a 5-year cropping sequence. Winter oilseed rape : winter wheat : winter oats : winter beans : winter wheat. This cropping sequence is compared with each phase of a "conventional" rotation of winter wheat : winter wheat : winter barley : winter oilseed rape : (winter wheat).

Cultivation Methods

The disposal of straw by incorporation as opposed to burning results in changes in the physical, chemical and biological condition of the soil. Cereal straw does not contain enough nitrogen for its own decomposition, but the deficit is not large and can come from the soil without detriment to yield of autumn-sown crops. Straw incorporation will increase organic matter content and organic nitrogen reserves in soil, but these increases are slow and only become apparent after incorporation over many years (Jenkinson, 1985).

The repercussions of these changes in terms of cultivation requirements, fertiliser and pesticide use, and on growth and yield of cereals has been the subject of a co-ordinated research programme between AFRC Institutes and in conjunction with MAFF (Prew & Smith, 1988).

Tillage systems have various effects on pests, diseases and weeds and also interact with other components. The plough has traditionally been used to loosen the soil and incorporate crop residues. Such complete inversion of crop residues has a considerable influence on mineralisation of plant nutrients and leaves bare soil which increases nitrogen volatilisation to the atmosphere. It affects the survival of beneficial invertabrates and of soil borne pests, pathogens and weeds. Biota present in the top soil layers are transferred to deeper CO2-rich layers, where bacteria make rapid use of the buried residues, multiply and exhaust the oxygen supply, leaving poor CO2 exchange possiblilities. Frequently in some soils, as a consequence of ploughing, soil structure is impaired through the development of a "plough pan". Minimum tillage and "direct-drilling", on the other hand, affect the incidence of diseases, encourage grass weeds because seeds remain close to the soil surface where plants readily emerge (Moss, 1985), and favour soil fauna, particularly predators of pests (El Titi, 1984). Research into the long term effects of an alternative soil tillage system, based on conditioning the soil and incorporating crop residues in one pass without turning the soil has shown considerable ecological benefits. Non-inversion tillage systems, which incorporate *ca* 70% of crop residues in the top soil layers and leave 30% on the soil surface, foster soil biota, provide a food source to support survival and population increases of earthworms, create semi-natural habitats that favour increased numbers and species diversity of "beneficial" soil surface fauna, conserve nitrogen in the system, and decrease soil erosion through improved water permeability, bulk density and aggregate stability (El Titi, 1989).

Set against these advantages, is the perceived problem of surface crop residues increasing the risk from trash-borne disease carry-over, the potential weed problem from seeds near the soil surface, and increased soil organic matter adsorbing and inactivating some pesticides. On balance, non-inversion tillage is considered the preferred option for exploitation of natural regulatory mechanisms and may, in time, reduce the applied nitrogen requirement.

The results of current research within AFRC and ADAS, on the interactions between straw disposal, cultivation methods and pesticide use are suggesting ways of increasing the integrated control of some pests and diseases which will both reduce costs and protect wildlife. For example, experiments at Long Ashton in 1989/90 (D.J. Kendall; B.D. Smith, pers. comm) showed significantly less BYDV-affected plants in untreated winter barley crops that were either direct-drilled (3.8%) or sown using a non-inversion tillage system (9.3%), than in crops that were sown following conventional ploughing (43.4%); in the insecticide-treated buffer areas, BYDV incidence was 1.3%.

Cultivars

Pathogen-resistant cultivars have made an important contribution to arable crop disease control for many years and continue to be an essential component of integrated disease control strategies. Genetic resistance has been effective in decreasing damaging disease levels of major foliar pathogens such as powdery mildew, rusts and *Septoria* spp., but the advantage is often short-lived because new virulences are rapidly selected in pathogen populations and most pathologists consider greater durability of disease resistance an important requirement. Additionally, very good resistance against one disease is not enough, there is a need for cultivars with broad resistance to all major pathogens. The recommended lists of cereal cultivars, produced annually by the National Institute of Agricultural Botany, incorporate yield and disease ratings for each cultivar, based on measurements of disease in many locations supplemented by controlled inoculation experiments with a representative range of pathogen isolates. Before being recommended in the UK, cultivars must show a minimum level of resistance to the most important pathogens. Risks of serious disease attacks can therefore be minimised by growing cultivars with resistance to pathogens that are most prevalent in the areas grown, especially where the choice is between cultivars with similar potential yield values.

Other options include cultivar diversification either between fields or within fields involving the use of cultivar mixtures with different genes for disease resistance. Not only can these mixtures limit the spread of disease in a crop stand, thereby providing disease control with little additional cost to the practitioner, but also mixtures give greater yield stability compared with pure stands (Wolfe *et al.*, 1981).

Crop yields in the UK have increased greatly over the past decade, mostly due to the introduction of new high yielding cultivars which respond well to inorganic fertiliser, and to improvements in pest, disease and weed control. These cultivars have not, however, been bred for suitability in lower input systems. There still remains considerable scope to improve disease resistance by conventional breeding, but it is unlikely that the use of fungicides can be totally eliminated whilst producing grain at a competitive price. Nevertheless, it is a realistic objective to breed cultivars that on average need a single fungicide application, or that have a lower nitrogen requirement (Bingham, 1990).

Other husbandry practices influence the yield performance of cultivars, especially rotational sequences and sowing date. There is much evidence that most cultivars yield more when grown as "first-wheats" than as "second wheats" or as continuous cereals, for a variety of reasons that include greater soil fertility and reduced disease risk. It is clear that stiff straw and good disease resistance are desirable characteristics for early sowing. However, cultivar responses have often occurred for no discernible reason and, over a period of years, it has not been possible to detect significant interactions between cultivar and sowing date. Analysis of results from sowing date trials at Bridgets EHF over the past 4 years (1985-1989) gave overall mean yields from eight cultivars of 8.14, 8.82, and 8.03 t/ha when sown by mid-September, 9 October and 6 November, respectively, with no significant interaction between the cultivars (Furber, 1990). These similar yields suggest that sowing decisions could be based on other factors, such as weather and soil conditions, or pest and disease risk, rather than on date. Thus, in developing a strategy to minimise disease-induced yield losses, information is already available to aid decisions on cultivar selection.

Sowing Date

Date of sowing has a pronounced effect on the incidence of pests, diseases and weeds, and a perceived influence on yield potential. During the past decade, sowing winter cereals in September has become more popular where early establishment is considered the basis for good crop growth and yield. Seldom, however, has there been any loss of yield potential from crops sown at the more traditional time, in mid-October.

Winter cereals sown early, in September, are at greater risk from aphids, the vectors of barley yellow dwarf virus, gout fly, frit fly and *Opomyza*, but less so from wheat bulb fly. Barley yellow dwarf virus is the most important virus disease of cereals in the UK, and is most damaging at early growth stages. Transmission is by autumn migration of winged aphids bringing virus from grasses and other cereals into crops. Research at Long Ashton has shown that, in most years, infectious individuals are caught before the end of September, therefore early autumn sowing is likely to increase the need for pest control measures. Crops sown later, in mid-October, are at less risk (Kendall *et al.*, 1988).

Early autumn sowing also invariably results in earlier and more severe disease outbreaks such as powdery mildew, rusts, *Septoria* spp., barley net blotch and the stem-borne diseases eyespot, sharp eyespot and take all. This results from reduced opportunities for disposal of trash and of volunteers (the "green bridge" effect), whilst weather conditions remain favourable for infection and disease spread. In such situations, the use of specific seed treatments and autumn fungicide sprays are frequently considered.

Weed problems also tend to increase in early sown crops. Fewer weed seeds germinate in the shorter interval after harvest, that can be killed by cultivations or non-selective herbicides, thus to avoid crop competition more effective selective herbicide treatments are necessary. These may not be persistent enough to give lasting control thus repeated applications could be required.

Nutrition

Nutrients, (nitrogen, phosphate and potash) are essential to a productive agriculture; crops suffering from a serious shortage of these nutrients exhibit restricted growth and are more susceptible to damage by soil borne pests and diseases, and also compete less well with weeds. In the UK, fields are rarely deficient in phosphate or potash, thus responses to application of these two nutrients are generally low, whereas nitrogen applications have a pronounced effect. At low input levels, increased nitrogen has a dramatic effect on yield, but as the amount increases the crop yield diminishes exponentially. However, increased nitrogen is considered important when wheat is grown for breadmaking and milling, because high nitrogen content in grain (grain protein) is a determinant of quality, and grain protein content is physiologically limited by nitrogen supply. Both inorganic and organic nitrogen fertilisers influence greatly the incidence and severity of disease, pests and weeds, the organic form less dramatically because nitrogen is released more slowly (Vereijken, 1979). Application of much nitrogen promotes vegetative growth and vigour, making crops more liable to lodge with the consequent need for plant growth regulator applications. Whilst not affecting disease incidence, there are many reports that increasing nitrogen increases the severity of attack of foliar diseases, in part through increased tissue susceptibility but also because of modifications in crop canopy structure and changes in microclimatological parameters favour disease becoming severe. There is evidence from many sources, that efficacy of nitrogen utilisation is often improved by control of crop diseases, and therefore routine prophylactic crop protection programmes are often adopted where much nitrogen is applied. The responses of the crop and the weed species to added nitrogen differ. Sometimes advantageously, as with blackgrass in winter wheat where the competitive effect of the weed is reduced if adequate nitrogen is applied. In general, nitrogen encourages weed populations and growth thereby increasing competition from weeds, and the need for control. Some of the important "modern" weeds are adapted to high nutrient status, and may be less damaging in reduced input systems. Thus further research on weed/crop competition in relation to soil nutrient status could provide opportunities to reduce herbicide requirement in such systems.

Opportunities to reduce applied nitrogen, and undesirable side effects of nitrogen, are expected to come from work on the prediction of nitrogen mineralisation in different situations; the release of nitrogen as crop residues decompose in soil; the time course of N mineralisation and losses by leaching (Powlson *et al.*, 1987). Reductions in applied nitrogen may also be achieved through rotations that include legumes.

Pesticides

Whilst agrochemicals are necessary to maintain the required level of food production, there may be ways of minimising their environmental risks. Examples are the use of chemicals that are more selective, use of minimal dosage and frequency of application, spot treatment or inter-row applications, seed treatments, slow release granules, low volume sprays with minimal drift and more careful timing of application. Ideally, such treatments need to be associated with prediction schemes for optimal response.

Research into integrated arable farming systems, with the basic aim of reducing inputs and protecting the environment is well advanced in the Federal Republic of Germany (El Titi, 1986; 1989) and in the Netherlands (Wijnands & Vereijken, 1988; Vereijken, 1989); pesticide input reductions (kg a.i./ha) of 36% (Federal Republic Germany) and even 60 - 90% (Netherlands) have been achieved in experiments over several seasons whilst maintaining quality production without economic loss. Moreover, in these integrated systems considerable savings in fertilisers have also been made, and values of biological indicators for health of crops and soils show that conditions have improved.

When agrochemicals are used routinely, or even on a recommended basis as part of a managed control approach, some treatments may be unnecessary or economically unsound. Opportunities for agrochemical reduction may be expected to come from more frequent rotations, increased crop diversity, appropriate soil management/cultivations, and rational manipulation of crop husbandry techniques. In certain combinations, these strategies could reduce input costs whilst maintaining productive, economical and ecologically sound sustainable agriculture.

Low Input Farming and the Environment (LIFE)

Calculations from previous component-research field experiments on arable crops (wheat, barley and oilseed rape) at Long Ashton indicate that a 50% input reduction could sustain a 17% yield penalty to give a similar level of profitability (Gross Margin). To test this hypothesis, preliminary investigations were made at Long Ashton, in 1988/89, using 14m wide field strips of "first-wheats" cv. Avalon. Although rigorous comparisons between "standard farm practice" and "low-input" were not possible because there was no true replication the responses were, nevertheless, encouraging. In crops sown on 25 September 1988, inputs were reduced by 59%, with a consequent 24% yield penalty and a 15% reduction in Gross Margin, whereas on later sown crops, 31 October 1988, inputs were reduced by 56%, the yield penalty was only 8%, resulting in a 6% improvement in Gross Margin compared to "standard farm practice".

With this background information, we have devised experiments for research into lower input, sustainable cost effective quality production. A farm scale project, begun in autumn 1989, and occupying approximately 19 ha, is comprised of five large fields, each divided into four field units in order to compare, within fields and between fields, a "conventional" rotation with an "integrated" rotation selected for its potential environmental and economical benefits, each with "standard farm practice" and "low input" regimes.

The "integrated" low input system is a 5-course rotation, growing only "first-wheats" and optimising the use of profitable break crops: oats, oilseed rape and beans. Data from Germany and from our own recent straw disposal/cultivation experiments at Long Ashton suggest that, on balance, non-inversion tillage (using the Dutzi tillage/seeding system as a 2-pass operation) is potentially valuable for conserving nitrogen in the system and for exploiting natural regulatory mechanisms. Crop residues will be incorporated after harvest and again later when the "first-wheat" is sown; the wheat straw will be baled and the following winter oilseed rape direct drilled, to conserve energy. After harvest, the rape crop residues will be incorporated prior to incorporation/ drilling of the following "first-wheat"; wheat residues will be incorporated prior to drilling winter oats; the oat straw will be baled and sold and culm bases incorporated; winter beans will be broadcast and ploughed in, and after harvest bean residues will be incorporated before the next "first-wheat".

Cultivars will be selected primarily for disease resistance rather than yield potential and not sown until early October. Nutritional requirements will be based on annual soil analyses, with consideration given to a further 25% reduction from predicted amounts. Crop protection sprays will be used only if considered essential, and chosen to be as benign as possible to the environment and non-target organisms. Thus, insecticide applications will be based on forecasting criteria, herbicides according to thresholds, and a single fungicide spray will be applied from GS 39 onwards, according to disease risk. Plant growth regulators will not be used.

In each field unit, the incidence and severity of pests, diseases and weeds will be measured and beneficial indicator species monitored. Crop yields and quality parameters will be taken. Full husbandry records will be maintained, including energy costs for novel machinery, so that full financial inputs can eventually be calculated.

Initially, to provide baseline data on soil structure and chemistry, indicator fauna, disease, pest and weed populations, field to field variation, and to test experimental methodology, all crops in the first years series of experiments were sown after grass, in autumn 1989. Data from these experiments provided indications where input reductions could be made when crop rotational effects commence in autumn 1990. In the low input regime on the "conventional" cropping sequence, energy costs for machinery operations (kw/ha) (N.J.Osborne, pers. comm.) were reduced by 23%, production costs by between 29 and 34%, and overall Gross Margin by 5%, compared with "standard farm practice". In the "integrated" cropping sequence there was < 1% difference in Gross Margin between "standard farm practice" and the "low input" regimes. Although in this first cropping year, the yield and Gross Margin from the two cropping sequences and input levels cannot be directly compared, the low input regime in the "integrated" cropping sequence resulted in an 11% reduction in energy for machinery operations, and overall, lower agrochemical inputs (kg/ai/ha) were used: 40% less nitrogen, 28% less herbicide, 80% less fungicide, 100% less insecticide, and 61% less plant growth regulator.

REFERENCES

Bingham, J. (1990) The potential for further improvement in winter wheat. *Proceedings NIAB South Region Fellows Conference - Which way with Wheat*, Sparsholt, 1990.

Davis, R.P.; Garthwaite, D.G.; Thomas, M.R. (1990) Pesticide useage survey report 78. Arable farm crops 1988. London: MAFF.

El Titi, A. (1984) Auswirkungen der Bodenbearbeitungsart auf die edaphischen Raubmilben (Mesostigmata:Acarina). *Pedobiologie*, **27**, 79-88.

El Titi, A. (1986) Management of cereal pests and diseases in integrated farming systems. *Proceedings British Crop Protection Conference - Pests and Diseases* **3**, 147-156.

El Titi, A. (1989) Farming Systems Research at Lautenbach, Oedheim, FR Germany. In: *Current Status of Integrated Farming Systems Research in Western Europe*, P.H. Vereijken & D.J. Royle (Eds) WPRS Bulletin 1989/XII/5, 21-36.

Furber, M.J. (1990) Current varieties and recent results from the south. *Proceedings NIAB South Region Fellows Conference - Which way with Wheat*, Sparsholt, 1990.

Jenkinson, D.S. (1985) How straw incorporation affects the nitrogen cycle. In: *Straw, soils and science*, Ed J. Hardcastle, London: AFRC, pp 14-15.

Kendall, D.A.; Chinn, N.; Wiltshire, C.R.; Bassett, P. (1988) Effects of crop agronomy and agrochemical use on incidence of barley yellow dwarf virus in autumn sown cereals. *Aspects of Applied Biology*, **17**, 143-151.

Moss, S.R. (1985) The survival of *Alopecurus myosuroides* Huds. seeds in soil. *Weed Research*, **25**, 201-211.

Powlson, D.S.; Brookes, P.C.; Christansen, B.T. (1987) Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to soil incorporation. *Soil Biology and Biochemistry* **19**, 159-164.

Prew, R.D.; Smith, B.D. Eds (1988) *Changing Straw Disposal Practices. H-GCA Research Review* **11**, pp 61. Home-Grown Cereals Authority, London.

Sly, J.M.A. (1982) Pesticide useage survey report 35. Arable farm crops and grass 1982. London: MAFF.

Vereijken, P.H. (1979) Feeding and multiplication of three cereal aphid species and their effect on yield of winter wheat. Doctoral Thesis, Agricultural Research Report 888, Wageningen.

Vereijken, P.H. (1989) Research on integrated arable farming and organic mixed farming in the Netherlands. In: *Current Status of Integrated Farming Systems Research in Western Europe*. P.H. Vereijken & D.J. Royle (Eds) WPRS Bulletin 1989/XII/5, 41-50.

Wijnands, F.G.; Vereijken, P.H. (1988) Integrated cropping of winter wheat. In: *Integrated Crop Protection in Cereals. Proceedings of a Meeting of the EC Experts Group/Littlehampton, 1986*. 295-303.

Wolfe, M.S. (1985) The curtrent status and prospects of multiline cultivars and variety mixtures for disease resistance. *Annual Review of Phytopathology*, 23, 251-273.

Wolfe, M.S.; Barrett, J.A.; Jenkins, J.E.E. (1981) The use of cultivar mixtures for disease control. In: *Strategies for the Control of Cereal Disease*. J.F. Jenkyn & R.T. Plumb (Eds), Blackwell Scientific Publications, pp. 73-80.

THE POTENTIAL OF ORGANIC FARMING SYSTEMS FOR REDUCED FARM INPUTS

R J UNWIN

ADAS, Ministry of Agriculture, Fisheries and Food, Burghill Road, Westbury-on-Trym, Bristol BS10 6LT

ABSTRACT

The reduction in the use of fungicides and insecticides which may result from organic systems production will depend upon the inter-related aspects of husbandry, science and economics. There is currently a strong demand for organic food and scope for more farmers in the United Kingdom to produce for this home market. Those producing organic food at the present time are generally able to do so with fewer problems from pest and disease than is commonly imagined by conventional farmers. This can be attributed to the fundamentals of good husbandry implicit in organic standards coupled with advances in science and technology, such as resistant varieties and plastic mulches, which have been adopted. These aspects are discussed drawing largely on papers presented at a BCPC Symposium held earlier this year.

INTRODUCTION

The subject of the Conference this year, is pest and disease control. Given the concept of the "Standards" organic agriculture will obviously reduce inputs compared to conventional systems. What we have to consider is the viability of organic systems on both a technical and economic level. These subjects were discussed in detail at a BCPC Symposium - Crop Protection in Organic and Low Input Agriculture - earlier this autumn, and the current paper draws heavily upon contributions presented at that meeting.

ORGANIC FARMING IN THE UNITED KINGDOM

What is Organic Farming?

In 1987 the Government supported the setting up of UKROFS (United Kingdom Register of Organic Food Standards). This independant body was charged with introducing and implementing an agreed voluntary national organic standard. It is worth considering the principles of organic production which they adopted (Anon 1989). Who can say that these tenets are not applicable to all agriculture in the 1990s?

- working with natural systems to enhance biological cycles

- maintain and develop soil fertility using a minimum of non-renewable resources
- avoidance of pollution and attention to animal welfare
- protection of the environment and consideration for the wider impact of farming systems

Modern organic farming is neither "muck and mystery" nor a return to a pre-war agriculture. It actively seeks to incorporate the advances of scientific knowledge and modern technology into production systems which are consistent with organic principles.

Crop Protection in Organic Standards

The standards emphasise the role of good husbandry - rotational design, manure management, crop nutrition, varietal selection, use of green manures and the timing of operations. Direct intervention, whether manual, mechanical, thermal, biological, or chemical is secondary and only used when necessary (Woodward and Lampkin 1990, Wijnands 1990). A restricted range of chemical controls are permitted but their routine use is discouraged.

Size of the Organic Sector

Woodward and Lampkin (1990) report a 30% increase in certified organic area in the 12 months to June 1990, to around 15-18,000 hectares. Such is the rate of change that up to a further 10,000 hectares is thought to in conversion (Holden private communication). The market for organic food was estimated to have grown from £36 million in 1987 to £50 million in 1989 and is likely to be £80-100 million in 1990. However a large proportion of this is imported and it was this together with the need to protect the consumer that prompted the setting up of UKROFS.

Economic Performance of Organic Farming

Detailed studies in the United Kingdom are scarce but the Ministry of Agriculture Fisheries and Food has commissioned a new study which will report in 1991 on a detailed examination of 300 organic farms throughout Great Britain.

Yields of organic crops tend to be more variable than those of conventional crops (Vine and Bateman 1981, Bockenhoff et al 1986, Guest et al 1990). This is to be expected given the unavailability of fertilisers and pesticides to help overcome the effects of seasonal weather patterns and pest and disease attack. These lower yields are compensated by higher prices with premiums commonly up to 150% (Woodward and Lampkin 1990). However such prices are not available to all phases of the rotation. Low variable costs, particularly on fertilisers and sprays can lead to impressive gross margins compared to conventional crops, Table 1 indicates the estimated gross margin for a range of crops grown organically with or without a premium (Woodward and Lampkin 1990) and for conventionally grown crops (derived from Nix 1989).

TABLE 1 Gross margins for selected organic and conventional crops

Crop		Milling Wheat	Milling Oats	Field Beans	Main crop Potatoes
Yield (t/ha)	Organic	4.5	4.5	3.5	24
	Conventional	6.75	5.5	3.25	37.5
Price (£/t)	Organic	220	170	200	200
	Conventional	110	110	180	100
Output (£)	Organic	990	765	700	4800
	Conventional	742	605	585	3750
Variable Costs (£/ha)					
	Organic	65	50	65	1995
	Conventional	230	165	130	2275
Gross Margin (£/ha)					
	Organic	925	715	635	2805
	Conventional	512	440	455	1475

The problems of the whole farm were well illustrated in a study of an organic farm in 1983/84, (Browning and Unwin unpublished data), which was summarised by Wookey (1987). Although margins on wheat crops were £200/ha higher than neighbouring conventional crops the livestock were relatively lightly stocked so that the overall performance was close to the average for the farm type in the area.

TABLE 2 A comparison of whole farm margins for a wheat/livestock system 1983/84

	Conventional	Organic (With premium)	Organic (No premium)
Wheat	423	521	323
Livestock (beef and sheep)	345	233	233
Average 50:50 grass/wheat	384	377	278

Arriving at an equivalent economic position after conversion is one thing but there can be substantial costs getting there. Up to £200/ha per year for 5 years has been calculated by Lampkin et al (1987) and Lampkin and Midmore (1988).

Future Development

It is very difficult to predict the effect of increasing output upon the market. As more producers appreciate the practicality of organic methods and supplies increase, the effect of price elasticity, import substitution and reduced costs due to economy of scale upon prices is unclear. What is clear is that an increasing number of farmers are prepared for whatever reason to initiate a conversion.

Realistically, a conversion of 10% of UK agriculture is the top end of any likely change. It has been suggested from modelling work (Woodward and Lampkin 1990) that even such a change would reduce the output of most crops and livestock by less than 3%. This is contrary to the dire consequences for food supply which are often assumed.

In conclusion we can give a qualified yes to the first part of our enquiry. There is potential for an increased organic sector in UK agriculture. How far it can rise from its current 0.2-0.3% of the crop and grass area of Great Britain is not clear although the retail trade clearly believe that a 20-fold increase is possible.

CROP PROTECTION

Disease Control

Organic farmers and growers commonly report a low incidence of disease in their crops (eg Brusko 1985, Peacock 1990) which is increasingly being confirmed by objective studies, (Guest et al (1990) Mackay and Watson (1990), Dover and East (1990).) This low incidence can be the result of a number of factors (Yarham et al (1990)).

1. The rotation practised by organic farmers reduces the risk of diseases such as Take-all (Gaeumannocyes graminis) and Eyespot (Pseudocercosporella herpotrichoides) of cereals.

2. Nitrogen supply to the crop is low compared to conventional systems. This decreases the susceptibility to most if not all cereal leaf diseases.

3. The incorporation of organic manures and green crop residues can favour organisms which are antagonistic to, or competitors of, soil borne fungal pathogens. Further work on this topic was reported by Lennartsson (1990) in relation to Take-all.

Organic crops are not however immune to pathogen attack although they often seem to be able to resist the full expression (Guest et al 1990). Attention does therefore need to be given to control practices and the following guidelines were suggested:-

1. Sound rotational practice is vital to minimise Take-all and Eyespot making full use of grass breaks and less demanding crops such as oats. Timing can be important and if possible autumn sowing should be delayed until mid-October to reduce fungal diseases and the risk of Barley Yellow Dwarf virus.

2. Choice of varieties with good resistance to diseases prevalent in the particular area is of major importance, as well as the information from standard variety testing. Work has been conducted by Guest et al (1990), Richards and Heppell (1990) and Dover and East (1990) to support this hypothesis. It must however be remembered that there is a relatively narrow genetic base for pathogen resistance (Bayles et al 1990). Work by Beale and Sweet (1990) has shown the possibilities of varietal choice in reducing the blemish diseases of vegetables and led to a booklet specifically aimed at organic vegetable producers (NIAB 1990). The subject of variety mixtures was reviewed by Wolfe (1990) who concludes that there seems no doubt that mixtures can play a significant role in restricting plant diseases and stabilising yield. This is also true for species mixtures of different cereals. Mixtures of cereals and legumes can be highly productive in the absence of nitrogen fertiliser although more work is needed on disease development within such crops. See also Bulson et al (1990).

3. Good farm hygiene is important. Volunteer plants should be ploughed under before the next seasons crops emerge and crop debris should be removed or buried, particularly where successive harvesting of vegetables is in operation. Weed control can be important in areas such as the carryover by couch of Take-all through a grass break. Dense weed cover can alter the micro climate around the stem base to the detriment of crop health.

4. Care is needed over the use of untreated seed to minimise the risk of seed borne diseases such as Bunt of wheat (Tilletia caries). In practice organic farmers appear to have little problems with home saved seed in this respect but it is something that has to be watched carefully. Establishment of cereals can be affected by seedling blight due to seed borne innoculum of Septoria nodurum and Fusarium spp (also Guest et al 1990). Seed rate is

often increased to aid weed suppression although this is not always beneficial in terms of final yield or disease incidence (Dover and East 1990). Deep sowing which is practiced by some organic producers can also increase susceptibility to Fusarium.

5. Provision of a balanced nutritional status for the crop is important. Deficiencies can increase disease, but the over supply of nitrogen has an even greater potential for the enhancement of disease development.

6. In organic systems permitted disease control agents are seen as a last resort. Sulphur can be used although Yarham et al (1990) concluded from trials work that a routine spray programme was not justified and that sprays against mildew should only be made if the disease was present between GS 37 and GS 59. Biological control agents are not in common use although interesting studies using yeast cell wall extracts (Reglinski and et al 1990) and water extracts of composts (Schueller et al 1990, and Weltzien 1990) were reported to the meeting. The latter indicated considerable potential for benefits to vegetables and fruit as well as field crops.

In conclusion it can be seen that current understanding of disease in crops has helped to explain why organic crops are less prone to disease. There have been considerable benefits to organic production as a result of the efforts of the plant breeders. Under current systems of organic management diseases in field crops are not commonly a limitation to production with the possible exception of potato blight where crops often have to be harvested early. There can be more problems associated with systems of intensive vegetable production although even here acceptable crops are commonly produced.

PEST CONTROL

The perceived need to restrict insecticide use has been evident in research programmes for many years. The development of biological control strategies for protected crops is established within both organic and conventional production. Apart from Bacillus Thuringiensis preparations which can be of benefit (Hughes 1990) there are no practical methods commonly in use for field crops in the United Kingdom.

Strategic use of insecticides has developed with the concept of threshold management. Whilst this is fine for integrated pest management systems it is of little value for organic production where suitable materials are not available to be used even when thresholds are exceeded (Parker 1990). However the components of the threshold system, notably forecasting and monitoring can be of great value in assisting the organic grower to choose the particular crop and the timing of planting or sowing operations. Peacock (1990) confirmed that these thoughts are uppermost in growers minds. In comparative work Mackay and Watson (1990) reported a reduced incidence of slug damage to organic potatoes than to conventional crops. Peacock (1990) also reported a conscious avoidance of certain crops which is confirmed by other growers notably Hughes (1990) reporting NIAB trials in which he clearly distinguished between varieties of cabbage. Aphid infestations were more serious on green than on white varieties. Aphid problems on brassicas were also highlighted by Mackay and Watson (1990) who reported that a 30% reduction in yield of organic swedes in 1988 was caused by aphids whilst yields were only reduced by 6% relative to conventional crops in 1987 and 1989 when there was few if any aphids.

Physical barriers for insect pests have long been established for small scale use. The development of plastic covers/floating mulches, (woven or non-woven) now offer considerable help for pest control. Their use is currently permitted under organic standards in the United Kingdom although Woodward and Lampkin (1990) note some disquiet with this technique. Although not grown to full organic standards Antill and Davies (1990) reported very encouraging results of covering against cabbage root fly (Delia radicum) on crops of summer cauliflower cv Dok and against carrot fly (Psila rosae) on carrots cv Nandor. Mackinlay (1987) had previously demonstrated the benefits of a floating mulch for culinary swedes against cabbage root fly. Subsequently the covers have been shown to reduce the caterpillar damage on cabbage cv Hildena, principally by small cabbage white (Pieris rapae) cabbage moth (Manustra brassicae) and diamond back moth (Pultela xylostella) (Mackinlay 1990).

The question of plant breeding for pest resistance was considered by Ellis (1990). He concluded that whilst there was evidence that new varieties are more susceptible to pest attack than their wild relatives he noted a welcome attempt to reverse this trend by plant breeders and the introduction of resistance genes to modern cultivars. Even partial levels of resistance can make a valuable contribution to crop protection. In organic systems it would be important to recognise that environmental, physical or physiological factors can affect the expression of resistance. In particular lower levels of nutrients, particularly nitrogen, in the crop will reduce pest pressure. Also rotations should be maintained to avoid the build up of pests even when, as with some lettuce varieties there is resistance to a common problem, in this case lettuce root aphid (Phemphigus busarius).

There can be a yield penalty from incorporating resistance genes. Under conditions of organic systems this extra reduction in yield could be a drawback if the tendency is particularly expressed under conditions of low fertility.

As with disease studies, and from theoretical considerations, there should be potential advantages for intercropping as a means of pest control (Coaker 1990). There is however a need to demonstrate yield increases due to reduction in pest populations in diverse systems, particularly to identify the scale and form of suitable systems.

One step back from crop integration is the encouragement of natural predators within and around the crop. The interplanting of flowers with vegetables is a tried and tested approach for organic gardens. However a more practical approach is required on a farm scale. Recent studies were reviewed for the Symposium by Wratten and Thomas (1990). They also described their work which attempted to redress the balance of hedgerow removal by creating new habitats which both reduce field size and create new overwintering sites for polyphagous predators. The provision of pollen and nectar sources at field margins, in ridges or strips across fields, and/or as green manures is receiving close scrutiny from many involved in organic and integrated systems research.

CONCLUDING COMMENTS

Pests and diseases are less of a problem to organic producers than is commonly assumed. However Peacock (1990) reported that 56% of vegetable growers feel that the losses of more than 10% which they incur, are more than they can afford. The practise of traditional husbandry methods supplemented with modern varieties and technology keeps the problem at manageable levels for much of the time. However complete crop loss can occur particularly in terms of the quality demanded by multiple retail outlets. The scope for flexible harvesting to avoid an incipient pest or disease outbreak can be limited by contracts to supply a particular outlet. In order to meet the quality demanded by the retailer on behalf of his customer, there is a move towards producing organic vegetables on better quality land. This can mean organic production in the vicinity of conventional crops with their reservoir of pests and diseases, resulting in greater pressures on the organic crops.

The demand for a reduction in pesticide usage will continue for the foreseeable future. Research aimed at low input or IPM systems is having a direct benefit to the fully organic system. It would be wrong to imply that there are not significant problems. Some such as potato blight have not been addressed in this paper. At least part of the premiums received by organic growers are required to offset losses due to pest and disease which is a price the consumer may or may not be willing to pay. Particularly in future as pesticide inputs are reduced throughout agriculture as a whole.

REFERENCES

Anon (1989) UKROFS Standards for organic food production. Food From Britain, London

Antill, D.N.; Davies, J.S. (1990) The use of non woven crop covers to prevent insect pests on field vegetables. In Crop Protection in Organic and Low Input Agriculture. R.J. Unwin (Ed), BCPC Monograph No 45, Farnham BCPC Publications, pp 213-217.

Bayles, R.A.; Channel, M.H.; Stigwood, P.L. (1990) The role of the United Kingdom cereal pathogen virulence survey in integrated disease control. In BCPC Mono No 45, p 221.

Beale, R.E.; Sweet, J.B. (1990). Control of diseases in field vegetables using resistant cultivars and their integration with biological and chemical methods. In BCPC Mono No 45, pp 131-136.

Bockenhoff, E.; Hamm, U.; Umhau (1986) Analyse der Betriebs-und Produktionsstrukturen sowie der Naturalertrage im alternativen Landbau. Berichte uber Landwirtschaft 64, pp 1-39.

Brusko, M. (1985) Ed Profitable Farming Now. Regenerative Agriculture Association. Emmaus Pa.

Bulson, H.A.J.; Snaydon, R.W.; Stopes, C.E. (1990). Intercropping of autumn sown field beans and wheat; effects on weeds under organic farming conditions. In BCPC Mono No 45, pp 55-62.

Coaker, T.H. (1990). Intercropping for pest control. In BCPC Mono No 45, pp 71-76.

Dover, P.; East, J. (1990). The effects of variety, blends and seed rates on disease and weed incidence in wheat grown in organic systems. In BCPC Mono No 45, pp 239-243

Ellis, P.R. (1990). The role of host plant resistance to pests in organic and low input agriculture. In BCPC Mono No 45, pp 93-102.

Guest, S.J.; Samuel, A.M.; Davies, W.P. (1990). Establishment, disease development and yield of organically grown wheats. In BCPC Mono No 45, pp 223-226

Hughes, G. (1990). Which cabbage? In New Farmer and Grower 26, Spring 1990 p11.

Lampkin, N.; Jones, W.; Mann, M.; Midmore, P. (1987). Proposal for an Integrated Rural Development Programme Focussing on Organic Production in the Teifi Valley, Dyfed, Aberystwyth: Dept of Economics and Agricultural Economics, University College of Wales.

Lampkin, N.; Midmore, P. (1988). Organic production as an alternative to set-aside. A response to the Agricultural Departments' Consultative Document on Extensification. Aberystwyth: Department of Economics and Agricultural Economics. University College of Wales.

Lennartsson, E.K.M. (1990). The effect of green manuring and mixed species cropping on take-all disease of wheat. In BCPC Mono No 45, p 219.

Mackay, M.J.; Watson, D.A. (1990). Organic system trials in the North of Scotland. In BCPC Mono No 45, pp 251-254.

McKinlay, R.G. (1989). Control of cabbage root fly in culinary swedes with and without synthetic insecticides. Tests of Agrochemicals and Cultivars No 8 (Annals of Applied Biology 110, Supplement, pp 32-33.

McKinlay, R.G. (1990). Pest management in vegetable brassicas without insecticides. In BCPC Mono No 45, pp 205-208.

NIAB (1990). Vegetable Varieties for Organic Growers. National Institute of Agricultural Botany, Cambridge.

Nix, J. (1989). Farm Management pocketbook. Nineteenth edition (1989). Wye College, Kent.

Parker, W.E. (1990). The derivation of economic thresholds for insect crop pests, and their role in crop protection decision making in low input and organic farming systems. In BCPC Mono No 45, pp 209-212.

Peacock, L. (1990). Practical constraints and opportunities for improving crop protection in organic vegetable production. In BCPC Mono No 45, pp 157-162.

Reglinski, T.; Newton, A.C.; Lyon, G.D. (1990). Elicitor - active yeast cell wall components as a novel crop protectant. In BCPC Mono No 45, pp 231-234.

Richards, M.C.; Heppel, V. (1990). Cereal varieties for the organic and low input grower. In BCPC Mono No 45, pp 147-155.

Schueller, C.; Vogtmann, H.; Stopes, C.E. (1990). The use of composted materials to control plant diseases. In BCPC Mono No 45, pp 235-238.

Weltzien, H.C. (1990). The use of composted materials for leaf disease suppression in field crops. In BCPC Mono No 45, pp 115-120.

Wijnands, F. (1990). Farming systems research for integrated arable and organic mixed systems in the Netherlands. In BCPC Mono No 45, pp 139-146.

Wolfe, M.S. (1990). Intra-crop diversification: Disease, yield and quality. In BCPC Mono No 45, pp 105-114.

Woodward, L.; Lampkin, N. (1990). Organic agriculture in the United Kingdom. In BCPC Mono No 45, pp 19-29.

Wookey, B. (1987). Rushall. The story of an organic farm. Blackwell Oxford p 133.

Wratten, S.D.; Thomas, M.B. (1990). Environmental manipulation for the encouragement of natural enemies of pests. In BCPC Mono No 45, pp 87-92.

Yarham, D.J.; Culshaw, F.A.; Sansford, C.E. 1990. Disease control in cereals grown to conservation grade and UKROFS standards. In BCPC Mono No 45, pp 121-130.

Vine, A.; Bateman, D.I. (1981). Organic farming systems in England and Wales. Department of Economics and Agricultural Economics, University College of Wales.

THE ROLE OF COST-BENEFIT ANALYSIS IN DETERMINING REDUCED INPUT CROP PROTECTION STRATEGIES

P.K. THORNTON, R.H. FAWCETT

Division of Rural Resource Management, Edinburgh School of Agriculture, West Mains Road, Edinburgh EH9 3JG

ABSTRACT

Information on crop protection decisions is increasingly required at both the policy and the farm levels, on the one hand to help government formulate socially and environmentally sound strategies and on the other to aid the farmer in their implementation. Cost-benefit analysis can be used to carry out ex ante assessments of particular crop protection activities, for guiding research priorities and for on-farm analysis. If economic and political pressures induce a move away from prophylactic spray programs, farmers have a variety of options available to them. Most of these will continue to have a role to play in reduced-input systems. The operational problems in applying cost-benefit analysis routinely are reviewed, and suggestions are made with regard to further research that could help facilitate its application.

INTRODUCTION

Public perception in some of the western democracies of the role of agrochemicals in crop production is likely to be a key driving force for initiating change in agricultural practices. As issues such as nitrate leaching and chemical residues in the human food chain come increasingly to the fore, there is a clear requirement for substantial information provision on two important fronts. First, to provide policy makers with scientific evidence to enable rational decisions to be made so that society's preferences can be catered for; and second, to provide farmers with information and decision making tools that allow them to make crop production decisions that fit in with society's goals as well as their own. An important ramification of the first of these is to be able to disseminate objective information to the public, in an attempt to make transparent the processes by which far-reaching policy decision are made. Such information is needed either to allay or confirm public fears about the indirect effects of current and proposed farming practices. For the second, producers at the farm level bear the brunt of policy decisions and market forces that affect the costs and prices of production. The evidence of the last thirty years and present government policy suggest that real margins for cereal growers in the UK will continue to decline.

Cost-benefit analysis is a powerful tool for the ex ante assessment of the likely effects of particular courses of action. In this paper, its use is described, at the farm level in relation to how producers might make decisions concerning low- or reduced-input pest and disease control, and at the policy level in relation to how public research and development might proceed to provide the information required. In subsequent sections, the technique of cost-benefit analysis is briefly outlined; procedures for its application are sketched out in relation to a tentative classification of pest and disease control strategies; finally, some key research areas are listed that require substantial input if the operational difficulties of cost-benefit analysis in crop protection are to be overcome.

COST-BENEFIT ANALYSIS

Strictly, cost-benefit analysis (henceforth CBA) refers to ex ante assessment of public investment projects at national or regional level (Pearce, 1983). The method involves the calculation of costs and benefits distributed over the life of the project (i.e. for as long as there are significant quantifiable effects). Costs and benefits accruing in the future are discounted back to the present and a positive net present value (NPV) is sufficient justification for a project. NPV is an absolute not a relative measure and can not be used to rank projects. The methods and language of CBA are common to all prospective value judgements. The critical differences between CBA and other investment appraisal techniques result from asking three questions: which costs and benefits are to be included, how are they to be valued, and what is the appropriate rate of discount. Environmentalists may be interested in the first of these, while the anthropocentric view considers to whom do the costs and benefits accrue, especially with regard to generations still to come.

CBA differs from a business value judgment in that a regional or national boundary is drawn, encompassing effects on all members of that society, rather than simply a business proprietor concerned with private costs and benefits. The business value judgment uses market prices to value costs and benefits, while CBA tends to use shadow prices that reflect the true cost of resources, since market prices reflect current distortions of taxes, subsidies, and import and export restrictions. Again, since businesses are usually constrained by capital, they may well choose to rank alternative investments in terms of return to capital (using a criterion such as internal rate of return). Society, on the other hand, must use a criterion such as net present value that employs the social rate of discount to reflect preferences. Furthermore, CBA involves a consideration of externalities; these are the costs and benefits that accrue outside the boundary of the project, the boundary being drawn to include the intended beneficiaries. These may be of a monetary nature (for instance, job creation or labour displacement brought about by a scheme) or of a technical nature (loss of wildlife or increased soil erosion, for example). On occasion, these secondary effects of projects may exceed the primary effects in importance. Judgmental elements are bound to be involved in such assessments, but their omission may lead to serious errors in estimations of respective costs and benefits (Dent, 1989).

A number of the elements of CBA sensu stricto are applicable to farm-level decision making, in particular the use of judgment, subjective probability distributions of likely outcomes, and the incorporation of important externalities or elements that usually do not enter farmers' calculations of the costs and benefits of particular courses of action. Unless there are ramifications for future seasons, many on-farm crop protection decisions can be taken with respect to the present season only, thus obviating the need for calculating flows of costs and benefits over future years. A consideration of reduced-input systems may well change this picture, since cropping systems designed specifically to lower pest and disease burdens over time, for example, will need to be considered in a dynamic framework.

A CLASSIFICATION OF PEST CONTROL STRATEGIES

A tentative classification of pest and disease control strategies is presented in Table 1. These are listed by site of primary action, i.e. whether the plant, the pathogenic organism or the interface between the two is affected by the strategy. There is some overlap: for example, the

TABLE 1. Pest-disease control strategies and their role in reduced input systems.

SITE OF PRIMARY ACTION	ROLE IN REDUCED-INPUT SYSTEMS
A PLANT & its ENVIRONMENT	
1 Resistance	
- breeding	yes
- genetic manipulation	yes
2 Cultural	
- multicropping	yes
- variety selection	yes
- site selection	yes
- timing of sowing & harvesting	yes
- use of barriers	yes
- crop-soil husbandry	
* use of fire	yes
* crop rotations	yes
* cultivations	yes
* irrigation	yes
B PATHOGENIC ORGANISM or VECTOR	
3 Spray	
- prophylaxis	no
- reduced doses and tank mixing	yes
- tactical decision making	
* monitoring & forecasting	yes
* spatial application	yes
4 Biological Control	
- pest predators, parasites, pathogens	yes
- genetically manipulated organism release, chemical action	unknown
C PLANT-ORGANISM INTERFACE	
5 Biological Control	
- genetically manipulated organism release, space exclusion	unknown

use of fire on crop residues could equally well be considered to affect the organism rather than the plant and its environment. Of the strategies listed in Table 1, only prophylactic spraying is assumed to have no role in reduced-input systems, on the basis that it might be said to contravene the spirit of low- or reduced-input agriculture (whatever the intrinsic justification of this may be). It is likely that biological control options that involve genetically engineered organisms will have a considerable role to play in low-input crop protection in the future, but for the present, more research is needed on these options, especially with regard to their riskiness and undesirable secondary effects.

Two factors emerge from Table 1. Firstly, apart from prophylaxis, crop protection is neither necessarily high- nor low-input, since each strategy allows flexibility in the degree to which it is used (although nothing is said about the relevant capacity to afford protection). Secondly, the strategies vary in the way in which information or technology is used for their implementation: breeding for resistance, for example, is the preserve of publicly-funded research and development bodies and, increasingly, of private institutions, while tactical decision making is essentially the preserve of the individual farmer for his or her own particular conditions. The application of CBA in guiding research and farm-level decision making is considered below.

COST-BENEFIT ANALYSIS OF RESEARCH PROJECTS

The literature on the evaluation of agricultural research and development is substantial (see, for example, Grieg, 1981; Lindner, 1987). A general framework for valuing the costs and benefits of a research proposal is presented in Harrison et al. (1990). This takes account of the following: (i) the direct costs of the research; (ii) the number of producers and consumers, and the producer and consumer benefit; (iii) the probability of research success and the proportion of adopters; and (iv) the social, environmental and secondary economic impacts of the research. Table 2 lists some of the impacts that may be associated with a crop protection research proposal.

The allocation of limited resources to crop protection research within such a framework is a difficult investment appraisal problem, for reasons that include the following:

(1) the benefits of research projects are difficult to isolate; outputs from different projects often interact, and the success of one may be dependent on the success of others. Indeed, much basic research is probably not amenable to assessment in any formal economic way; direct benefits may accrue many years after the research is carried out, if at all.

(2) returns to research are uncertain; there is a risk that resources spent on research will not generate technology that can be adopted by farmers. Even if technology is produced, it is unlikely that all the target population will adopt it. If the technology is in some sense inappropriate, for biological, economic, social or cultural reasons, then adoption may not occur at all.

(3) the externalities that may arise from the technology, be they economic, social or environmental, favourable or unfavourable, are difficult both to foresee and to quantify. For many research projects, realistic orders of

TABLE 2. Some costs and benefits that may be associated with a crop protection research proposal (adapted from Harrison et al., 1990).

PRIMARY BENEFITS	
	Reduced production costs
	Reduced yield variability
	Lower consumer prices
	Increased information
SECONDARY BENEFITS	
	Staff training
	Adding to the store of scientific knowledge
PRIMARY COSTS	
	Salaries, consumables
	Equipment depreciation
	Costs of maintenance research
	Costs of extension
SECONDARY IMPACTS	
	Changes in genetic diversity
	Pollution of soil, water, air
	Effects on wildlife and landscape
	Viability of non-adopters & employment
	Changes in consumption patterns of non-renewable resources
	Export earnings, import replacement
OTHER VARIABLES	
	Duration of research
	Probability of research and development success
	Proportion of adopters, speed of adoption
	Life of technology before obsolescence

magnitude of the secondary impacts are largely unknown, in an ex ante sense.

Consider the production of resistant varieties. Resistance to pests and diseases can be carried out using traditional plant breeding methods or by direct genetic manipulation. Breeding programs will normally have a number of objectives, such as yield increases as well as resistance to major diseases. It is not easy to partition success, should it occur, among the various characteristics that are bred for. The secondary effects of plant breeding, especially the social consequences, may be profound (not all those associated with the "Green Revolution" in south-east Asia were favourable (Simmonds, 1990)).

The difficulties in valuing externalities increase when considering the biological control of pests and diseases. This encompasses a number of options: the release of predators into the environment that feed upon crop pests, or the release of genetically manipulated organisms (GMOs) into the crop. The GMO might act by chemical means upon the pathogen or pest in an antibiotic fashion, or by simple space exclusion, as in the case of a highly competitive but non-pathogenic strain of the organism that causes damage. In assessing the returns to the use of such organisms, account must be taken of the small but finite risks of genetic recombination or of spread to non-target biological populations (Gillet, 1986; Teng, 1990).

The externalities associated with spray applications are treated in some sense by the testing procedures set up by government for the approval of particular chemicals. This involves an understanding of the spatial and temporal behaviour of the pesticide during and after application (Tooby, 1988). Assessments of the environmental and social costs of pesticides in US agriculture were made by Pimentel et al. (1980, 1990) that included human and animal poisoning, reduced pesticide resistance, and fishery and wildlife losses. A recent report lists 1 million human pesticide poisonings with 20,000 deaths annually, on a global basis (WHO/UNEP, 1989). The problems in obtaining trustworthy data for such assessments are considerable, as are the difficulties in assigning a monetary value to loss of human life. The Pimentel studies concluded that more complete accounting would yield a value of the indirect costs of pesticide use that would be several times the value reported.

COST-BENEFIT ANALYSIS AT THE FARM LEVEL

If the secondary effects of pest control decisions at the farm level are either ignored, or, in the case of chemical control, assumed to have been internalised in some way (perhaps as a tax on the purchase price of the chemical), then assessment of costs and benefits of particular control strategies is comparatively straightforward, given relevant information.

Farm-level decision making for appropriate pest control strategies may involve a wide variety of cultural practices (Table 1). Carried out in isolation, many of these will not be particularly effective: hence the requirement for whole-farm cultural management, if conventional spray products are to be banished from a farming system (Jackson, 1988). There are other options open to farmers; in the tropics, intercropping is often practised, apparently as a risk-reducing measure in response to weather, pest and disease uncertainty. For many farmers in the developed world, the path of least resistance to lowering inputs in crop protection is to reduce the quantity of chemical spray applied.

A variety of tools has been developed for the analysis of the costs and benefits of chemical pest and disease control, including decision trees (Menz and Webster, 1981), simulation models (Teng et al., 1980), look-up tables (Thornton and Dent, 1984), and expert systems (Lemmon, 1986). The threshold concept generally runs through all such approaches, either implicitly or explicitly. This involves finding the pest population or disease incidence (or severity) such that the benefits of spraying are equal to the costs of doing so. If observed pest or disease levels exceed the economic threshold, or if they are predicted to do so, then spraying is warranted (Norton, 1976). Various refinements can be applied to the threshold concept for field use; an example is the consideration of spatial distribution or "patchiness" of weeds in a field, with substantial effects on the economic threshold (Thornton et al., 1990). Any movement away from prophylactic control will increase the importance of such decision making aids. Options open to farmers who follow this route include the use of reduced doses (Davies, 1988), tank mixing of different chemicals to reduce application costs (Blackshaw, 1986), and tactical decision making.

To illustrate the latter, consider the situation where a farmer is faced with the decision whether or not to spray for a particular pest. For comparative purposes, the monetary value of not spraying and of spraying can be written

$$MV(N) = P * Y_d \quad \text{and}$$
$$MV(S) = P * Y_s - V_s$$

where P is the price received for the crop, Y_s is the yield after spraying (taking account of the efficacy of the spray), Y_d is the yield if no spraying takes place, and V_s are the variable costs associated with spraying (spray and application costs). Only if MV(S) exceeds MV(N) should the farmer apply spray. The information requirements for one solution to this decision problem include the following: a functional relationship, relating pest density, d, to percentage yield loss, r; the price received by the farmer for the crop, p; the yield of the crop in the absence of the pest, Y_h; the efficacy of the spray, e; and the percentage yield loss due to wheeling damage, w. These variables can be combined to find the yield if no spray is applied,

$$Y_d = Y_h * (1 - r_d/100),$$

and the yield if spray is applied,

$$Y_s = Y_h * (1 - r_s/100) * (1 - w/100),$$

where the yield reductions r_d and r_s are obtained from the function relating yield loss to pest density. An illustration for a hypothetical crop and pest is shown in Table 3; the yield loss function, for simplicity, is assumed to be linear at low-to-medium pest densities. The

TABLE 3. Calculation of the monetary value of spraying and of not spraying: a hypothetical illustration

DATA		
Expected yield	Y_h = 5 t/ha	
Expected price	P = £90 /t	
Spray costs	V_s = £40 /ha	
Spray efficacy	e = 0.85	
Observed pest density	d = 40 /m^2	
Wheeling damage	w = 2.5%	
Yield loss function	r = 0.3*d,at low-to-medium pest densities	
CALCULATIONS		
Pest density post-spraying	$d_s = (1-e)*d$	= 6 /m^2
Yield reduction post-spraying	$r_s = 0.3*d_s$	= 1.8 %
Yield post-spraying	$Y_s = Y_h*(1-r_s/100)*(1-w/100)$	= 4.79 t/ha
Monetary value of spraying	$MV(S) = P*Y_s-V_s$	= 390.9 £/ha
Yield reduction, no spray	$r_d = 0.3*d$	= 12 %
Yield, no spray	$Y_d = Y_h*(1-r_d/100)$	= 4.4 t/ha
Monetary value, no spray	$MV(N) = P*Y_d$	= 396 £/ha

monetary value of not spraying exceeds that of not spraying, so the recommendation would be not to apply spray, in this particular example.

This solution can be made more realistic by using distributions of the key variables, rather than expected values. Price, healthy yield and spray efficacy distributions are illustrated in Figure 4, together with a non-linear yield loss function. These distributions can be combined to find the monetary value distributions associated with spraying and not spraying. Economists have developed a number of procedures to compare such distributions in a way that takes account of the farmer's attitude to risk, such as mean-variance analysis and stochastic dominance analysis (Anderson et al., 1977), so again the preferred option can be identified.

The analysis can be made as simple or as complex, and as general or as specific, as required. The yield loss function can be constructed from field trial data or from expert opinion, or the yield and yield loss distributions can be derived using simulation models of crop growth and pest dynamics for the farmer's own conditions. The analysis can also include factors not shown in Tables 3 and 4: the spatial distribution of the pest in the field, the effects of spray material on subsequent growth and development of the crop, and the use of short-term weather forecasting to modify the shape and location of the distributional and functional forms in Table 4, are but three refinements.

CONCLUSIONS

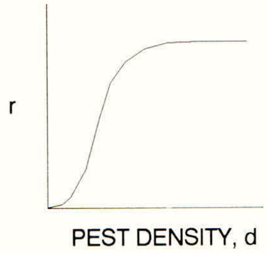
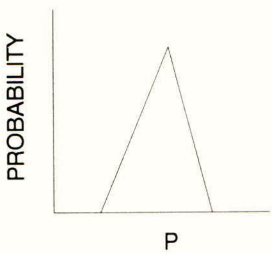
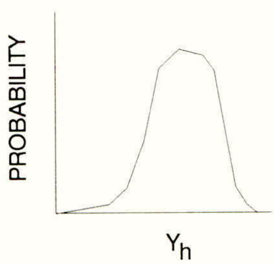
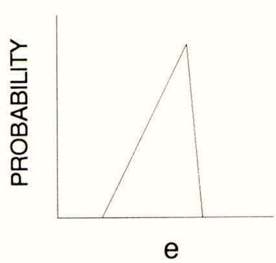
Cost-benefit analysis provides a comprehensive framework for thinking about the impacts of particular courses of action. The quantification of these impacts is difficult, and it is the task of researchers to provide practicable methodologies for doing so. At the farm level, a key activity is the production of better decision making tools and improved information to allow farmers to react to economic and political change in a way that meets their objectives. Refinements to threshold models, improvements in simulation modelling techniques, simple forecasting models, and to the user interface of such tools, are all areas that require substantial research input if this objective is to be met.

The problems of information provision at the policy level have even wider implications. Perhaps the fundamental question relates to whether cheap food for consumers on the one hand and a healthy population and a clean environment on the other are necessarily competing objectives. To answer this question, the risks associated with particular crop protection strategies have to be quantified, if society's fears (groundless or justified) are to be adequately addressed. Any assessment of impacts is bound to contain elements of a subjective nature, but clearly this does not obviate the need for as much rigour as possible. Cost-benefit analysis has a crucial role to play as farmers and society at large adapt to the climate of change in agriculture, and the provision of scientific information to enable such analyses to be carried out should be high on the research agenda.

ACKNOWLEDGEMENTS

The authors thank Barry Dent and Gareth Edwards-Jones for comments on an earlier draft of this paper.

TABLE 4. The assessment of costs and benefits at the farm level: some distributional and functional variables associated with the decision to apply spray or not.

VARIABLE	SAMPLE DISTRIBUTIONAL OR FUNCTIONAL FORM	DEPENDENT FACTORS
Yield reduction, r, %		crop-pest relationship, weather, abundance of predators, ...
Price received for crop, P		external factors beyond the farm gate
Healthy Yield, Y_h		soil type, weather, management, ...
Efficacy of spray, e		timing, weather, dose, ...

REFERENCES

Anderson, J.R, Dillon, J.L. and Hardaker, J.B. (1977) Agricultural Decision Analysis. Iowa State University Press, Ames, Iowa.
Blackshaw, R.P. (1986) Resolving economic decisions for the simultaneous control of two pests, diseases or weeds. Crop Protection, 5, 93-99.
Davies, D.H.K. (1988) Yield response to the use of herbicides in cereal crops; East of Scotland trials 1979-88. Aspects of Applied Biology, 18, 47-56.
Dent, J.B. (1989) Benefit-cost analysis and beyond in the economics of crop protection. In: The Use of Cost-Benefit Analysis in Crop Protection, BCPC.
Gillett, J.W. (1986) Assessment methodologies for biotechnology impact assessment. Environmental Management, 10, 515-532.
Grieg, I.D. (1981) Agricultural research management and the ex ante evaluation of research proposals. Review of Marketing and Agricultural Economics, 49, 73-94.
Harrison S.R.; Dent, J.B.; Thornton P.K. (1990) Assessment of the benefits and costs of risk-related research in crop production. Proceedings, Climatic Risk in Crop Production, Brisbane, July (in press).
Jackson, A.W. (1988) Organic farming: crop protection implications. 1988 British Crop Protection Conference - Pests and Diseases, 3, 103-109.
Lemmon, H. (1986) COMAX: an expert system for cotton crop management. Science, 233, 29-33.
Lindner, R.K. (1987) Towards a framework for evaluating agricultural economics research. Australian Journal of Agricultural Economics, 31, 95-111.
Menz, K.M.; Webster, J.P.G. (1981) The value of a fungicide advisory programme for cereals. Journal of Agricultural Economics, 32, 21-30.
Norton, G.A. (1976) Analysis of decision making in crop protection. Agro-Ecosystems, 3, 27-44.
Pearce, D.W. (1983) Cost-Benefit Analysis, 2nd ed. MacMillan, London.
Pimentel, D. and 11 others (1980) Environmental and social costs of pesticides: a preliminary assessment. Oikos 34, 126-140.
Pimentel, D. and 10 others (1990) Environmental and economic impacts of reducing U.S. agricultural pesticide use. In: D. Pimentel (ed), Handbook of Pest Management, CRC Press, Boca Raton, Florida (in press).
Simmonds, N.W. (1990) The social context of plant breeding. Plant Breeding Abstracts, 60, 337-341.
Teng, P.S. (1990) Assessing the potential impact of planned releases of bioengineered organisms using modelling and non-modelling approaches. Phytopathology (in press).
Teng, P.S.; Blackie, M.J.; Close, R.C. (1980) Simulation of the barley leaf rust epidemic: structure and validation of BARSIM-1. Agricultural Systems, 5, 85-103.
Thornton, P.K; Dent, J.B. (1984) An information system for the control of Puccinia hordei: implementation. Agricultural Systems, 15, 225-243.
Thornton, P.K.; Fawcett, R.H.; Dent, J.B.; Perkins, T.J. (1990) Spatial weed distribution and economic thresholds for weed control. Crop Protection (in press).
Tooby, T.E. (1988) Aims and objectives of pesticide regulations; a challenge to industry. Aspects of Applied Biology, 18, 285-291.
WHO/UNEP (1989). Public Health Impact on Pesticides Used in Agriculture. Report of a WHO/UNEP Working Group. World Health Organization, Geneva; United Nations Environment Programme, Nairobi.

THE U. S. EXPERIENCE IN LOW-INPUT SUSTAINABLE AGRICULTURE (LISA)

PAUL F. O'CONNELL

U.S. Department of Agriculture, CSRS, 14th & Independence Ave., SW, Suite 342, Washington, DC 20250-2200

ABSTRACT

In the United States, as in other industrialized countries, agricultural farming practices are in a state of reexamination. There are increasing concerns about water quality, food safety, wildlife habitat, high costs of modern agriculture, and sustainability of soil resources. Low-Input Sustainable Agriculture or LISA addresses many of these issues by depending more on internal resources available on the farm while maintaining a profitable enterprise. Initial evidence of success for this type of farming is limited, but convincing.

INTRODUCTION

In the United States, as in other industrialized countries, agricultural farming practices are in a state of reexamination. Consumers of food and fiber, many farmers, and those who call themselves environmentalists are expressing concerns about how modern agriculture is being practiced. Looked at in a broader perspective we should welcome this increased interest. Modern agriculture has done a tremendous job of providing high quality and reasonably priced food for the consumer. All you have to do is visit any supermarket to realize the tremendous variety of products available. One of the first things East German citizens looked for when they were allowed to visit the West was the broad selection of food supplies available in a capitalistic economy.

However, like all enterprises, there are areas where improvements can be made, and these improvements can occur without disrupting the many positive aspects of today's agriculture. The concerns or issues can be captured under these categories:

- In the 80's, many U.S. farmers experienced severe economic problems. Recent income data indicates some improvement, but there are still many uncertainties.

- Water quality and food safety concerns

- Sustainability and overall health of the soil resource

- Loss and quality of fish and wildlife habitat

DEFINITION

Before discussing how LISA addresses these issues let me say a few words about what it is. Low-input Sustainable agriculture, or LISA, is a popular term for farming in ways that protect the environment, conserve resources, and assure food safety, as well as provide farmers with adequate net returns. If a method of farming is not profitable it is not sustainable. This approach means lessening the farm's dependence on inputs which can harm the environment, impair food safety, and decrease the farm's profitability. It includes more thorough incorporation of natural processes such as nutrient cycling, nitrogen fixation, and knowledge of pest-predator relationships into the agricultural production process. LISA farming practices vary from farm to farm but commonly include:

- Crop rotations that mitigate weed, disease, insect and other pest problems; increase available soil nitrogen; reduce soil erosion; and reduce risk of water contamination by agricultural chemicals

- Pest control strategies that are not harmful to natural systems, farmers, their neighbors, or consumers. This includes integrated pest management techniques that reduce the need for pesticides by practices such as scouting, use of resistant cultivars, timing of planting, and biological pest controls

- Increased mechanical/biological weed control; more soil and water conservation practices; and strategic use of animal and green manures.

LISA takes a hard look at where modern agriculture has taken us during the last 40 years and asks the basic question -- do we want to continue that trend? It uses the wisdom of the past and combines it with the improved knowledge we have today about biological, ecological, and economic processes. In essence it looks for compliments between production and environmental goals. This type of farming can include farming without any manufactured chemicals (commonly known as organic farming) if that is the farmer's choice. However, it is not limited to that option. The wise use of chemicals is also compatible with the goals of low input/sustainable agriculture.

LISA PROGRAM

The U.S. Department of Agriculture's research and education effort is a relatively small program supporting the development and dissemination to farmers of practical and reliable information on LISA farming practices. Funding in Fiscal Year 1990 is $4.45 million, growing from $3.9 million in 1988, when it started.

Each of four U.S. regions has a host institution and procedures for inviting, reviewing, and approving project proposals from teams made up of farmers, private nonprofit organizations, university research and education staff, and public agencies. The Cooperative State Research Service administers the LISA program in cooperation with the Extension Service.

In the three years since LISA began (1988 - 90) the program has funded 100 team projects, plus nine planning grants and 45 renewals. This is a total of 154 proposals approved out of 800 applications reviewed, or about 18 percent. To date, 1,860 farmers have participated in LISA-funded projects. Hundreds of farmers have helped generate ideas for these projects and have provided land for studies and demonstration plots. They also helped manage the project and over 500 evaluated the outcomes. Most importantly, farmers are actively involved in the leadership of the LISA program, helping to decide which projects to fund. As LISA project results become available they will be disseminated to farmers through special reports, publications, and video presentations; through a LISA information delivery system now being developed under the program; and through existing channels, including the State Cooperative Extension System and Soil Conservation Service (Madden, 1989).

Type of LISA projects being funded can be illustrated with a listing of a few titles from each region.

Northeast

- Development of a Reduced-Input Apple Production System

- Role of Cereal Grain Cover Crops in Nitrogen Management in The Chesapeake Bay Region

North Central

- Crop Rotation, Legume Intercropping and Cultural Pest Control as Substitutes for Purchased Inputs in a Cash Grain Cropping System

- Assessing Soil Phosphorus Availability in Low-Input Systems

South

- Comparisons of Cropping Systems Managed Conventionally or with Reduced Chemical Inputs

- Evaluation of Low Input Crop and Livestock System for the Southern Region

West

- Application of Alternative Management Water Systems to the Cultural and Biological Control of Root Diseases

- Substituting Legumes for Fallow in Great Plains Wheat Production

An offshoot of this interest in sustainable agriculture is a new program begun this year by the Agricultural Stabilization and Conservation Service in USDA. It is called Integrated Crop Management (ICM) with the aim to reduce pesticide or fertilizer use by at least 20.0 percent from current farming practices. To qualify, participants must follow a written ICM plan developed by the Extension Service, Soil Conservation Service, or private consultations and approved by the state ASCS committee. It is restricted to 20 farms in each of five counties per state. First year funding is limited, but according to ASCS officials, interest is high.

LIKELY IMPACT

Discussing what LISA is and why it came into existence is interesting, but does it work in practice. Initial evidence is limited, but convincing. (Madden & O'Connell, 1989; Dobbs & Mends, 1989; and Duffy, 1990).

A recent analysis of U.S. farm costs by USDA economists (McBride & Elosta, 1989) shows that many farmers are using more chemicals than needed for efficient production. Table 1 summarizes the results:

TABLE 1 Farm Chemical Expenses and Yields[1/]

Item	Corn	Wheat	Soybeans	Rice	Cotton
Fertilizer ($ per acre)					
Low-cost producers	32.02	11.52	3.59	28.99	31.57
All other producers	41.75	15.19	6.50	39.94	18.18
Pesticides ($ per acre)					
Low-cost producers	18.75	3.97	10.81	1.43	68.31
All other producers	20.61	3.39	12.68	6.16	36.72
Yields (per acre)					
Low-cost producers	136 bu.	42 bu.	43 bu.	55 cwt	982 lbs
All other producers	104 bu	24 bu.	30 bu.	51 cwt	457 lbs

[1/] Data for corn and cotton were collected in 1987; soybeans and wheat in 1986; and rice in 1984.

The comparison was made between 25.0% of U.S. farms with lowest per-unit production costs and all other farm operations. Production costs included all variable and fixed cash expenses, plus opportunity costs of owned inputs. For corn, wheat, soybeans, and rice the lowest-cost farms spent less on chemicals, but had higher yields. The most notable exception is cotton where the low-cost farms spend 80.0% more for chemicals and doubled the yield. Other expenses on these cotton farms were sufficiently lower to allow them to fit into the low-cost category.

This analysis shows that cost efficient crop producers are not necessarily the heaviest users of synthetic chemical fertilizers and pesticides. Yields of four of the five crops shown did not suffer with reduced chemical expenditures -- in fact they were enhanced. In contrast, chemical expenditures were highest for the most cost efficient cotton producers -- yields also were highest. Much of the U.S. cotton crop is produced in areas where weed and insect pressures are typically high. Herbicides and pesticides are essential to insure a good crop.

A team of scientists at South Dakota State University started a crop rotation study in 1985, comparing conventional, a choice of ridge tillage or minimum tillage, and low-input crop rotations (Dobbs and Mends, 1989). The study now includes experimental plots at two locations, Watertown and Madison. When this study became a LISA project in 1988, the scope of investigations was expanded to include whole-farm studies on several cooperating farms, biological control of pests, nutrient cycling, and soil properties. Economists on the project team have adapted the experimental findings from the first three years experimentation to develop preliminary estimates of the net returns that would be earned by a typical family farm of 540 tillable acres.

During the drought of 1988, the only systems tested in this South Dakota study that were expected to earn a profit were the low-input systems. At the Watertown site the low-input farming system was estimated to earn a profit of about $4,900, using a crop rotation of oats, alfalfa, soybeans, and spring wheat. The simulated farms using a conventional rotation (corn, soybeans, and spring wheat) with chemical pesticides and conventional tillage, incurred a net loss of about $23,000 and $25,000, respectively -- a difference of about $30,000 compared with the low-input system. At the Madison site, the differences were much smaller. The low-input system was estimated to break even, while the minimum tillage and conventional systems lost about $15,000.

In view of consumer alarm over pesticide residues on fruits, scientists in Georgia -- Dan Horton and Floyd Hendrix and in Virginia -- Douglas Pfeiffer (1990) developed alternative methods of controlling fungus diseases and insect pests. Instead of relying on heavy preventive spraying to control the fungus diseases sooty blotch and flyspeck, these scientists developed a post-harvest technique for dipping the fruit in a household bleach solution. Sooty blotch is completely removed, and flyspeck is reduced by 73 percent. When sprayed fruit is dipped in bleach solution, virtually all the residues of fungicides are removed. Using this bleach dipping method, growers may eliminate up to eight sprayings. These scientists have also found that major insect pests are effectively controlled by pheromone disruption plus a single well-timed spray. Alternative-row spraying and ground cover management help conserve natural enemies of the pests and reduce the need for sprays. The overall pest control system developed in this study achieved equal or better control of insect and disease injury compared with Georgia Field Guide recommendations, while reducing the number of sprays from 19 to 9.5, and reducing pest control costs from $247 to $99 per acre.

In 1989, the Board on Agriculture in the National Academy of Sciences published a four year study on alternative agriculture - which is a synonym for low input sustainable agriculture. A few of the authors notable findings were:

- wide adoption of proven alternative farming systems would result in greater economic benefits to farmers and environmental gains for the nation.

- as a whole, current federal farm policies work against environmentally benign practices and the adoption of alternative agricultural systems, particularly those involving crop rotations, certain soil conservation practices, reduction in pesticide use, and use of biological and cultural means of pest control

CONTROVERSIAL ASPECTS OF LISA FARMING PRACTICES

The support for LISA type farming in the U.S. has not been universal. The publication in 1989 of "Alternative Agriculture" by the National Academy of Sciences generated the most discussion. I have separated these concerns into two categories: 1) legitimate or lack of understanding and, 2) criticisms of little or no merit.

Legitimate or Lack of Understanding

One consequence of any new idea or movement is the exaggerated claims of some proponents. Some people would suggest that we have a unsafe food supply and attribute many health hazards to that source. Although there is room for improvement, current evidence does not support that contention. In addition, some proponents of sustainable or organic agriculture say that all synthetic chemicals are bad. This statement is also invalid. Excess nitrogen loading can be the result of improper manure handling as well as that coming from a bag. Many LISA oriented farmers find they must obtain phosphorus or potash from off-farm sources. The point is to use what is needed and no more. The same situation is true for pesticides and herbicides -- if on-farm solutions can't be identified or they are found to be impractical.

Because the agriculture research community in the U.S. deemphasized mixed enterprise farming about 40 years ago in favor of specialized dual culture or monoculture systems -- there is currently a considerable lack of good information on LISA type farming. This includes:

- Bottom line economics of LISA for different types of farming.
- Contribution of crop rotations and reduced chemical use to soil productivity and vitality.
- Long term effects on water quality, fish and wildlife habitat, and human health.
- Implications for farming life styles of shifting to LISA type farming i.e. full time versus part time.
- Macro-economic impacts on trade, competitiveness, livestock numbers, and overall supply.

Criticisms of Little or no Merit

- Conventional agriculture is science based -- LISA or alternative agriculture isn't.
- LISA farming practices are only profitable for small farms or farms with specialized markets.

- Dire effects on world food supply

- Assume linear relationship between chemical use and yields.

- Traditional agricultural scientists are being left out of the LISA program.

- Alternative nutrient sources and weed and pest control practices are impractical.

- LISA type research not needed. Takes resources away from maximum economic yield (MEY) systems.

These statements are not valid and require little explanation. Rather than finding fault with the pro's and con's of conventional versus LISA type agriculture we need to build bridges. The question isn't whether environmentalists and consumers will have a say in future farm policies in the U.S.? The answer to that question is a resounding yes. The question is how to build bridges between those people that have concerns about modern agriculture -- including legitimate and perceived -- and those people directly involved in agriculture. There are polarized positions out there that need to be defused. Exaggerated claims do not build understanding, and we have a lot of that now on both sides. I expect a similar situation exists in other countries and I would like to learn from their experiences at this conference.

REFERENCES

Committee on the Role of Alternative Farming Methods in Modern Production Agriculture (1989) Alternative Agriculture, Board on Agriculture, National Academy of Sciences, Washington, D.C. 20418.

Dobbs, Thomas L. and Clarence Mends (1989). Economic Results of SDSU Alternative Farming Systems Trials: 1988 Compared to 1987 Brookings, SD: South Dakota State University.

Duffy, Michael (1990). Economic Considerations in Sustainable Agriculture presented at National Workshop on Sustainable Agriculture (National Academy of Science), April 3-4, 1990. Proceedings due out in Fall, 1990.

Horton, Don L.; Pfeiffer, Douglas G.; and Hendriz, Floyd F. (1990) Southeastern Apple Integrated Pest

Management presented at National Workshop on Sustainable Agriculture, National Academy of Sciences, April 3-4, 1990. Proceedings due out in fall, 1990.

Madden, J. Patrick and O'Connell, Paul (1989) Early Results of the LISA Program National Agricultural Bulletin, Volume 15, No. 617 National Agricultural Library, Beltsville, MD 20705.

Madden, J. Patrick (1989) Low-Input Sustainable Agriculture Research and Education Projects funded in 1988 and 1989. CSRS-USDA, Washington, DC 20250.

McBride, W.D. & EL-OSTA, H. (1990) Do Efficient Producers Use More Chemicals? Situation and Outlook Report, Economic Research Service, USDA, AFO-37, May, 1990.

AUTHOR INDEX

Abraham, Y. J. 4B-14
Addor, R. W. 2-3, 2-4
Aebischer, N. 3B-4
Ager, B. P. 9B-4
Ahmed, R. 3C-12
Akers, A. 7C-29
Al-Ayoubi, L. M. 7C-31
Allen, R. 8C-13
Allison, D. A. 7C-17
Aloi, C. 3A-1
Ammermann, E. 5-2
Andersch, W. 2-5
Anderson, A. L. 4B-10
Antill, D. N. 4B-8
Arenare, D. 6C-1
Arnold, D. J. 8C-13
Allen, R. 8C-13

Bain, R. A. 9C-3
Baldwin, N. A. 3A-6
Bale, J. S. 3B-2
Ball, S. F. L. 6A-2
Balls, M. 7B-1
Barlow, J. N. 7C-23, 9C-2
Barnett, E. A. 3C-2
Barrera, J. F. 4B-14
Barrett, K. L. 8C-8
Barson, G. 6C-2
Bateman, G. L. 7C-18
Bater, J. E. 8C-3
Bernier, R. L. 3C-11
Berry, C. L. 1-1
Birchmore, R. J. 7C-20, 9C-9
Bleiholder, H. 7C-1
Blood-Smyth, J. 4B-8
Bluett, D. J. 2-2
Bowerman, P. 7C-2
Brokenshire, T. 7C-21
Brown, K. C. 3B-1
Brown, R. A. 6B-4, 8C-5, 8C-6
Buckley, G. A. 6C-7
Budenberg, W. J. 7C-4
Burkart, S. E. 2-7
Burn, A. 4A-3
Buschhaus, H. 9C-9

Cain, R. B. 8A-4
Campbell, C. A. M. 4B-4
Campbell, R. 7A-2
Carter, A. D. 8C-10, 8C-11
Carter, N. 7C-6
Cavelier, A. 7C-18
Chakrabarti, B. 9C-14
Chandler, D. 3C-13
Channer, A. G. 3C-12
Chapman, P. 6C-2
Cheer, A. B. 7C-24
Church, V. J. 7C-13
Clark, D. C. 7C-24
Clark, L. 8C-11
Clarke, S. E. 9C-17
Clements, R. O. 3B-2
Clifton, A. L. 9C-14
Coggon, D. 7B-4
Cole, R. A. 3C-5, 4B-6
Collier, R. H. 3A-4, 4B-7
Cook, R. J. 6A-3
Cooke, L. R. 9C-1
Cooper, D. A. 3B-3
Coulson, J. M. 6B-4, 8C-5
Cousins, S. F. B. 7C-8
Cox, J. 6C-6
Crossland, N. O. 6B-1
Crosby, K. E. 7C-34

Daniels, A. 7C-30
Daudi, A. T. 3C-12
Davies, J. 4B-8
Davies, J. M. L. 3A-3
Davies, L. G. 6C-7
Dawson, H. B. 6C-2
Dayan, A. 7B-2
De Boer, R. F. 3A-2
De Bruyne, E. 3C-8
Decker, U. M. 7C-4
Denholm, I. 9C-13
Dercks, W. 7C-15, 7C-16
Devey, J. P. 7C-23, 9C-2
Devonshire, A. L. 8A-2, 9C-13, 9C-18, 9C-19
Dewar, A. M. 7C-10, 8C-7
Dively, G. P. 4B-5
Dobson, S. 6B-3
Drewes, H. R. 9A-2
Drinkall, M. J. 4B-2
Duffield, S. J. 8C-2

Eadsforth, C. V. 8C-1
Edmonds, G. H. 6C-8
Edwards, C. A. 7C-3, 8C-3
Edwards, P. J. 3C-6, 8C-5
Elbert, A. 2-1
Eldon, S. 7C-7
Elliot, M. S. 3A-4, 4B-7
Ellis, P. R. 3C-4, 4B-6
El-Sebae, A. H. 3C-10
Emmett, B. 4B-8
Eschenbrenner, P. 5-7
Everett, C. J. 8C-4
Eynard, R. 7C-32

Fattori, M. 3C-8
Fawcett, R. H. 10-3
Ferguson, A. W. 7C-12
Finch, S. 3A-4, 4B-7
Fish, J. D. 9A-2
Fitt, B. D. L. 7C-12, 7C-13
Flowerdew, J. R. 3B-5
Fordham, L. R. 8C-12
French, D. A. 8C-14
Froment, M. 7C-8
Frost, M. 7C-8
Fukuchi, T. 2-6, 2-7
Furk, C. 9C-18

Gannon, D. J. 3C-11
Gard, I. E. 2-3, 2-4
Garibaldi, A. 3A-1
Gehmann, K. 5-1
Gelernter, W. D. 7A-3
Georgis, R. 3C-16
Gilbert, A. J. 6C-3
Gilmour, J. 9C-10
Gisi, U. 9C-11
Godwin, J. R. 5-7
Gold, R. E. 7C-29
Gomme, J. 8C-11
Gorman, K. 9C-13
Gough, H. J. 8C-6
Gowen, S. R. 3C-12
Grayer, R. J. 3C-2
Greene, L. 6C-11
Greig-Smith, P. W. 3B-5
Grenier, A. 5-6
Griffiths, D. C. 6A-4
Griffiths, M. M. 3C-11
Grothaus, G. D. 7C-15
Guest, P. J. 3C-11
Gullino, M. L. 3A-1, 9C-4
Gurer, M. 4B-3
Gutteridge, R. J. 7C-18

Hackett, B. S. 9C-16
Hamaguchi, H. 2-8
Hand, L. 8C-15
Hardman, J. A. 3C-4, 4B-6
Hardwick, N. V. 6A-3
Harris, D. C. 3A-5
Harris, R. C. 8C-11
Harris, R. I. 7C-25
Harrison, E. G. 8C-1
Hartwig, J. 2-5
Hayashi, Y. 5-4
Head, I. M. 8A-4
Heale, J. B. 3C-13
Heatherington, P. J. 2-2, 7C-24
Heaney, S. P. 9C-12
Heye, C. C. 6C-1
Hines, C. M. 9C-18
Hiscock, H. 6C-3
Hoffmann, G. M. 7C-14
Hofman, T. W. 5-5

Hollis, J. M. 8C-10
Hollomon, D. W. 7C-17, 8A-1, 9C-5
Holmes, S. J. 4B-12, 9C-3
Hornby, D. 7C-18
Howe, P. D. 6B-3
Huber, J. 7A-1

Iriarte, V. 3C-8
Iwaya, K. 2-1

Jackson, D. 6B-4
Janssen, B. 5-2
Jarrett, P. 4B-11
Jayasena, K. W. 3C-3
Jellis, G. J. 8B-1
Jepson, P. 8C-2
Johnson, I. P. 3B-5
Johnson, L. E. B. 7C-17
Johnson, S. 4A-2
Jones, A. T. 8B-3
Jones, D. R. 9C-6
Jordan, V. W. L. 10-1

Kajihara, O. 2-8
Kamhi, V. M. 2-3, 2-4
Karbach, S. 5-2
Kendall, S. J. 7C-17, 9C-5
Kimmins, F. M. 3C-2
Kirk, W. W. 9C-7
Köhle, H. H. 7C-29
Kohyama, Y. 2-6, 2-7
Komeil, A. M. 3C-10
Konno, T. 2-8
Koster, D. L. 5-5
Kuipers, J. 5-5
Kuriyama, K. 2-8
Kyomura, N. 2-6, 2-7

Labit, B. 7C-17
Lahdenpera, M. L. 3C-7
Laidler, S. T. 7C-26
Lancashire, P. D. 7C-1
Langelüddeke, P. 7C-1
Lankford, W. T. 6C-7
Lauber, J. W. 9A-2
Leadbeater, A. J. 5-1, 7C-27
Leahey, J. P. 8C-14
Lennard, J. H. 9C-10
Lewis, F. J. 8C-5
Lewis, G. B. 8C-6
Linduska, T. J. 4B-5
Linfield, C. A. 3C-7
Litterick, A. M. 4B-12
Liu, G. 3C-1
Llewellin, J. A. 9C-15
Löchel, A. 7C-20
Lockley, K. D. 6C-4
Löcher, F. 5-2, 7C-28
Lorenz, G. 5-2
Lovell, J. B. 2-3, 2-4
Lucas, J. A. 7C-30
Lucas, P. 7C-18

Luff, M. L. 3B-2

Maden, S. 4B-3
Maeno, S. 5-3
Magarey, P. A. 3A-2
Makisumi, Y. 5-4
Malais, M. 3C-14
Mansfield, R. W. 7C-33
Margot, P. 3A-6, 9C-7
Marshall, J. 7C-25
Martin, J. J. 8B-2
Masuda, K. 5-3
Masuko, M. 5-4
Mathieson, I. C. 4B-9
Mazzarello, M. 3C-11
McCaffery, A. R. 9C-17
McIlwraith, N. R. 7C-26
McMullin, L. C. 6B-4
Mead, A. 3C-5
Mercer, C. W. L. 4B-13
Meredith, R. 2-2
Merriam, T. L. 2-7
Meyer, N. 5-2
Meyers, P. 6C-11
Miller, S. A. 7C-15, 7C-16
Miller, T. P. 2-3, 2-4
Mills, K. A. 9C-14
Mitchell, S. J. 7C-22
Mittermeier, L. 7C-16
Miura, I. 5-3
Montfort, F. 7C-18
Moore, D. 4B-14
Moores, G. 9C-13
Morgan, P. C. 6C-2
Mortensen, L. 9B-1
Moser, G. P. 3C-11
Motojima, S. 2-6, 2-7
Mrowczynski, M. 7C-9
Muggleton, J. 9C-15
Munro, J. M. 7C-21
Murabayashi, A. 5-4
Murant, A. E. 3C-2
Murphy, M. 6A-1
Murphy, M. J. 9B-3
Murphy, S. T. 4B-14

Nagata, T. 5-3
Nevill, D. 5-1, 7C-27
Newman, D. 9C-10
Niemeyer, H. M. 3C-6, 8B-2
Noon, R. A. 9C-12
Nordmeyer, D. 7C-27
Nyfeler, R. 5-1

Oakley, J. N. 7C-8
O'Connell, P. F. 10-4
Oetting, R. D. 4B-10
O'Leary, A. L. 7C-34
Oliver, G. 7B-3
Osmer, J. 6C-10
Overbeck, H. 2-1
Oxley, S. J. P. 7C-21

Padgham, D. E. 3C-2
Pegg, K. G. 3A-2
Peng, G. 3C-9
Pepin, R. 5-6
Percivall, A. L. 6C-8
Petersen, F. P. 7C-15
Pettitt, T. R. 6C-9
Pickering, B. A. 9A-3
Pickford, R. J. J. 4B-9
Pinniger, D. B. 6C-2
Plumb, R. T. 6A-2
Pollak, R. T. 4B-2
Poole, N. J. 9B-4
Porras, L. 9C-11
Potts, G. R. 3B-4
Powell, K. 3C-8
Powell, W. 7C-4
Prickett, A. J. 9C-15
Prior, C. 4B-14
Pruszynski, S. 7C-9

Rabatin, S. C. 7C-34
Rajapakse, R. H. S. 3C-3
Ranga Rao, G. V. 3C-2
Ravensberg, W. 3C-14
Rawlinson, C. J. 7C-13
Read, L. A. 7C-10, 8C-7
Redbond, M. R. 7C-23
Reinecke, P. 2-5
Renn, N. 3C-15
Renwick, A. 3C-8
Reobond, M. R. 9C-2
Rhind, D. 8B-2
Riggall, W. E. 3C-5
Rittenburg, J. H. 7C-15
Robertson, S. 9C-10
Rollason, S. A. 4B-6
Rowland, M. W. 9C-16
Rudgard, S. A. 6C-9
Ruess, W. 6C-1
Russell, P. E. 9C-9
Ryan, J. 6B-4

Saunders, D. W. 7C-17
Saur, R. 7C-28
Savvidou, N. 9C-14
Saw, P. L. 3C-4
Sawicki, R. M. 9C-16
Saxena, R. C. 3C-1
Scheinpflug, H. 9C-8
Schelberger, K. 7C-28
Schmeer, H. E. 2-2
Schulz, U. 9C-8
Schumtz, P. 6C-1
Senior, D. 4B-8
Shephard, M. C. 7C-31, 7C-32
Shirane, N. 5-4
Simmons, N. D. 6B-2
Simons, S. A. 7C-19
Skidmore, M. W. 8C-15
Smith, C. M. 7C-17
Smith, S. D. J. 9C-18, 9C-19

Smith-Downey, S. 8C-12
Sotherton, N. W. 8C-9
Southcombe, E. S. E. 6C-3
Sozzi, D. 5-1
Spaull, A. M. 7C-7
Sreenivasan, T. N. 6C-9
Staehle-Csech, U. 9C-11
Stangel, C. P. 4A-2
Stauss, R. 7C-1
Steck, B. 7C-27
Stephenson, R. R. 3B-1
Stenzel, K. 2-5
Stinner, B. A. 7C-3
Stott, I. P. H. 9C-12
Stribley, M. F. 9C-16
Suett, D. L. 8A-3, 8A-4
Sutherland, K. G. 7C-21
Sutton, J. C. 3C-9

Tarrant, K. A. 3B-5
Taylor, A. C. 9C-7
Thabet, A. A. M. 3C-10
Thacker, J. R. 8C-2
Thackray, D. J. 3C-6
Thomas, B. 9B-2
Thomas, C. F. 8C-2
Thomas, M. B. 7C-5
Thompson, A. R. 6C-8
Thornhill, W. A. 8C-7
Thornton, P. 10-3
Thwin Myint-Nu 7C-22
Tinsley, M. R. 4A-3
Treacy, M. F. 2-3, 2-4
Trespeuch, J. 6C-1
Tseriotis, G. 8C-15
Tsuboi, S. 2-1

Umpelby, R. 4B-1
Unwin, R. J. 10-2
Uoti, J. 3C-7
Urech, P. A. 4A-1

Van den Boom, T. 7C-1
Van der Schaaf, D. A. 3C-14
Van Emden, H. F. 8B-4
Van Wambeke, E. 6C-5
Vaughan, J. A. 8C-1
Verreet, J. A. 7C-14
Von Maltzahn, C. 2-7

Walker, A. S. L. 9C-1
Walker, C. H. 9C-17
Waller, C. D. 5-7
Watson, E. 6C-2
Webster, M. W. 6C-7
West, S. 7C-16
White, J. G. 3C-7
White, J. S. 8C-4
White, P. F. 4B-11
Wicks, T. J. 3A-2
Wiggins, T. E. 7C-33
Wightman, J. A. 3C-2
Wiles, J. A. 8C-2
Wilkins, R. M. 3C-1, 9A-1
Willis, F. B. 7C-25
Winder, G. H. 7C-11
Woodhead, S. H. 7C-34
Worthington, P. A. 8C-15
Wratten, S. D. 3C-6, 7C-5
Wright, A. F. 7C-4
Wright, D. P. 2-3, 2-4
Wright, P. 6C-3

Yang, J. 3A-5
Young, D. C. 2-9
Young, J. E. B. 4B-1, 7C-8

Zech, B. 5-6
Zhou, X. 7C-6