SESSION 9A

ADVANCES IN SEED TREATMENTS

Chairman	Dr D D Slawson *Pesticides Safety Directorate, York, UK*
Session Organiser	D J Leaper *Monsanto plc, High Wycombe, UK*
Papers	9A-1 to 9A-4

Strategies for controlling seed-borne diseases in cereals and possibilities for reducing fungicide seed treatments

B J Nielsen
Danish Institute of Agricultural Sciences, Research Centre Flakkebjerg, DK-4200, Denmark

A Borgen
Danish Agricultural University, Agrovej 10, DK-2630 Tåstrup, Denmark

G C Nielsen
Danish Agricultural Advisory Service, Udkærsvej 15, Skejby, DK-8200 Århus N, Denmark

C Scheel
Danish Plant Directorate, Skovbrynet 20, DK-2800 Lyngby, Denmark

ABSTRACT

In the short term there is no useful alternative to chemical seed treatment for controlling the important seed-borne diseases in cereals. The only way to secure high quality seed is by discarding seed lots, which have more than a specified level of disease. Without any other effective control measure than seed treatment large quantities of cereal seeds would be expected to be discarded. Another reduction model might be a differentiated use of seed treatments in the different certified seed generations. An important condition for the models is a quick and representative seed test, which for the moment only is possible in spring cereals. The threshold levels for the different diseases should under these circumstances be re-evaluated. In the long term other measurements may be possible. Investigations have begun on variety resistance to demonstrate effective genetic resistance against leaf stripe and common bunt, but for the moment only little is known on the distribution of resistance in modern Danish varieties. Other possibilities may be microbiological products and non-chemical methods but also here further investigation is required.

INTRODUCTION

Today most cereal crops are seed treated in Denmark on a routine basis. This routine treatment has maintained serious seed-borne diseases at a very low level for many years.

In Denmark legislation has dictated that the use of pesticides should be reduced by 50 % by January 1st 1997 compared with the average usage during 1981 to 1985. This goal was not achieved and the programme is now under review. Seed treatments were not included in the first programme but this is now under consideration and different strategies are discussed in order to reduce the use of fungicidal seed treatments. The work with strategies for reducing fungicidal seed treatments is part of a bigger review on different scenarios for pesticide reduction in Denmark. This paper summarises the present use of seed treatments in cereals in Denmark and possible alternatives to the chemical control. Different scenarios for reducing the routine use of seed treatments will be discussed.

THE PRESENT USE OF SEED TREATMENTS IN DENMARK

It is estimated that approximately 85% of the winter cereal acreage and 90% of spring cereal acreage are sown with certified seed in Denmark. A large proportion of both certified seed and farm-saved seed (85-90%) is treated against seed-borne diseases with products approved by the Danish Institute of Agricultural Sciences (Nielsen & Scheel, 1997). The total consumption of fungicide and insecticide seed treatments in Denmark is approximately 80-110 tons of active substance (table 1, Anon. 1995,1996,1997) and, in 1994, fungicide and insecticide seed treatments were respectively 11% and 12 % of the total applied. Compared with the total use of pesticides in Denmark, seed treatments only account for 2-3 % by active ingredient (table 1). The volume for 1996 is lower than previous years, mainly due to a reduction in the use of maneb and thiram. The use of guazatine in wheat has decreased but the use of bitertanol has increased.

The major use for seed treatments are on cereals (72%) with the greatest proportion of this on the winter crops (approx. 48 t). Insecticide seed treatments are not used on cereals.

Table 1. Amount of fungicide and insecticide used as seed treatments for agricultural purposes including non cereal crops in Denmark (Anon., 1995, 1996, 1997).

	1994	1995	1996
	kg active ingredients		
Fungicides			
carboxin	1410	1960	1280
bitertanol	20541	28932	37087
carbendazim	3095	1190	
fuberidazole	1440	1880	2384
guazatine	19140	16547	7200
imazalil	6276	8469	5714
maneb	12378	4758	
prochloraz	20	40	
thiabendazole	6070		
Other fungicides [1]	30088	28325	20756
Total fungicide seed treatments	101258	92101	74421
All fungicides, in total	*892000*	*1055329*	*630740*
Fungicide seed treatments in % of all fungicides	*11*	*9*	*12*
Insecticides [2]	11377	7964	8720
Seed treatments in total	*112635*	*100065*	*83141*
Total use of pesticides	*3919000*	*4809000*	*3669000*
Seed treatments in % of the total	*2.9*	*2.1*	*2.3*

1) hymexazole, metalaxyl, pencycuron, thiram, tolclofos-methyl 2) Mainly furathiocarb in beets and rape.

THE IMPORTANT SEED-BORNE DISEASES IN DENMARK

Several serious seed-borne diseases would spread rapidly if cereals were grown without efficient methods of control. Ultimately this would lead to significant yield loss and a drastic reduction in seed quality. If no seed treatments were used, common bunt (*Tilletia caries*) in wheat, leaf stripe (*Drechslera graminea)* and loose smut (*Ustilago nuda)* in barley and possibly stem smut of rye (*Urocystis occulta*) would be expected to cause the greatest problems in Denmark.

Common bunt in wheat is subject to great concern, as infections make the seed unfit for bread and feeding purposes and this could cause the rejection of the entire crop. This disease has been seen more frequently in Denmark since 1989 mainly on farms where untreated seed has been used (Nielsen & Jørgensen, 1994). The situation is complicated by the fact that common bunt can be soil-borne (Nielsen & Jørgensen, 1994; Nielsen & Nielsen, 1994; Borgen & Kristensen, 1997). Leaf stripe in barley is commonly not seen but experiences from the early 1970's, where the use of mercury seed treatment was reduced, showed that the disease could increase rapidly if the control level is reduced. Other seed-borne pathogens like *Microdochium nivale, Fusarium spp* and *Septoria nodorum* which are very dependant on the climatic conditions during the growing season can also cause problems but there will not necessarily be an increased infection from one growing season to another. These diseases have not been very common over the past few years (Nielsen & Scheel, 1997) and expected yield losses under Danish conditions are estimated to be 5 – 10 % under moderate to severe infections.

Table 2. Seed borne diseases in wheat, barley, rye, triticale and oat and recommended threshold levels for seed treatments in Denmark (Nielsen & Scheel, 1997; Scheel, 1997).

Crop	Disease	Threshold level for seed treatment
Wheat	*Fusarium spp.*[1)]	15 % infected seeds
	Glume blotch of wheat (*Septoria nodorum*)	5 % infected seeds
	Common bunt (*Tilletia caries*)	Spores present
Barley	*Fusarium spp.*[1)], *Bipolaris sorokiniana*	15 % infected seeds, winter barley
	Fusarium spp.[1)], *Bipolaris sorokiniana*	30 % infected seeds, spring barley
	Net blotch (*Drechslera teres*)	5% infected seeds [2)]
	Leaf stripe (*Drechslera graminea*)	5% infected seeds
	Loose smut (*Ustilago nuda*)	0,2 % infected seeds
Rye	Fusarium spp. [1)]	15% infected seeds
	Stem smut of rye (*Urocystis occulta*)	Spores present
Oat	*Fusarium* spp. [1)]	15 % infected seeds

[1)] Includes *Microdochium nivale* (syn. *Fusarium nivale*) and *Fusarium spp.* [2)] *D. teres* and *D. graminea* can not be separated by current used methods. Threshold level for *D. teres* is probably higher.

THRESHOLD LEVELS FOR SEED TREATMENTS

There is no general requirement for seed treatment in the Danish national regulations or certification schemes but the recommendations are based on certain threshold levels (table 2). These thresholds are determined on the basis of experiments and experience, as well as an understanding of the efficacy of current seed treatments (Nielsen & Scheel, 1997, Scheel, 1997). In practice, the threshold recommendations are seldom used and more than 85-90 % of certified seed is treated with approved products on a routine basis.

ALTERNATIVES TO CHEMICAL SEED TREATMENTS

Cereal production with limited use of or in the absence of seed treatments must be based on other equally effective control measures if seed health is to be maintained. Possible control measures are summarised in below.

Potential for resistant varieties

Resistance is, in principle, able to replace the chemical seed treatment but only minor efforts have been made regarding resistance towards seed-borne diseases and knowledge in this field is limited. In the short term the greatest potential is specific resistance against leaf stripe and common bunt. The aim is to have varieties resistant to many pathogens, but it can be difficult to combine all resistance characters in the same variety.

Resistance to leaf stripe (*D. graminea*) is based on a combination of single genes, giving a high degree of resistance, and polygenic based resistance giving different degrees of resistance. Haahr, Jensen and Skou (1989) found race specific resistance in Danish and European barley varieties and discovered that the gene was closely linked to the MlLa-gene giving resistance to powdery mildew (*Erysiphe graminis*). The resistance has been shown to be effective in field trials (Skou, Nielsen & Haahr, 1994) but the distribution of the resistance gene in the modern Danish varieties is not known. The first results from screening in new Danish varieties show great variation in resistance. In field experiments 4 varieties out of 18 tested were resistant and 5 had moderate resistance (B J Nielsen, unpublished results). The experiment has continued with tests in most of the Danish varieties and some new breeders' lines.

In barley, most varieties exhibit passive resistance to loose smut (*U. nuda*) because of closed blooming and the need for treatment can be focused on the most susceptible varieties. The possibility of improving varieties, for example by incorporating specific resistance, are considered poor within the near future.

In wheat at least 15 specific resistance genes *(Bt)* against common bunt (*T. caries*) are known from the literature, but also partial resistance has been described (Gaudet et al., 1993). A number of Danish winter and spring wheat varieties were tested and the results showed great variation in resistance. A number of varieties had full resistance including the Swedish varieties Tjelvar and Stava and a group of varieties had some resistance (B. J. Nielsen, unpublished results). Tjelvar and Stava have been marketed in Sweden and are resistant towards seed as well as soil-borne bunt (Jönsson and Svensson, 1990). However, since the resistance is based upon specific resistance genes, there is a risk that new virulent races could propagate. The bunt fungus varies a lot and the efforts to incorporate race specific resistance genes have not been very successful in the United States due to occurrence of new virulent races (Hoffmann and Metzger, 1976). Tests so far in triticale seem to show very low susceptibility to seed-borne pathogens. However, there is a continuous need to test these varieties.

Potential for biological control and other non-chemical methods

In recent years, there has been a development in biological control of plant diseases and several products are also potential suitable for seed treatment. However, the products are not fully developed and they require further testing for efficacy and their practical application. Other alternative control methods are available including hot water, hot air, and irradiation of seed or brush treatment for diseases like bunt where there is surface infection. Organic products like acetic acid, mustard and milk products have shown some effects against common bunt in wheat (Borgen, Kristensen & Kølster, 1995; Borgen 1997). These alternative methods are for the moment not usable in practice but must be considered in future together with other control methods and possible integrated with a differentiated use of chemical seed treatment.

OPTIONS FOR REDUCING CHEMICAL SEED TREATMENT

Different scenarios for reducing the reliance on chemical treatment are discussed together with an evaluation of the consequences for Danish agriculture. In table 3 an overview is shown of the various stages of seed production and where decisions could be made about the need to treat or discard seed with infections above defined threshold levels.

Table 3. Different scenarios for managing seed health.

	PB seed (0.6)	*B seed* (4.9)	*C1 seed* (26.8)	*C2 seed* (229.5) [1]
Current Situation	+	+	+	+
Reduced Chemical Scenario	+	+	+	+/- chem
Discard Scenario	+	+	+/- disc	+/- disc
Complete Reduction Scenario	+/- disc	+/- disc	+/- disc	+/- disc

where: + Routine, standard seed treatment
+/- chem Use of chemical seed treatment based on seed testing
+/- disc Seed lots discarded based on seed testing or use of alternative methods if available
PB Seed Pre basic seed used for producing basic seed
B seed Basic seed used for producing certified C1 seed
C1 seed Seed used for producing certified C2 seed
C2 seed Certified seed sold for ware production. C2 seed is not produced in rye
1) Amount of Danish certified seed 1996/97 in '000 t are indicated in brackets. Amount of farm saved seed is estimated to be 40000 t

Possible future strategies for seed health and seed treatment use have also been discussed elsewhere e.g. in UK where a limited 'treatment according to need' approach to the use of fungicide seed treatment to spring cereals were regarded as feasible in the short term with existing seed testing techniques (Paveley *et al.*, 1996). This approach is very close to the 'reduced chemical scenario' stated in table 3. Long-term change towards a wider strategy of treatment according to need in UK and possible treatment based on compulsory testing of all seed was also discussed. The Danish discussion is more radical with focus upon a maximum in reduction in fungicide use eventually a complete reduction.

Reduced chemical scenario

In this scenario the breeding generations including certified seed C1 are treated with chemical seed treatments. This would reduce the possibilities for transmitting serious seed-borne diseases to the C2 generation. However, pathogens like *Microdochium nivale, Fusarium spp.*, *Drechslera teres* and *Septoria nodorum* could infect during the growing season and there is a risk of spreading of the other seed borne pathogens to neighbouring fields during summer or harvest. Moreover *T. caries* can infect wheat through the soil. This makes seed analysis in the big seed generation C2 (80 % of the seeds) necessary and based on this analysis seeds are *only* treated if the level of pathogens is above defined threshold levels (table 2). A more selective use of chemical seed treatments or alternative methods, if available, would be possible depending on target pathogens. A crucial condition for this model is a fast, effective and representative seed analysis in the period from harvest to sowing. This approach is only feasible with existing techniques in spring cereals where the expected reduction in chemicals would be between 30 and 70 % of fungicides used in spring cereals. This scenario is the most realistic even in the nearest future. If suitable analytical methods were available selective use of seed treatments would, however, also be feasible in winter cereals.

Reduced chemical scenario with discard of infested seed

The underlying principal in this scenario is the same as that above, but use of chemicals is *only* allowed during the production of basic seed (table 3). This ensures that seed with high seed health is produced. The seeds used for C1 or C2 are analysed and the seed lots are discarded if seed infestations are above threshold levels. In this case, however, the threshold levels have to be re-evaluated because they are defined for a system where chemicals are available. The threshold levels in C1 seed should be made as low as possible, especially for *T. caries*, *U. nuda* and *D. graminea* (zero tolerance). For C2 seed, the threshold levels could be as stated in table 2 because it is assumed that there will be no further multiplication of seeds and that the farmers buy new certified seed. The basic problem in this scenario is the same as stated above. The system must be based on seed analyses, which for the moment is impossible to achieve in winter cereals. The use of chemicals would be reduced by approximately 80 % but very large quantities of seeds could be expected to be discarded. If other non-chemical methods were available (e.g. biological control, alternative techniques), they could be integrated to reduce the quantity of seed that would otherwise be discarded. This scenario is close to the actual practice regarding seed health in organic farming.

Complete reduction scenario

If the use of seed treatments for seed-borne disease control were ceased immediately in all seed generations, then the possibilities for producing cereals would be very limited. The only realistic possibility, in the long term, would be seed analysis followed by rejection of the infested seed together with the full integration of alternative control measures. Resistance and biological control methods would play an important part but our knowledge today is too limited for us to tell if these methods could completely replace the use of chemical seed treatments

PROBLEMS

The development of a quick and reliable seed test will be important if there is to be any shift away from the current situation and if chemical seed treatments are going to be reduced, particularly for the 'reduced' and 'complete reduction' scenarios, where lack of certified seeds is likely to be a problem.

Seed testing

There are some important problems with seed analysis, which must be solved before a threshold-based system can be used effectively. There is need for new, quick and reliably methods especially in winter cereals where there is a short time from harvest to sowing. In Denmark this period is very short, approx. 3-6 weeks. An enlargement in the range of analyses would demand a fundamental and substantial expansion of the analytical capacity.

Another problem is specificity of the existing diagnostic tests. For example, leaf stripe (*D. graminea*) and net blotch (*D. teres*) of barley can not be separated from each other by a normal analysis. The threshold for net blotch of barley is different than that of leaf stripe and recommendations for seed treatment in barley could in many cases be triggered by the presence of seed-borne net blotch, which frequently occurs in barley. It is anticipated that a PCR-based seed health test that can detect and differentiate *Drechslera* spp. pathogenic on barley will become available to agriculture in the future (Stevens *et al.*, 1997).

The third and probably the most difficult problem to solve is the sampling technique. In Denmark, the basis for one seed analysis is 25 tonnes of seed, which strongly underlines the necessity to make any sample representative. There can be significant variation within the field crop and a seed batch may often be taken from several different fields. For the majority of stored seed, a representative sample can not be taken with today's sampling equipment and there is a need to develop new techniques.

Seed availability and seed quality

In the 'discard' and 'complete reduction' scenarios there will be a potential for rejection of large quantities of seeds including the valuable early seed generations and it may be necessary to increase the breeding area considerably if this approach was adopted. Furthermore, a move towards genetic resistance to seed-borne disease could mean that the choice of varieties is restricted and it may not always be possible to use the varieties with the highest yield potential.

A reduction in the systematic use of seed teatments could entail the uncontrolled spread and propagation of a number of seed-borne diseases and perhaps also of new, so far, rare diseases.

REREFERNCES

Anon. 1995, 1996, 1997. *Orientering fra Miljøstyrelsen*, Nr 8,1995; Nr. 8,1996; Nr. 10,1997

Borgen A; Kristensen L; Kølster P (1995). Bekæmpelse af hvedens stinkbrand uden brug af pesticider. *SP-rapport* **4** (1995), pp 149-158.

Borgen A; Kristensen L (1997). Markforsøg med flerårig overlevelse af stinkbrand (*Tilletia tritici*) i jord. *SP-rapport* **8** (1997), pp 113-119.

Borgen A (1997). Effect of seed treatments with EM (effective micro-organisms) in control of common bunt (Tilletia tritici) in wheat. *Proceedings of the 5th International Scientific Conference on Kyusei Nature Farming*, 1997. In Press.

Gaudet D A; Puchalski B J; Kozub G C; Schaalje G B (1993). Susceptibility and resistance in Canadian spring wheat cultivars to common bunt (*Tilletia tritici and T. laevis*). *Can. J. Plant Sci.* **73**, pp 1217-1224.

Hoffmann J A; Metzger R J (1976). Current status of virulence genes and pathogenic races of the wheat bunt fungi in the Northwestern USA. *Phytopathology* **66**, pp 657-660.

Jönsson J; Svensson G (1990) Tjelvar-ny höstvetesort med resistens mot dvärgstinksot. *Weibulls Årbok 1990*, pp 14-16.

Nielsen B J; Jørgensen L N (1994). Control of common bunt (*Tilletia caries*) in Denmark. BCPC Monograph no. 57, *Seed Treatment: Progress and Prospects*, pp 47-52.

Nielsen B J; Nielsen G C (1994). Stinkbrand og jordsmitte. *SP Rapport* **7** (1994), pp 89-103

Nielsen B J; Scheel C S (1997). Production of quality cereal seed in Denmark. *Proceedings of the ISTA Pre-Congress Seminar on Seed Pathology*, ISTA, Zürich, pp 11-17

Paveley N D; Rennie W J; Reeves J C; Wray M W; Slawson D D; Clark W S; Cockerell V; Mitchell A G (1996). Cereal seed health and seed treatment strategies. HGCA Research Review No. XX. London: Home-Grown Cereals Authority.

Scheel C (1997). Review on Policy Developments with Regard to Seed health Testing and Seed Treatment in the Nordic Countries with Special Reference to Denmark. In: *"Seed Health Testing Progress towards the 21st Century"*. CAB International, pp 107-114.

Skou J P; Nielsen B J; Haahr V (1994). Evaluation and importance of genetic resistance to leaf stripe in Western European barleys. *Acta Agric. Scand., Sect. B*, Soil Plant Science **44**, pp 98-106.

Stevens E A; Blakemore E J A; Reeves J C (1997). Development of a PCR-based test to detect and identify *Pyrenophora* spp. In: *"Seed Health Testing Progress towards the 21st Century"*. CAB International, pp 139-145.

Disease control by a formulation of a living bacterium

B Gerhardson, M Hökeberg, L Johnsson
Plant Pathology and Biocontrol Unit, P. O. Box 7035, SE-750 07 Uppsala, Sweden

ABSTRACT

Treatment with the naturally occurring bacterial strain MA 342 (*Pseudomonas chololoraphis*) controlled several cereal seed-borne diseases as effectively as standard fungicides in over 100 field trials. The strain does not multiply above 33° C, and has shown no detrimental effects in pathogenicity, toxicity and animal feeding tests. An oil-based formulation containing only food-quality ingredients has been developed that is feasible for large-scale use and has a good environment and toxicological profile.

INTRODUCTION

Unless properly controlled, seed-borne diseases, including smut, bunt and several leaf spots, cause severe production constraints in cereals. The quality and yield reductions that can be encountered are well established from historical accounts as well as from a number of investigations (Neergaard 1977). Early control measures, e. g. hot water treatment, were often inadequate and difficult to perform, while several modern fungicides, appropriately applied, usually give satisfactory control.

Environmental and health concerns and the ensuing endeavour to reduce fungicidal usage, have nevertheless given high priority to research for alternative control methods. In line with this, an inter-Scandinavian research project with the proclaimed aim to find new, biological control agents effective against cereal seed-borne diseases was started in 1989. Several newly isolated soil fungi and bacteria were screened for these effects (Knudsen *et al.* 1997), and some of them were further tested under field conditions (Knudsen *et al.*, 1995, Johnsson *et al.*, 1998). This paper reports on field effects, and the development of a formulation for commercialisation of one of the bacterial strains, MA 342, unusually effective in suppressing cereal seed-borne diseases.

METHODS AND MATERIALS

Bacterial strains, disease-infested seed lots, and plant material were maintained and handled as described by Hökeberg *et al.* (1997). The necessary greenhouse bio-assays were performed using *Drechslera teres* infested barley seeds (Hökeberg *et al.*, 1997), and field plot experiments were carried out with different cereal seed-borne diseases using randomised block designs. Experimental procedure, seed lots, pathogen infestation and disease assessment are described by Johnsson *et al.* (1998). The experiments were placed on experimental stations or, when convenient, in commercial crops. Most were located across Sweden but a number were placed in other European countries, as far south as Spain.

Bacterial isolations from soil and roots were carried out on diluted Tryptic Soy Agar as described in Hökeberg *et al.* (1997), and strains were identified using mainly commercial biochemical tests (API, Biolog). Toxicological and pathogenicity data given were collected by commercial, certified laboratories according to official regulations.

Table 1. Results obtained in single years in field experiments testing effects of MA 342 against *Drechslera graminea* and *D. teres* in barley and *D. avenae* in oats (After data from Johnsson *et al.*, 1998).

Treatment	Mean no. of infected plants/m^2 in the year:						
	1991	1992	1993	1994	1995	1996	Tot. mean
	Drechslera graminea-infected barley (cv. Agneta)						
Control	31 a[1]	101 a	60 a	19 a	36 a	22 a	52 a
Guazatine/imazalil[2]	2 b	5 b	4 b	4 b	4 b	3 b	4 b
MA 342 3)	1 b	7 b	12 b	7 b	7 b	4 b	7 b
	D. teres-infected barley (cv. Golf)						
Control	46 a[1]	48 a	89a	68 a	86 a	54 a	63 a
Guazatine/imazalil[2]	1 b	1 b	1 b	1 b	4 b	0 b	1 b
MA 342 3)	1 b	1 b	5 b	7 b	10 b	1 b	4 b
	D. avenae-infected oats (cv. Vital)						
Control	74 a[1]	22 a	73 a	19 a	13 a	nt[4]	34 a
Guazatine/imazalil[2]	32 b	13 b	16 b	7 b	6 b	nt	13 b
MA 342[3]	17 c	3 c	20 b	4 b	7 b	nt	8 b

[1]Within column means followed by the same letter are not significantly different at P = 0.05 according to Duncan's multiple range test; [2]Guazatine/imazalil applied at 600mg/40 mg ai kg^{-1} seed; [3]MA 342 broth applied at a dosage of 200 (1993) or 300 ml kg^{-1} seed; [4] nt = not tested.

Table 2. Evaluation of control effects of MA 342 in field experiments of a number of seed-borne cereal diseases.

Disease and crop tested	Pathogen	Disease control effect	No. of field experiments
Net blotch, barley	*Drechslera teres*	> 95 %	30
Leaf stripe, barley	*D. graminea*	> 95 %	21
Leaf spot, oats	*D. avenae*	76 - 90 %	11
Spot blotch, barley	*Bipolaris sorokiniana*	40 - 50 %	4
Covered smut, barley	*Ustilago hordei*	> 85 %	3
Loose smut, barley	*U. nuda*	None	11
Loose smut, oats	*U. avenae*	80 - 90 %	13
Common bunt, wheat	*Tilletia caries*	> 95 %	12
Soil-borne common bunt, wheat	*T. caries*	None	1
Dwarf bunt, wheat	*T. contraversa*	None	1
Snow mould, wheat	*Microdiochium nivale*	35 - 50 %	17
Leaf and glume blotch, wheat	*Septoria nodorum*	> 95 %	2[1]

[1] One field experiment and one greenhouse experiment

Oil-based formulations for greenhouse testing were prepared by mixing MA 342 cell pellets, collected through centrifugation, into rape-seed oil or a rape-seed oil-surfactant mixture containing a blue stain. For field experiments a formulation was used that was based on industrially fermented and concentrated MA 342 slurry, mixed in a carrier based on rape-seed oil, surfactant, and stain as described above.

RESULTS

Disease control under field conditions

Field testing was carried out in barley, wheat, rye and oats during eight growing seasons, namely 1991 to 1998 during which time it was tested under a wide range of climatic conditions in Sweden and in other European countries. MA 342 showed control of several seed-borne diseases similar to that given by standard fungicide seed treatments. Table 1 shows results from six years of field trials on the control of *Drechslera graminea* and *D. teres* in barley and *D. avenae* in oats. Table 2 gives an evaluation of field effects obtained against other seed-borne pathogens.

Strain characteristics

The MA 342 strain was isolated from roots of *Empetrum nigrum* collected in Sweden. In using conventional identification procedures including API 20 NE (API System Ltd. France), Biolog GN MicroPlate (Biolog Inc. USA) and fatty acid analysis (MIDI, Newark Ltd., USA), the strain shows closest affinity to the species *Pseudomonas chlororaphis*. It is unable to multiply above 33° C, and has shown no detrimental effects in pathogenicity, toxicity and animal feeding tests, Table 3.

MA 342-type bacteria (*Ps. chlororaphis*) are common in nature and have been isolated from cultivated and non-cultivated soils, and from plant roots collected in Sweden and in various European countries. The type MA 342 strain does not proliferate in river water and no residue was detected in plant material or soil after treated plants were harvested.

Table 3. Results of toxicological and pathogenicity tests performed with strain MA 342.

Test performed	Test results
Acute oral toxicity study in the rat	No signs of toxicity and no animal died
Acute pulmonary toxicity/ pathogenicity study in the rat	MA 342 caused no harm to the tested animals
Skin irritation study in the rabbit	MA 342 is not a skin irritant
Acute eye irritation/corrosion study in the rabbit	MA 342 is not an eye irritant
The Buehler test for skin irritation	No signs of delayed contact hyper-sensitivity
Feeding test in chicken	No adverse effects observed

Table 4. Emerged plants and suppressing effect of MA 342 on *D. teres* infections in barley (cv. Golf) after seed treatment with different dosages of bacterial broth culture. Results from a typical greenhouse experiment. Figures are means of four replications.

Treatment	Formulation dose, ml kg $^{-1}$ seed	Applied cells x 10^{10} kg $^{-1}$ seed	Emerged plants, % of sown	Diseased plants, %
Non treated	0	0	90.0 b[1]	24.1 b[1]
MA 342 broth	300	80	94.5 ab	0.5 d
MA 342 broth	200	80	96.5 a	2.1 d
MA 342 broth	50	80	92.0 ab	17.4 c
MA 342 broth	10	80	95.5 a	31.4 a
MA 342 in oil formulation	10	80	92.0 ab	1.1 d

[1]Within column means followed by the same letter are not significantly different at P = 0.05 according to Duncan's multiple range test

Table 5. The effect of dose, and cell concentration on the biocontrol effect of seed treatment with oil-based formulations of MA 342 against *D. teres* infections in barley, and *Tilletia caries* infections in spring wheat. Result from field experiments carried out in 1997.

Treatment	Formulation dose, ml kg^{-1} seed	Applied cells x 10^{10} kg^{-1} seed	No. of plants m^{-2}	No. of diseased plants m^{-2}
	Barley experiments			
Non treated	0	0	200 a[1]	56 a[1]
MA 342 broth	300	120	182 a	0 d
Oil formulation alone	7.5	0	226 a	34 b
MA 342 in oil formulation	7.5	45	238 a	3 d
MA 342 in oil formulation	6.0	36	234 a	4 d
MA 342 in oil formulation	4.5	27	226 a	11 c
	Wheat experiments			
Non treated	0	0	250 a[1]	10 a[1]
MA 342 broth	20.0	8	226 ab	1 b
MA 342 in oil formulation	7.5	45	163 c	0 b
MA 342 in oil formulation	6.0	36	192 bc	1 b
MA 342 in oil formulation	4.5	27	180 bc	0 b

[1]Within column means followed by the same letter are not significantly different at P = 0.05 according to Duncan's multiple range test

Formulation, storability and bacterial mode of action

Since for most diseases simple bacterial broth treatment required up to 300 ml of broth kg^{-1} infested seeds to be fully effective (Table 4), a formulation was developed where the bacteria were mixed with rape-seed oil containing small amounts of a surfactant, and a blue stain. Using this oil-based formulation satisfactory efficacy was obtained at dosages of 6 - 8 ml kg^{-1} seed, Table 5. The formulation was compatible with existing industrial seed treatment equipment and was used in large scale treatment of barley. It can, under conditions of fast seed

seed, Table 5. The formulation was compatible with existing industrial seed treatment equipment and was used in large scale treatment of barley. It can, under conditions of fast seed germination, e. g. high temperature and adequate water supply, delay crop emergence in wheat (Table 5), and a modified formulation is presently in field trials to overcome this effect.

Without specific precautions the formulation is storable for about half a year (Fig. 1). However, by adequate preparation (water content 8 % or less) it may be stored for a year or longer with retained biological effect (data not shown). On treated seeds the biocontrol effect is retained for years independent of treatment method, bacterial broth versus oil formulation.

The bacterial mode of action is complex and is not elucidated in detail. Studies have shown that bacterial cells must be present on the seed for efficient disease control. In broth as well as on seeds the bacterial strain produces low amounts of a specific fungi-inhibiting metabolite, a macrolide. However, this alone is not responsible for its efficacy, as mutants not producing this substance retain biological effect.

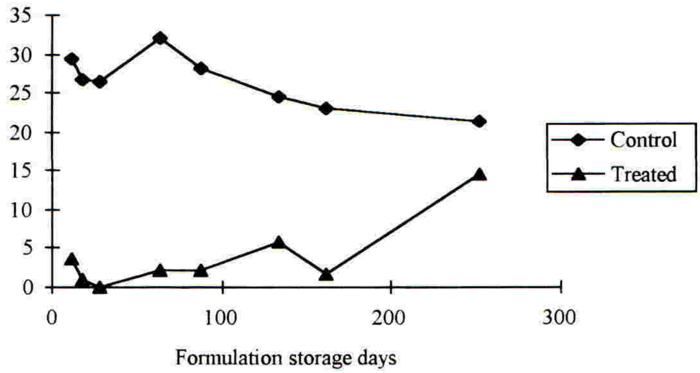

Figure 1. Suppression of *D. teres* infection in barley by oil-based formulation after storing the formulation at 4° C for up to eight months. The curves are at all points significantly different statistically (P=0.05).

Commercial use

The strain MA 342 is patented and its registration as a biological control agent within the EU is pending. An oil-based formulation, sold under the name Cedomon™, is presently registered in Sweden and Norway where it is used commercially for treatment of barley. Seeds of about 60,000 ha of spring barley was treated in Sweden in 1998. Registration is pending in a number of European countries. In Sweden, the product is accepted for use also in organic farming.

DISCUSSION

The results show that MA 342 can be used as a biological control agent for the control of seed-borne diseases of wheat, barley and oats. It has shown similar activity to standard fungicide seed treatments and has performed consistently over several seasons and in different parts of Europe. The bacterial strain controls a broad spectrum of seed-borne diseases, but has somewhat weak effects against *Fusarium* spp. and *Bipolaris sorokiniana,* and is not

MA 342 has shown compatibility with all the commercial fungicides and insecticides so far tested, except for one fungicidal preparation consisting of metalaxyl and mancozeb in mixture which at high dosages may decrease the bacterial disease-controlling effect. These findings allow use in common seed treating equipment without extra cleaning or precautions, and also the use of this preparation in integrated pest management.

Toxicological studies have shown that the MA 342 strain is harmless to humans, animals and to the environment, as it is a natural, commonly occurring bacterial strain. As a result, there are no risks from residues in products, no restrictions in the handling of treated seeds and there is the possibility to reuse packaging and even to feed treated seeds to animals, if not used for sowing. In addition to facilitating distribution and handling of the product and the treated seeds, these characteristics make the bacterial strain and the oil-based formulation containing only food-quality ingredients, compatible with organic farming regulations.

Current experience says that the formulation is commercially acceptable for use in barley. The existing vegetable oil-based formulation meets industrial demands for low volume application (< 10 ml kg^{-1} seed), adequate storage stability and compatibility with industrial scale application equipment, but presently has some weaknesses in delaying wheat emergence under certain conditions. Work is in progress to address this factor that will extend the attractiveness of this unique and environmentally acceptable method of combating cereal seed-borne diseases.

ACKNOWLEDGEMENTS

We thank Mrs Annika Gustafsson, Mrs Janna Krovacek and Mrs Britt-Marie Jingström for excellent technical assistance and MISTRA for financial support.

REFERENCES

Hökeberg M; Gerhardson B; Johnsson L (1997). Biological control of cereal seed-borne diseases by seed bacterization with greenhouse-selected bacteria. *European Journal of Plant Pathology*, **103**, 25 - 33.

Johnsson L; Hökeberg M; Gerhardson B (1998). Performance of the *Pseudomonas chlororaphis* biocontrol agent MA 342 against cereal seed-borne diseases in field experiments. *European Journal of Plant Pathology*. In Press.

Knudsen I M B; Hockenhull J; Jensen D F (1995). Biocontrol of seedling diseases of barley and wheat caused by *Fusarium culmorum* and *Bipolaris sorokiniana*: effects of selected fungal antagonists on growth and yield components. *Plant Pathology*, **44**, 467-477.

Knudsen I M B; Hockenhull J; Funk Jensen D; Gerhardson B; Hökeberg M; Tahvonen R; Teperi E; Sundheim L; Henriksen B (1997). Selection of biological control agents for controlling soil and seed-borne diseases in the field. *European Journal of Plant Pathology*, **103**, 775-784.

Neergaard P (1977). *Seed Pathology*. The MacMillan Press Ltd, London and Basingstoke.

Seed treatment with fluquinconazole for control of cereal take-all, foliar and seed-borne diseases

M Wenz, P E Russell, A M Löchel, H Buschhaus, P H Evans, E Bardsley, F Petit, T Puhl
Hoechst Schering AgrEvo GmbH, Postfach 800320, 65926 Frankfurt/Main, Germany

ABSTRACT

Fluquinconazole, already used commercially as a fungicide for foliar application has also been developed as a cereal seed treatment in order to exploit its unique properties more fully. It provides exceptional control of cereal take-all (*Gaeumannomyces graminis* var. *tritici*) arguably the most important cereal disease which cannot be controlled by available commercial products as well as giving long term protection against infection by *Puccinia* spp. and *Septoria* spp. leaf diseases comparable to that from foliar applications. In addition, control of seed borne diseases such as *Tilletia* spp. and *Ustilago* spp. is provided.

INTRODUCTION

The use of a seed treatment fungicide is a standard commercial precaution against seed and soil-borne diseases. Some seed treatment fungicides are already available, which complement or can even replace foliar fungicide sprays (Mugnier *et al.*, 1991). However, the devastating effects of take-all cannot (Jenkyn & Prew, 1973) or can only partially (Bateman, 1986) be controlled by current fungicide treatments, and cultural practises such as crop rotation, sowing time, and fertiliser use are normally relied upon to reduce the impact of this disease. The solution to all three problems with a single measure would be a significant advance in plant protection.

The unique properties of the triazole fluquinconazole as a foliar fungicide have been described by Russell *et al.* (1992). Fluquinconazole products, applied via the seed, now offer the grower a one-shot solution to protect cereal crops against take-all and classical seed and soil-borne diseases. This treatment can also provide almost season-long control of the most important foliar pathogens. This paper describes the unique properties of fluquinconazole applied as a seed treatment fungicide.

MATERIALS AND METHODS

Formulation:	A water based FS-type formulation, containing 167 g/l fluquinconazole.
Dose rates:	300–900 ml/100 kg seeds (i.e. 50–150 g a.i./100 kg seeds).
Application:	Ready for use (undiluted) application to clean cereal seeds prior to sowing.
Data collection:	Assessments according to standard methods (details are given in the results section).

The results reported in this paper were obtained from small plot field trials in winter wheat unless otherwise stated.

RESULTS

From the considerable research programme conducted to date, representative single trial results or compilations on crop safety and on the activity of fluquinconazole seed treatment against different pathogens are reported.

Crop safety

The crop safety of fluquinconazole seed treatment was assessed in all field trials. Results from six UK selectivity trials on winter wheat with the proposed and double dose rate conducted in 1995/96 are given. Assessments were made at crop emergence. Table 1 shows the emergence and Table 2 the vigour score, relative to two standard commercial products.

Table 1. Emergence counts at growth stage BBCH 9 - 11 (6 trials, UK 1995/96)

	Emerged plants / m²			
Product (dose rate g a.i /100 kg seed)	Minimum	Maximum	Average	Average Relative
untreated	233	450	345	100
fluquinconazole (75)	279	425	341	99
fluquinconazole (150)	281	440	352	102
triadimenol (37.5) + fuberidazole (4.5)	228	420	320	93
triadimenol (75) + fuberidazole (9.0)	238	390	302	88
bitertanol (56.25) + fuberidazole (3.45)	247	447	344	100
bitertanol (112.5) + fuberidazole (6.9)	246	377	325	94

Table 2. Vigour score figures at growth stage BBCH 9 - 11 (6 trials, UK 1995/96)

	Vigour score (0 - 10 scale, where 10 = full vigour)			
Product (dose rate g a.i /100kg seed)	Minimum	Maximum	Average	Average Relative
untreated	7.8	10.0	8.9	100
fluquinconazole (75)	8.0	10.0	8.9	100
fluquinconazole (150)	8.0	9.8	8.8	100
triadimenol (37.5) + fuberidazole (4.5)	4.0	9.0	6.2	69
triadimenol (75) + fuberidazole (9.0)	2.3	6.8	4.2	47
bitertanol (56.25) + fuberidazole (3.45)	5.5	9.8	8.1	92
bitertanol (112.5) + fuberidazole (6.9)	2.8	9.8	7.5	85

Fluquinconazole showed no adverse effect on the number of emerged plants or on plant vigour at either the proposed label rate of 75g a.i./100 kg seed or double dose rate compared with standard products which were generally less selective.

Gaeumannomyces graminis var. *tritici*

Gaeumannomyces graminis var. *tritici*

Table 3 shows the effect of a fluquinconazole treatment (75 g a.i./100 kg seeds) applied alone, or in combination with a conventional seed treatment, in a high infection situation on take-all root infection levels (BBA-scale – Mielke, 1974), the occurrence of white heads and yield effects.

Table 3. Effects of fluquinconazole seed treatment against take-all (Germany, 1997).

Product / dose rate (g a.i./100 kg seed)	Root infection (BBCH 39) (1-9 scale)	White heads %	White heads relative: untr.=100	Yield t/ha	Yield relative: untr.=100
untreated	7.0	6.5	100	5.88	100
fluquinconazole (75)	3.5	3.5	54	7.41	126
prochloraz-Cu (16.63) + carboxin (80)	6.9	7.1	109	5.76	98
prochloraz-Cu (16.63) + carboxin (80) + fluquinconazole (75)	4.5	4.9	75	6.94	118

Treatment with fluquinconazole reduced the take-all root incidence by 2 to 3 disease classes. There was no significant difference, whether fluquinconazole was applied alone or in combination with a conventional fungicide seed treatment. The effect of fluquinconazole treatment on the take-all root incidence resulted in a 30–50% reduction of white heads and gave a corresponding yield increase of 1.2–1.5 t/ha (20–26%). More results from field trials evaluating fluquinconazole specifically for control of take-all are reported by (Löchel *et al.*).

Puccinia recondita

The results from French trials (1995–1997) against *P. recondita* are compiled in Table 4. Fluquinconazole showed commercially acceptable and long-lasting activity, and the target dose of 75 g a.i./100 kg seeds was at least equal to the standard treatment with a triticonazole-based product.

Puccinia striiformis

The efficacy of fluquinconazole against yellow rust was confirmed in French trials and the results are shown in Table 5. The fluquinconazole treatments showed a flat dose response with even the lowest rate being equivalent to a standard triazole-based treatment.

Puccinia hordei

In South Africa, a high level of activity against rust was confirmed on barley (Figure 1). There was no dose-related response with fluquinconazole, and all rates tested were superior to the standard treatment with a triadimenol-based product.

Table 4. Effect of fluquinconazole seed treatment against *P. recondita* (% control).

	BBCH 39 - 49			BBCH 51 - 60		BBCH 65 – 71		
Product /dose rate (g a.i./100 kg seed)	L4 (n=2)	L3 (n=4)	L2 (n=3)	L2 (n=7)	L1 (n=4)	L3 (n=1)	L2 (n=2)	L1 (n=3)
triticonazole (120) + anthraquinone (84)	83	74	62	60	65	82	54	44
fluquinconazole (50)	91	89	86	62	54	82	68	52
fluquinconazole (75)	88	83	77	67	66	76	54	52
fluquinconazole (100)	95	87	85	68	66	90	63	59
fluquinconazole (125)	96	90	86	70	71	71	72	61

Table 5. Effect of fluquinconazole seed treatment against *P. striiformis* (France, 1997)

Product / dose rate (g ai / 100 kg seed)	% control (min. – max.) n=16
triticonazole (120) + anthraquinone (84)	93 (69 – 100)
fluquinconazole (50)	91 (30 – 100)
fluquinconazole (75)	90 (45 – 100)
fluquinconazole (100)	93 (67 – 100)
fluquinconazole (125)	96 (82 – 100)

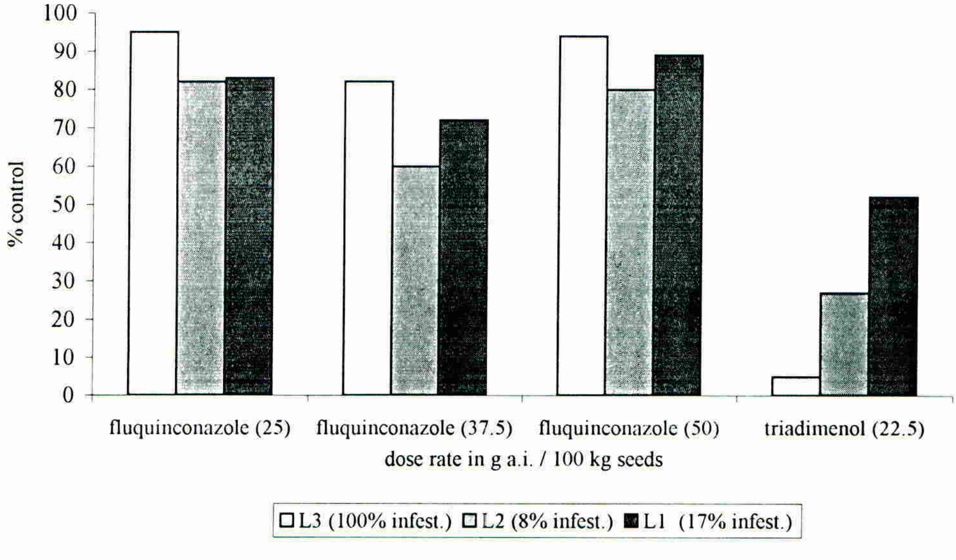

Figure 1. Effect of fluquinconazole seed treatment against *P. hordei* (RSA, 1994).

Septoria tritici

Table 6 compares the activity of the fluquinconazole seed treatment with a standard seed treatment and a foliar application of a triazole fungicide applied at BBCH 37–39. The fluquinconazole treatments were superior to the standard seed treatment and comparable with the foliar fungicide application up to BBCH 51–65.

Tilletia caries* and *Tilletia controversa

The activity against bunt (*Tilletia caries*) was confirmed in five UK trials and the results are shown in Table 7.

Table 6. Activity (% control) of fluquinconazole against *Septoria tritici* (France, 1995–97).

Growth stage	GS32		GS39		GS51-65	GS77
Product (g a.i./100 kg seed)	L6 (n=2)	L5 (n=3)	L4 (n=2)	L3 (n=2)	L3 (n=3)	L1 (n=1)
foliar spray (tebuconazole 250 g a.i./ha)			32		53	84
triticonazole (120) + anthraquinone (84)	4	6	12	43	14	25
fluquinconazole (50)	41	26	45	58	42	39
fluquinconazole (75)	53	41	42	68	39	58
fluquinconazole (100)	49	44	47	65	48	65
fluquinconazole (125)	56	46	45	68	49	69

All treatments achieved complete control. The level of control required for registration in Germany is 99.5%. Current (1997/98) seed treatment trials in Germany show also a high level of activity of fluquinconazole against dwarf bunt (*Tilletia controversa*).

Table 7. Effect of fluquinconazole against *Tilletia caries* (number of infected ears/m² at BBCH 73–85) (UK 1995/96).

Product (dose rate g a.i./100 kg seed)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean
untreated	226.2	107.4	44.8	13.8	91.6	96.8
fluquinconazole (50)	0.0	0.0	0.0	0.0	0.0	0.0
fluquinconazole (75)	0.0	0.0	0.0	0.0	0.0	0.0
fuberidazole (4.5) + triadimenol (37.5)	0.0	0.0	0.0	0.0	0.0	0.0

Ustilago nuda* f. sp. *tritici

The activity of fluquinconazole against loose smut in wheat was confirmed in three German registration trials in 1996/97. At a dose rate of 75 g/100 kg seeds fluquinconazole achieved an average control of 99.5% in excess of the minimum 95% requirement for registration in Germany.

DISCUSSION

The data have shown that fluquinconazole seed treatment provides versatile and comprehensive control of take-all, seed-borne and foliar diseases of cereals. The farmer will benefit from increased yields, a simplified disease control programme and greater flexibility in crop rotation, all of which will fit well with an integrated approach to crop production.

The unique biological performance of fluquinconazole is believed to be due to its physicochemical properties. Compared with commercially available triazole seed treatments it is extremely crop safe even at high dose rates. Research into how it achieves these effects is continuing. Preliminary investigations (Buchenauer, pers. com.) suggest that a long lasting protection zone is created around the seed which in turn provides a source for the uptake of the compound into the plant over a prolonged period.

The target dose rate for practical use is 75 g a.i./100 kg seed (450 ml formulated product/100 kg seed). To enlarge the spectrum to include seed-borne diseases notably *Fusarium* spp., coformulations with prochloraz are available. For simultaneous protection against other targets, e.g. insect pests, fluquinconazole can be applied in mixture with other seed treatment products.

Fluquinconazole-based seed treatment products will be marketed under the trade name 'Jockey®'.

REFERENCES

Bateman G L (1986). Effects of triadimenol-containing seed treatment on winter wheat infected with take-all. In: *Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz* **93** (4), 404-414.

Jenkyn J F; Prew R D (1973). Activity of six fungicides against cereal foliage and root diseases. *Annals of Applied Biology* **75**, 241-252.

Mielke H (1974). Untersuchungen über die Anfälligkeit verschiedener Getreidearten gegen den Erreger der Schwarzbeit *Ophiobolus graminis* Sacc. *Mitteilungen der Biologischen Bundesanstalt für Land- und Forstwirtschaft, Berlin-Dahlem* **160**, 1-61.

Mugnier J; Chazalet M; Gatineau F (1991). RPA 400727: Un nouveau fongicide pour le traitement des semences de céréals. *ANNP; Troisième, Conférence Internationale sur les Maladies des Plantes, Bordeaux – 3, 4, 5 Decembre 1991*, 941-948.

Russell P E; Percival A; Coltman P M; Green D E (1992). Fluquinconazole, a novel broad spectrum fungicide for foliar application. *Brighton Crop Protection Conference - Pests and Diseases - 1992*, 411-418.

The effects of a novel seed treatment, MON 65500, on take-all severity and crop growth in winter wheat

J H Spink, A P Wade
ADAS Rosemaund, Preston Wynne, Hereford, UK

N D Paveley
ADAS High Mowthorpe, Duggleby, Malton, N. Yorks, UK.

J M Griffin
Monsanto plc, Agriculture sector, PO Box 53, Lane End Road, High Wycombe, Bucks, UK.

R K Scott, M J Foulkes
The University of Nottingham, Division of Agriculture and Horticulture, Loughborough, Leics. UK.

ABSTRACT

Experiments at ADAS Rosemaund in Herefordshire, UK. in harvest years 1994-6, investigated the effect of a novel seed treatment for the control of take-all, on 8 varieties of winter wheat, grown as either first, second or third successive wheat crops. In the 1996 season, sequential measurements of take-all severity and crop growth were taken. Take-all reached moderate levels from May onwards. Treatment with MON 65500 provided significant control. Nitrogen uptake of the crops declined with increasing number of preceding wheat crops from 225 kg ha^{-1} to 202 kg ha^{-1} in third wheats in 1996. This effect was removed by the seed treatment. The seed treatment also increased green area retention during early grain filling and increased harvest above-ground biomass of the crops. In 1996, yield in the absence of the seed treatment tended to decline with increasing number of preceding wheat crops from 9.6 t ha^{-1} in first to 8.8 t ha^{-1} in third wheats and there was a trend for this effect to be negated by the seed treatment. A cross-year analysis of first and second wheats showed that MON 65500 produced a significant yield benefit, averaging 0.47 t ha^{-1}. There was a significant interaction between variety and seed treatment, indicating the importance of variety in determining the likely yield response to treatment. Three third wheat experiments conducted by Monsanto, demonstrated significant beneficial effects of the seed treatment on yield. The work shows that MON 65500 minimises the yield reducing effects of take-all by ameliorating the principal effects by which the disease is thought to reduce yield.

INTRODUCTION

A significant proportion of UK wheat is grown following another cereal crop. Over the period 1989 - 1996, non-first wheats have accounted for between 36 and 59 % of the UK crop. Although the proportion of non-first wheats has been lower in recent years, following the widespread introduction of set-aside (Polley, unpublished data), a large proportion of set-aside is in the form of natural regeneration, which does not form a complete take-all break (Jones *et al.*, 1996). Hence, a high proportion of wheat crops are still at risk of take-all infection. Non-first wheats are widely recognised as being lower yielding than first wheats. Nix (1995) estimated that second wheat crops yield 12.5% less than first wheats, and that third wheat crops yield 10-15% less than second wheats. The lower yield of non-first wheats is due to a number of factors, namely; lower soil fertility than following high residue break crops, increased stem-base disease and increased take-all. The impact of the first two of these can, to a large extent, be minimised through careful crop husbandry; accurate accounting for mineral N residues in deciding on fertiliser N applications, and control of stem-base disease through varietal resistance and early season fungicide application. Vaiydanathan *et al.*, (1987) reported that, in non-first wheat crops, after discounting the effects of N, mean yield loss due to take-all was in the order of 1 t ha^{-1}. Control of take-all remains difficult. It has been reported that varietal resistance to take-all has not been found (Hollins *et al.*, 1986), and that the identification of resistance in wheat and breeding of resistant varieties is unlikely (Scott *et al.*, 1989). There are currently no fully effective, commercially available means of chemical control of the disease and novel methods of control such as biological control agents have proved unreliable. The most effective method of minimising the impact of the disease through husbandry is delaying drilling of the crop, which may also directly reduce the yield potential of the crop. The work reported here tested a novel seed treatment, MON 65500, for control of take-all.

MATERIALS AND METHODS

MON 65500 was included in a Home-Grown Cereals Authority (HGCA) funded experiment at ADAS Rosemaund in harvest years 1994-6. The experiment investigated responses of varieties to take-all control. Different levels of take-all were produced by phasing in either a first, second or, in harvest year 1996, a third wheat crop, on each of three main plots. Each treatment was replicated three times. Main plots were split into two and each of eight varieties of wheat were grown in both halves of the main plot either with or without MON 65500. The eight varieties were chosen to contrast for characteristics thought to bestow tolerance or intolerance to take-all (Spink *et al.*, 1996), tolerance being defined here, as the capacity of a crop to minimise yield loss per unit disease severity. The varieties were Brigadier, Cadenza, Lynx, Rialto, Riband, Soissons, Spark and Zentos.

In 1996, progress of the take-all epidemic was recorded by sampling cv. Spark from each sub-plot on an approximately fortnightly basis from December until harvest the following year. In addition, during grain filling, take-all severity was measured on all plots using an index (Spink *et al.*, 1996) with a range of 0 (no disease) to 100 (all roots infected). Four varieties (Brigadier, Riband, Soissons and Spark) from each rotational position and seed treatment, crop samples of 0.81 m^2 were used to assess nitrogen uptake, above ground dry mass production and partitioning and crop canopy production in terms of green area index (GAI; the number of units of planar area of green stem, leaves and ears per unit ground they occupy). Some limited sampling was also done in harvest year 1995, and nitrogen uptake results are reported.

In addition, experiments investigating the response of up to ten varieties of winter wheat to MON 65500 were conducted by Monsanto. These experiments were carried out on three third cereal sites in 1996-7. There were two sites in the UK at Oakham, Rutland and Wellington, Shropshire, and one in the Republic of Ireland at Ballyragget, Co. Kilkenny.

RESULTS

Take-all

In 1996, take-all remained at a low level until the end of April, associated with cold spring temperatures, thereafter on second and third wheats it started to rise rapidly, achieving a final index on untreated third wheat crops of 31 (Figure 1). The disease was consistently less severe on first wheat crops. Second and third wheat crops were difficult to distinguish until later in the season. MON 65500 reduced take-all in all rotational positions. The greatest reduction in take-all was seen in the latest assessment on third wheat crops, where the disease severity was reduced by an average of 33% ($P = 0.009$). There was no significant difference in the level of disease between cultivars (Table 1).

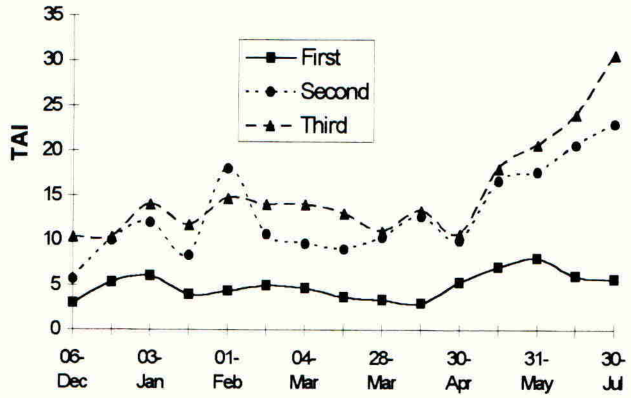

Figure 1. ADAS Rosemaund, 1996, Take-all progression on cv. Spark expressed as an index on untreated wheat crops.

Table 1. Final take-all indices for each variety, grown as first, second and third successive wheat, without MON 65500, ADAS Rosemaund, 1996.

		Rotational position		
Variety		First	Second	Third
Brigadier		10.3	20.7	23.0
Cadenza		8.7	15.3	22.3
Lynx		12.0	20.3	21.3
Rialto		11.3	18.0	21.7
Riband		10.3	19.0	20.3
Soissons		12.7	18.7	26.0
Spark		5.7	23.0	30.7
Zentos		8.3	18.3	18.3
Mean		9.9	19.2	23.0
			s.e.d.	*P*
Rotational position	(df = 4)		1.92	0.012
Variety	(df = 84)		1.91	NS
Position x Variety	(df = 84)		3.64	NS

Crop growth

The main effects of take-all on the crop are to restrict water and nutrient uptake (Hornby and Bateman, 1991). In 1995 and 1996, the final nitrogen content of the crop was measured to indicate any effects of the disease on nitrogen acquisition. In 1996, total nitrogen uptake for the first wheat crops averaged 225 kg N ha^{-1}, whether treated or untreated with MON 65500. As wheat crops were grown in successively longer runs and the level of the disease increased, total nitrogen acquisition by the crops declined to 215 and 202 kg N ha^{-1} for second and third wheat crops respectively. Where treated with MON 65500 the level of nitrogen uptake remained consistent across the rotational positions varying from 223 to 225 kg N ha^{-1}. A similar but minor effect was noted in 1995. In the absence of seed treatment, nitrogen off-take dropped from 182 to 177 kg N ha^{-1} when grown as a second as opposed to a first wheat. Nitrogen off-take was maintained with the seed treatment at 190 kg N ha^{-1} in both the first and second wheat (Figure 2).

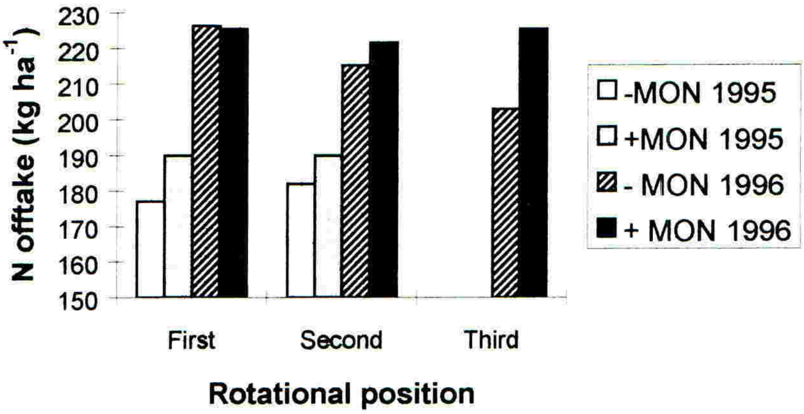

Figure 2. Total harvest nitrogen off-take (kg ha^{-1}) averaged across the varieties, for first, second in 1995 and 1996, and third wheat plots in 1996, with and without MON 65500.

Total GAI, at either GS 31 or 39, was little affected by rotational position or seed treatment (Figure 3). By GS 65 however, both the second and third wheat plots had significantly poorer green area retention than the first wheat plots. MON 65500 significantly increased green area retention across all rotational positions at this stage, the magnitude of the effect increased with rotational position, increasing GAI by 0.7 (from 7.0 to 7.7), 0.8 (from 6.2 to 7.0) and 1.0 (from 6.5 to 7.5) on first, second and third wheat crops respectively (Figure 3). By mid-grain filling, as green area was declining rapidly, the effect of the seed treatment was diminished.

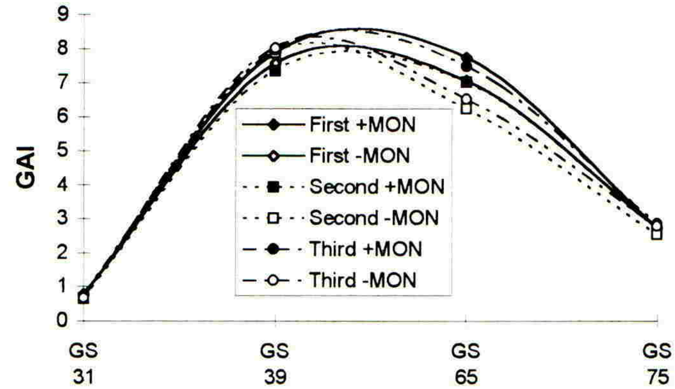

Figure 3. Green area index for first, second and third wheat crops, with and without MON 65500 in 1996. Seed treatment s.e.d for GS 65 = 0.335, (P = 0.05).

Increased green area retention due to MON 65500 resulted in greater total crop growth, which was seen in significantly (P<0.05) increased total above-ground biomass at GS 87 (Figure 4.). The effect was greatest in first and third wheat crops, there being no apparent effect on second wheat crops.

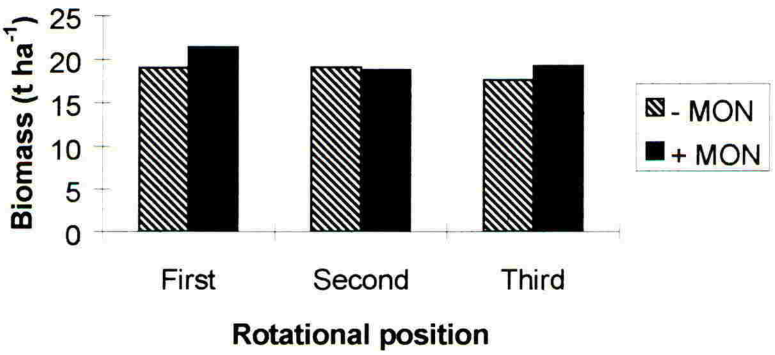

Figure 4. Total crop biomass (t ha^{-1} @ 100% d.m.) measured at GS 87, on first, second and third wheat crops, with and without MON 65500, in 1996.

Yield

In the Rosemaund experiment, yield of untreated first wheats averaged 8.73 t ha^{-1} @ 85% d.m. Across the three years of the experiment, on first and second wheats, the seed treatment significantly increased yield by an average of 0.47 t ha^{-1}. In 1996, yields tended to decline with increasing rotational position, first, second and third wheats yielding 9.58, 9.47 and 8.75 t ha^{-1} respectively although these differences were not statistically significant. Where MON 65500 was applied, yields were maintained across rotational positions at 9.34, 9.58 and 9.49 t ha^{-1} for first, second and third wheats respectively. However, increased error variation, brought about by the patchy nature of the disease prevented some effects reaching statistical significance. In a cross-year analysis of first and second wheats, there was a significant interaction between variety and seed treatment, with some varieties producing larger yield responses (e.g. Brigadier) to seed treatment than others (e.g. Rialto). Within the third wheats in 1996, responses of the varieties to the seed treatment were consistently positive and ranged from about 0.5 t ha^{-1} to 1.35 t ha^{-1}.

Table 2. Yield (t ha^{-1} @ 85% d.m.), for each variety, grown as a first, second (1994 - 6) or third (1996 only) wheat, with or without MON 65500, ADAS Rosemaund. Statistics apply to cross-year analysis of first and second wheats only.

	First		Second		Third	
	- MON	**+MON**	**- MON**	**+MON**	**- MON**	**+MON**
Brigadier	8.90	9.77	8.77	9.80	8.81	10.16
Cadenza	8.22	8.92	8.56	9.12	8.76	9.54
Lynx	9.13	9.80	9.03	9.58	9.18	9.70
Rialto	9.60	9.72	9.32	9.33	9.62	10.15
Riband	8.39	8.91	8.70	8.88	8.32	9.12
Soissons	8.94	9.55	8.56	9.42	9.00	9.72
Spark	8.61	8.55	8.09	8.48	8.36	8.92
Zentos	8.08	8.35	8.10	8.43	7.96	8.63
Mean	8.73	9.19	8.64	9.13	8.75	9.49

		s.e.d	*P*
Rotational position	(df = 6)	0.387	NS
Seed treatment	(df = 12)	0.211	0.044
Position. x Seed treatment		0.441	NS
Variety	(df = 182)	0.118	<0.001
Posn. x Variety		0.417	NS
Seed treatment x Variety		0.262	0.002

Table 3. Yield t ha^{-1} @ 85% d.m. from the Monsanto experiments.

	Shropshire		Rutland		Co. Kilkenny	
Varieties	- MON	+ MON	- MON	+ MON	- MON	+ MON
Beaufort	7.90	8.60	7.25	7.70	-	-
Brigadier	7.75	8.30	7.73	7.88	8.10	9.55
Cockpit	8.40	8.73	8.43	8.60	-	-
Consort	-	-	-	-	8.35	10.00
Crofter	7.90	8.23	7.73	7.30	-	-
Encore	7.85	8.05	7.30	7.65	-	-
Hereward	7.38	7.75	7.75	7.60	-	-
Hussar	-	-	-	-	7.95	10.10
Madrigal	8.00	8.78	7.98	7.93	8.50	10.50
Mercia	7.75	8.93	8.03	8.83	8.93	10.23
Reaper	-	-	-	-	8.13	9.73
Rialto	-	-	-	-	8.78	10.45
Riband	7.68	8.65	7.05	7.13	-	-
Ritmo	-	-	-	-	8.25	8.80
Soissons	-	-	5.95	6.25	7.75	8.65
	s.e.d.	*P*	s.e.d.	*P*	s.e.d.	*P*
Seed Treatment	0.099	<0.001	0.080	<0.05	0.145	<0.001
Variety	0.330	<0.05	0.311	<0.001	0.430	<0.05
Seed trt * Variety	0.397	NS	0.359	NS	0.539	NS

In the Monsanto experiments, there were consistent significant effects of both seed treatment and variety on yield. The average response to treatment varied according to severity of take-all, as measured at GS 75, the lowest being 0.17 t ha^{-1} in Rutland (T.A.I = 22), then 0.51 t ha^{-1} in Shropshire (T.A.I. = 44) and 1.52 t ha^{-1} in Co. Kilkenny (T.A.I. = 73). The varieties showed a range of response to the treatment, but the interaction between seed treatment and variety was not statistically significant.

DISCUSSION

Take-all is thought to reduce crop yield by reducing water and nitrogen acquisition by the crop, through a reduction in root function. The effect of take-all in reducing water uptake by the crop may be considered as being analogous to the crop experiencing drought. One of the main effects of a post-anthesis drought (which would be comparable to the timing of the take-all epidemic in the 1996 Rosemaund experiment) is to reduce canopy persistence (Foulkes *et al.*, 1997). The main effects of MON 65500 on the crop in this study were to maintain nitrogen content of the crop across the rotational positions and to improve green canopy retention during grain filling. These effects indicate that the chemical was having a real effect in reducing the impact of take-all on the crop.

Although in the Rosemaund experiment in 1996, the chemical reduced the severity of the disease, it did not provide complete control. The reduction in disease severity by the chemical was, however, sufficient to maintain yields at first wheat levels. This type of study needs repeating in a more severe take-all epidemic, to establish the level of yield recovery.

In the Monsanto experiments, on third wheat crops, MON 65500 consistently produced a significant increase in yield. In the experiment in the Republic of Ireland, this effect was large compared to the average yield loss due to take-all estimated by Vaidyanathan *et al.* (1987). However, in the absence of a comparison with a first wheat crop in the same field, it is impossible to judge whether the treatment completely restored the yield of the crop.

A number of approaches may be combined to reduce the severity or impact of the disease on yield, such as; crop rotation (Hornby and Bateman, 1991), avoidance of early sowing date (Yarham, 1986; Prew *et al.*, 1986) and increased amounts of early spring nitrogen fertiliser (Prew *et al.*, 1986). An additional approach could be the selection of varieties which have been shown to exhibit traits thought to associate with take-all tolerance (Anon, 1998). The work reported here shows that variety is also likely to be an important factor in determining the likely yield response to treatment with MON 65500. Brigadier and Rialto represent varieties close to the extremes in terms of trait expression likely to bestow intolerance and tolerance respectively to take-all, (Spink *et al.*, 1996). Over the three years, Brigadier produced the largest response to seed treatment and Rialto the smallest. This effect was also seen in the responses measured in the third wheat comparison made during 1996.

The studies reported here have shown that MON 65500 could play a valuable part in an integrated approach to managing wheat crops in take-all risk situations.

REFERENCES

Anon (1998, in press). Varietal responses to drought and rotational position. *HGCA Final Project Report **No. 166E** 'Exploitation of Varieties for UK Cereal Production'*. Vol. II, Parts 1 and 2, 56 pp. & 51 pp.

Foulkes M J; Scott R K; Sylvester-Bradley R (1997). Optimising winter wheat varietal selection on drought-prone soil types. *Aspects of Applied Biology* **50** *(Optimising cereal inputs :Its scientific basis)*, 61 - 76.

Hollins T W; Scott P R; Gregory R S (1986). The relative resistance of wheat, rye and triticale to take-all caused by *Gaeumannomyces graminis* var. *tritici*. *Transactions of the British Mycological Society* **35**, 93-100.

Hornby D; Bateman G L (1991). Take-all disease of cereals. *HGCA Research Review* **No. 20** 146 pp.

Jones D R; Froment M A; Jenkyn J F; Gutteridge R J (1996). Effects on wheat diseases of three and five year set-aside covers. *Aspects of Applied Biology* **47**, *Rotations and cropping systems*. pp. 441-444.

Nix J (1995). *Farm Management Pocketbook 26th edn.* Wye College Press: Wye College, Kent.

Prew R D; Beane J; Carter N; Church B M; Dewar A M; Lacey J; Penny A; Plumb R T; Thorne G N; Todd A D (1986). Some factors limiting the growth and yield of winter wheat grown as a third cereal with much or negligible take-all. *Journal of Agricultural Science* **107**, 639-671.

Scott P R; Hollins T H; Summers R W (1989). Breeding for resistance to two soil-borne diseases of cereals. *Vorträge für Pflanzenzüchtung* **16**, 217-230.

Spink J H; Foulkes M J; Clare R W; Scott R K; Sylvester-Bradley R; Wade A P (1996). Physiological traits of winter wheat varieties conferring suitability to rotations with continuous successions of wheat. *Aspects of Applied Biology* **47,** 265-275.

Vaidyanathan L V; Sylvester-Bradley R; Bloom T M; Murray A W A (1987). Effects of previous cropping and applied nitrogen on grain N content in winter wheat. *Aspects of Applied Biology* **15**, 227-237.

Yarham D J (1986). Change and decay - the sociology of cereal foot rots. *Proceedings 1986 British Crop Protection Conference - Pests and Diseases*, 401-410.

SESSION 9B

FIELD BUFFER ZONES – ECOLOGICAL HAVEN OR THREAT TO PRODUCTION?

Chairman	Mr T Tooby *Jellinek, Schwartz & Connolly, Harrogate, UK*
Session Organiser	Dr P J Campbell *Zeneca Agrochemicals, Bracknell, UK*
Papers	9B - 1 to 9B - 4

Buffer zones to protect the aquatic environment

A C Croxford
Environment Agency, Ecotoxicology and Hazardous Substances National Centre, Evenlode House, Howbery Park, Wallingford, Oxfordshire, OX10 8BD, UK

ABSTRACT

Some pesticides are highly biologically active and may harm aquatic life if they enter water. Pesticides may reach water via spray drift, surface run-off, movement through the soil and soil erosion. One way of reducing the amount of pesticide entering water, particularly from spray drift, is by the use of buffer zones or no-spray zones. This paper describes the current scheme for buffer zones in the UK and proposals for the introduction of a scheme of Local Environmental Risk Assessment for Pesticides (LERAP). It also discusses further ways in which LERAP may be developed and alternative methods of providing the necessary protection of the aquatic environment.

INTRODUCTION

Some pesticides are highly active and very small quantities entering water can have serious impacts on aquatic species. Pesticides can reach water by a number of different routes. These include direct over-spray or spillage, spray drift, surface run-off, lateral flow through the soil, drain flow, and on soil particles via soil erosion.

As part of the process of considering pesticides for approval or review, the risk to the aquatic environment needs to be assessed. Should this risk be considered unacceptable, there are a number of options available to the agrochemical manufacturer that may be used to mitigate the risk. These risk management options include limiting the dose rate, crop range, time of application, application technology and area of application. In addition, under the conditions of approval, a specified width of land alongside watercourses where it is not permitted to apply the product can be imposed. This area has become known as the no-spray or buffer zone. The primary aim of the buffer zone is to minimise water contamination by spray drift. The buffer zone can also reduce contamination from surface run-off and soil erosion but has little influence over lateral flow through the soil, drain flow or movement to shallow groundwater.

CONSIDERING THE NEED FOR AND SETTING BUFFER ZONES

Tooby (1997) provides a detailed description of the methodology required under the Pesticides Authorisation Directive, 91/414/EEC and the Uniform Principles to calculate the risk of a pesticide product to the aquatic environment and the potential effectiveness of a buffer zone in risk reduction. Essentially, the process involves calculating the Predicted Environmental Concentration

(PEC) in water from applying the pesticide alongside a watercourse and comparing this with the toxicity of the product to aquatic organisms. From this a Toxicity : Exposure Ratio (TER) is calculated. Should the TER be below 100 for acute exposure or below 10 for chronic exposure an authorisation cannot be granted without considering risk management options or further field data demonstrating no unacceptable impact.

In considering reducing the risk from spray drift, drift curves such as those produced by Ganzelmeier *et al.* (1995) are taken into account to recalculate the PEC and TER for different widths of buffer zone. For instance, it is estimated that a 6m buffer zone for field crops will reduce the PEC and hence increase the TER by approximately an order of magnitude. In this way, the size of buffer zone required to protect the aquatic environment can be determined.

Using this methodology, over 400 products containing nearly 100 active substances now have a statutory buffer zone requirement in the UK. Typically buffer zones have been set at 6m for field crops, 2m for hand-held applications and 18m for orchards reflecting the levels of drift associated with application techniques used in these situations.

DIFFICULTIES WITH THE CURRENT SCHEME

In theory, the current buffer zone scheme should provide the protection required for the aquatic environment. However, despite the scheme being a statutory requirement under the Control of Pesticides Regulations (1986), it is difficult to enforce without a mechanism to check compliance.

In practice, farmers find the scheme complex and inflexible. There is some confusion over which pesticides carry buffer zone requirements and there are difficulties over practical implementation. For instance, leaving a buffer zone unsprayed can provide a source of further infection for the main part of the field necessitating repeated pesticide application. To overcome this difficulty, farmers may be able to use a product without a buffer zone requirement either across the whole field or in the buffer zone alone. However, in some cases farmers may have to resort to not cropping the 6m alongside watercourses.

Tank mixes of pesticides with and without buffer zone requirements also present practical difficulties. In this situation, to adhere to the law, farmers can either operate the buffer zone for the whole tank mix or apply those pesticides without a buffer zone requirement to the areas adjacent to watercourses before adding to the spray tank those pesticides with buffer zone requirement and applying the mixture to the rest of the field. The former option may not provide the level of crop protection required in the buffer zone while the latter increases the time to complete the application.

Under the Water Resources Act 1991, watercourses include dry ditches which temporarily carry water for part of the year. This means that buffer zone requirements apply to ditches even when dry at the time of spraying. To avoid needing to apply buffer zones in these circumstances, farmers may be tempted to fill in or pipe dry ditches with a consequent loss of what can be an important semi-natural habitat.

As well as, these practical difficulties, the current buffer zone requirements are inflexible and take no account of local factors which may reduce the risk to the environment. Current buffer zones adopt a precautionary approach and are based on worst case scenarios of spraying alongside small watercourses with modest dilution at maximum recommended rates.

LOCAL ENVIRONMENTAL RISK ASSESSMENT FOR PESTICIDES (LERAPS)

In recognising the difficulties with the current scheme, the UK's Advisory Committee on Pesticides (ACP) has proposed a new scheme which was put out to consultation in November 1997 (Pesticides Safety Directorate, 1997). The proposed scheme should be more enforceable and hence achieve improved protection of the environment.

Under the proposals, farmers would undertake a Local Environment Risk Assessment for Pesticides (LERAP) for those products which attract a buffer zone. The LERAP would determine whether local factors may allow the size of the buffer to be reduced without compromising protection of the environment. There would be an underpinning minimum buffer zone of 1 - 2m irrespective of local conditions. The LERAP would be recorded and available for inspection by Health and Safety Executive (HSE) farm inspectors, hopefully leading to improved compliance and enforceability.

The ACP has identified a range of possible local factors that could be taken into account when considering the necessary size of buffer zone. These have been presented as those which could be included immediately (size and flow rate of watercourse, use of reduced rates), those which could be considered in the future (engineering controls, windbreaks) and those which should not be included (quality of watercourse, wind direction).

Size and flow rate of watercourse

In calculating the PEC and TER as described above, it is assumed that the receiving watercourse is static, 30 cm deep and 1 m wide. This size of watercourse is relatively small and would only provide a modest degree of dilution. In addition, greater dilution would generally be expected with a flowing watercourse than with a static water body. The ACP has therefore proposed that a larger and/or a flowing watercourse could require a smaller buffer zone whilst maintaining the same level of environmental protection.

In addition, the ACP suggested that ditches dry at the time of spraying do not need the same level of protection as bodies containing water throughout the year. This is because, before water and aquatic life returned to such ditches, pesticide levels are likely to decline due to adsorption to soil particles and/or degradation. It has therefore been proposed that ditches dry at the time of spraying only require the underpinning minimum buffer zone.

Reduced application rates

In setting buffer zones it is assumed that pesticides are applied at the maximum application rate. However, many farmers may apply pesticides at reduced rates and in these circumstances it should be possible to reduce the buffer zone accordingly.

Engineering controls

As well as local weather conditions, the level of spray drift is greatly influenced by a variety of factors within the control of the operator. These include forward speed of the sprayer, spray pressure/velocity of spray, delivery technology, nozzle type and boom height. By manipulating these factors it is possible to have a dramatic effect on the level of drift. For instance, operating at slower forward speeds, higher spray pressures, lower boom heights and with coarser sprays will significantly reduce drift (Miller, 1998).

There are a number of nozzles on the market which claim to reduce drift. For instance, Cecil (1997) has shown that, by using nozzles specifically designed to reduce the proportion of very small drops and incorporate air bubbles in the larger drops, drift can be reduced by over 50% whilst maintaining pesticide efficacy. Hobson *et al* (1993) have developed a computer simulation model to examine spray drift from hydraulic spray nozzles and Southcombe *et al* (1997) have proposed a drift potential classification system for nozzles. In addition, modern sprayer technology such as air assisted spraying, shrouded boom spraying and electrostatic charging systems can also reduce drift (Miller, 1988).

Spray drift is also influenced by the properties and formulation of the pesticide. There are a range of adjuvants available for addition to the product that have been specifically designed to lower drift by reducing the volume of fine droplets with no loss in pesticide efficacy (Wills *et al*, 1997).

The ACP considered that engineering controls that reduce drift could be included in a LERAP approach in the future but that further drift data were required to calculate appropriate reductions in buffer zone width. In this respect, the Pesticides Safety Directorate is considering the future use of an "official recognition scheme" to authorise low drift sprayers for which reduced buffer zones could apply.

Windbreaks

Planting trees as windbreaks around orchards is common practice in the UK to protect the crop from wind damage. The ACP considered that, in theory, such windbreaks would seem likely to reduce pesticide contamination of watercourses by trapping some spray drift. However, it concluded that, before windbreaks could be included in the LERAP arrangements, further scientific evidence to support the theory was required.

Quality of the Watercourse

Watercourses vary in their ecological value. The Environment Agency classify the water quality of larger rivers and canals in England and Wales using the General Quality Assessment scheme (GQA) (Environment Agency, 1997). This includes assessment of biological quality of each stretch of river covered by the scheme. Whilst some stretches of river have improved and others declined, between 1990 and 1995 there was a net 26% improvement in river biology across England and Wales.

The ACP considered the possibility of excluding buffer zones from or providing lower protection to watercourses of lesser ecological value. However, such an approach would detract from the current efforts and success in reducing water pollution from a variety of sources and the overall improvement in the biological quality of rivers. It was therefore concluded that the quality of the watercourse should not be included in the LERAP.

Wind direction

In theory, wind direction should influence the extent of spray drift, however, there is no firm supporting scientific evidence. Wind direction is variable and may change between undertaking the environmental assessment and making the spray application. It would also be open to abuse since there is no ready way of independently verifying wind direction at the time of spraying. For these reasons the ACP concluded that wind direction should not be included in the LERAP.

ADVANTAGES AND DISADVANTAGES OF THE PROPOSED LERAP SCHEME

As discussed above, the current scheme of buffer zones has been criticised because it takes no account of local conditions, it poses practical difficulties and it is difficult to enforce. The proposed LERAP scheme overcomes some of these difficulties in that it would take account of local conditions in determining the size of buffer zone required. The record keeping aspect of the proposal means that the scheme should be more enforceable leading to improved compliance. Experience of health and safety legislation by the HSE indicates that those that undertake a risk assessment are likely to follow it, whilst the need to produce a written assessment at routine inspections should make it easier to police those that do not comply. The LERAP proposal is also scientifically sound and should highlight the importance of buffer zones to pesticide users.

However, the LERAP does not address some of the difficulties with the current scheme. LERAP will be more complex and possibly more difficult to understand that the current arrangements. There will be a greater management requirement for the farmer and increased paperwork. The proposals also do little to address the practical difficulties of operating buffer zones. Concerns about leaving unsprayed strips as possible reservoirs of pest infestation will remain, and problems of tank mixes of products with and without buffer zone requirements will not be overcome.

FURTHER DEVELOPMENT OF LERAP AND SOME POSSIBLE ALTERNATIVE APPROACHES

The LERAP proposal provides an initial step in overcoming problems with the current buffer zone scheme. However further development of LERAP or alternative approaches might better address these problems. For instance, enforcement of buffer zones with the LERAP proposal might be improved if LERAP was made a requirement of crop assurance schemes and crop protocols that have been put in place by the farming and food industries to improve consumer confidence in crop production. Alternatively, it could be made a requirement to include LERAP paperwork with annual returns for arable area payments. This latter proposal is certainly likely to improve compliance with buffer zones, although it is unlikely to be popular with either farmers or those administering the arable area scheme.

Problems with the practicality of buffer zones stem largely from making a scientifically-based distinction between those products that need buffer zones to provide adequate protection of water and those which do not. One way of overcoming these problems might be to not make this distinction. For instance, Swedish authorities (Swedish Nature Conservation Department *et al*, 1998) have introduced a scheme which treats all pesticides alike and requires a minimum buffer zone of 2m. The scheme requires the farmer to take into account temperature, windspeed, sensitivity of surroundings (all watercourses are considered "sensitive"), field size, boom height, droplet size and dose rate. On the basis of these factors the farmer determines the size of buffer required.

Whilst the Swedish scheme overcomes problems associated with distinguishing between products requiring buffer zones and those which do not, it is still a complex way of protecting watercourses and requires a significant management input from the farmer. Another alternative deserving consideration is the introduction of a standard buffer zone for all pesticides. For instance, a small buffer set for all pesticides would be simple to understand and relatively easy to adopt. Although for some pesticides this might not provide the ideal level of protection required for aquatic life, if widespread adoption were achieved the overall level of water protection would be considerably greater than that achieved with poor compliance under the current scheme. Further protection of water would be realised if the use of engineering methods of reducing levels of drift, as outlined above, were made mandatory.

The current work on protecting watercourses from pesticides is concentrating largely on not permitting spraying of cropped land alongside water. Another approach that has been widely advocated (Environment Agency, 1996; Farming and Wildlife Advisory Group *et al.*, 1997; Willmot Pertwee, 1997) is the use of non-cropped vegetated strips around field edges. Such strips provide suitable protection from pesticide drift but also have a number of other environmental benefits. They can reduce nutrient run-off and soil erosion and also have conservation value in providing a habitat for invertebrates, small mammals and birds. They can also improve the landscape value of the farm. However, such field margins can be expensive to the farmer because of lost crop area and maintenance costs and limited discretionary compensatory payments are available under the Countryside Stewardship Scheme. Given the overall environmental value of these strips, there is clearly a case for further exploring ways of encouraging their uptake, possibly through expanding the Countryside Stewardship Scheme.

CONCLUSIONS

The UK's future policy on buffer zones and the possible introduction of a LERAP scheme are currently being considered by Government Ministers. As part of this, Government officials are working up fuller proposals. Whichever scheme is finally adopted it is essential that it is effective at protecting aquatic life whilst being practical to the farmer.

REFERENCES

Cecil A R G (1997). Modified spray nozzle design reduces drift whilst maintaining effective chemical coverage. Proceedings *The 1997 Brighton Crop Protection Conference - Weeds*, **2**, 543 - 548

Environment Agency (1996). Understanding buffer strips. The Environment Agency, Rio House, Aztec West, Bristol, BS12 4UD.

Environment Agency (1997). The quality of rivers and canals in England and Wales 1995. The Environment Agency, Rio House, Aztec West, Bristol, BS12 4UD.

Farming and Wildlife Advisory Group; Scottish Environmental Protection Agency; Scottish Agricultural College; Rhone-Poulenc Agriculture Limited (1997). Buffer strips - good farming practice.

Ganzelmeier H; Rautmann D; Spangenberg R; Streloke M; Herrmann M; Wenzelburger H; Walker H (1995). Studies on the spray drift of plant protection products. BBA Braunschweig, Germany. Blackwell - Wiss - Verl.

Hobson P A; Miller P C H; Walklate P J; Tuck C R; Western N M (1993). Spray drift from hydraulic nozzles: the use of a computer simulation model to examine factors influencing drift. *Journal of Agricultural Engineering Research*, **54**, 293-305.

Miller P C H (1988). Engineering aspects of spray drift control. *Aspects of Applied Biology*, **17**, 377- 384

Miller P C H (1998). The measurement and prediction of spray drift - work at Silsoe Research Institute. Proceedings *North American Conference on Pesticide Spray Drift Management* (in press)

Pesticide Safety Directorate (1997). Pesticide buffer zones: proposal from the Advisory Committee on Pesticides for a system of local environmental risk assessment for pesticides (LERAP).

Southcombe E S E; Miller P C H; Ganzelmeier H; Van de zande J C; Miralles A; Hewitt A J (1997). The international (BCPC) spray classification system including a drift potential factor. Proceedings *The 1997 Brighton Crop Protection Conference - Weeds*, **1**, 371-380.

Swedish Nature Conservation Department; LRF; IVT; Jordbruks Verket; KEMI; Svenska Lantmannen (1998). Guide for determining safety distance according to wind conditions. Song & Co AB, Stockholm.

Tooby T E (1997). Buffer zones: their role in managing environmental risk. Proceedings *The 1997 Brighton Crop Protection Conference - Weeds*, **1**, 435-442.

Willmot Pertwee (1997). Field margins: making them work - and pay. Wilmot Pertwee, 14 New Hythe Lane, Larkfield, Aylesford, Kent, ME20 6PN.

Wills G D; Hanks J E; Jones E J; Mack R E (1997). Effect of drift control adjuvants and a surfactant on a herbicide applied at conventional and ultralow volumes. Proceedings *The 1997 Brighton Crop Protection Conference - Weeds*, **2**, 539-542.

The use of field buffer zones as a regulatory measure to reduce the risk to terrestrial non-target arthropods from pesticide use

R Forster and H Rothert

Federal Biological Research Centre for Agriculture and Forestry (BBA), Biology Division, Braunschweig, D-38104, Germany

ABSTRACT

The use of plant protection products might cause adverse effects on populations of non-target arthropods within the field but also in off-crop habitats via spray drift. Measures of risk mitigation are therefore deemed necessary in order to preserve species susceptible to local extinction and so maintain species diversity. The paper describes the background of the current view of the Federal Biological Research Centre (BBA) of how to reduce the risk of pesticide use, especially for populations living in off-crop habitats.

INTRODUCTION

High input of pesticides can have adverse effects on the diversity of arthropod species, when (recedent) species are eradicated from agroecosystems (Anonymous, 1987). Even when properly applied for the purpose intended, the use of pesticides might severely affect populations of non-target arthropods (Sherratt & Jepson, 1993). Wetzel (1993) identified a proportion of 97 % of the arthropods found in an open cereal ecosystem to be non-targets (35 % beneficial and 62 % indifferent species). Therefore it seems to be important to reduce the risk, e.g. in those habitats, which might contribute to recolonize sprayed areas and help (meta)populations to recover (Wratten et al., 1993; Halley et al., 1996). Species predominantly found at the field edges, like butterflies, syrphids and honeybees, were also found at risk (Davis & Williams, 1990; Davis et al., 1993; Cilgi & Jepson, 1994; de Snoo et al., 1996). It was, however, demonstrated that buffer zones to adjacent natural and semi-natural habitats, e.g. hedgerows, unimproved grassland, could significantly reduce exposure and severity of effects (Cilgi, 1993; Cilgi & Jepson, 1995; de Snoo et al., 1996).

GENERAL REQUIREMENTS AS LAID DOWN IN DIRECTIVE 91/414/EEC

As laid down in the Directive the protection of the environment should take priority over the objective of improving plant production and where appropriate, Member States shall impose conditions or restrictions with the authorization they grant. The nature and severity of these measures must be selected on the basis of, and be appropriate to, the nature and extent of the expected advantages and the risk likely to arise. No authorization shall be granted, unless it is clearly established that there is no unacceptable impact after use of the plant protection product according to the proposed conditions of use.

The SETAC/ESCORT guidance document responsible for setting out the regulatory framework for EU risk assessment for non-target arthropods (Barrett et al., 1994) defines the term unacceptability as follows:

- i) within crop non-target arthropods: effects are unacceptable if no recovery occurs within reasonable time (e.g. maximum one season), (...),
- ii) off-crop non-target arthropods: effects are unacceptable if ecologically significant effects occur on non-target arthropods.

Directive 91/414/EEC neither focuses on any particular group of non-target arthropods, e.g. beneficials, nor on any particular situation, e.g. in-crop or off-crop habitats, in general. It might, however, be helpful to distinguish between in-crop and off-crop situations, because protection of in-crop populations will often be limited especially when insecticides are applied on a broad scale. Off-crop habitats, e.g. hedgerows and field margins, should therefore attain special attention, because these areas are considered to be important refugia for many arthropods and sources for recolonization of depleted areas.

Taking these two different scenarios into account, the primary aim of risk mitigation strategies shall be to protect populations of non-target arthropods in off-crop refugia and to facilitate the recolonization of sprayed areas in order to avoid local extinction of non-target species.

THE RISK OF LOCAL EXTINCTION

Sherratt & Jepson (1993) illustrated the likelihood of a local extinction of populations by using simulation models for carabid beetles. The authors demonstrated the role of some key factors, e.g. related to the pesticide used and the farming practice:

1. the toxicity of the pesticide applied;
2. the frequency of pesticide applications;
3. the proportion of fields sprayed;
4. the permeability of the field boundaries to invertebrate movement.

The authors further explained that the susceptibility of certain carabid species to extinction may be a result of their relatively low reproductive rates, univoltine phenology, low dispersal rate and the fact that they complete their life cycles within the field. We know, however, that these characteristics more or less apply for a high number of non-target arthropod species, and we further assume that an extrapolation to populations inhabiting off-crop habitats might be appropriate, in principle. We can see this from the distribution of woodland species and field species with different degree of specialization, as illustrated by Tietze & Grosser (1985) for an idealized landscape (Figure 1). We may conclude from this scheme, that species predominantly living in the open field (i.e. stenoecious field species) are very likely to be at risk through direct spray compared to other species, e.g. woodland species or less specialized field species (i.e. euryoecious field species), due to a higher exposure of individuals and a higher proportion of the population exposed when fields are sprayed. On the other hand, species predominantly inhabiting off-crop patches (i.e. stenoecious woodland species) are very likely to be at risk through spray drift of pesticides compared to other species, especially when the size of patches is small. Based on these findings appropriate risk mitigation measures can be identified (Forster et al., 1997). These should, however, be put into a general framework regarding landscape structure, field size and size of field margins as outlined below.

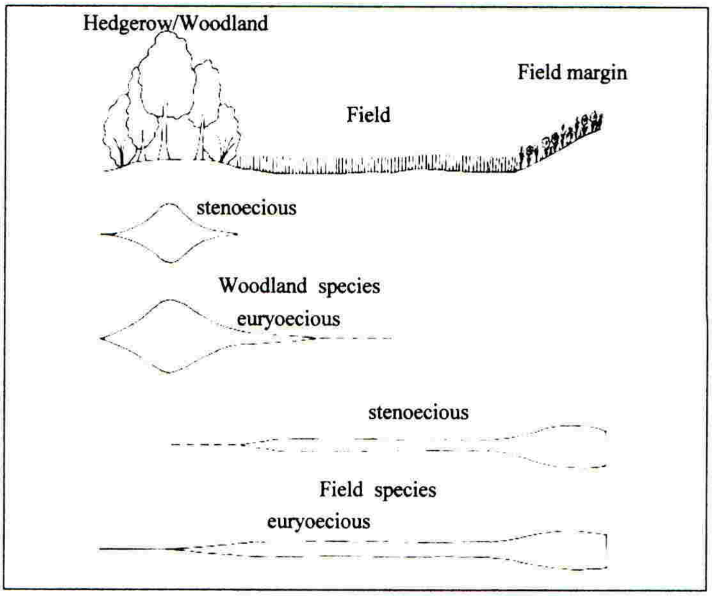

Figure 1. The distribution of woodland species and field species with different degree of specialization in an ideal landscape covering hedgerow/woodland, field and field margin (Tietze & Grosser, 1985; in Röser, 1995)

The role of landscape structure, field size and size of field margins

Landscape structure

In a rich and diverse agroecosystem it is most likely, that some habitats can be kept free from pesticides, and fields are not sprayed all at the same time. Because of this local populations might persist in the longer term as a result of both recovery and recolonization if species have a sufficient dispersal rate compared to field size and permeability of field boundaries. We take the findings of Kretschmer et al. (1995), who found an increasing number of species with increasing proportion of natural and semi-natural habitats (Figure 2), as an indication for the correctness of this assumption. For carabid beetles the authors found more or less the same number of species when the proportion of natural and semi-natural habitats was less than 5 % but a signifcant increase of species with increasing proportion of off-crop habitats. For butterflies, however, a very steep curve was established, especially in the range of up to 5 % off-crop habitats. In general, these findings support the recommendations of a number of authors who recommend a proportion of 5 % to 20 % of the agro-ecosystem being uncultivated in order to protect the typical fauna of the respective area (Bohn et al., 1989; Kaule, 1991; Anonymous, 1992; Röser, 1995). We conclude from this, that an environment with a proportion of less than 5 % off-crop habitats might be unfavourable for populations to persist in the longer term. This conclusion should be taken into consideration, when risk management measures are specified.

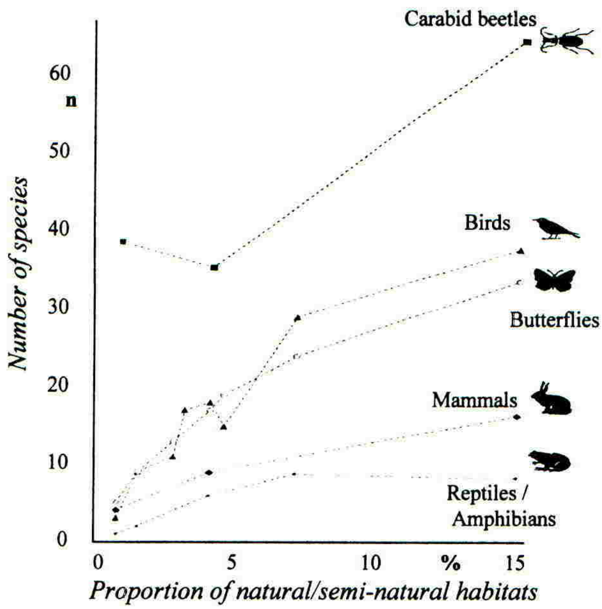

Figure 2. Relationship between the proportion of natural and semi-natural habitats and number of species in each group, areas analysed 100 ha each (Kretschmer et al., 1995)

Field size

Because populations are linked to each other by dispersal, field size seems to be an important factor with respect to the ability of organisms to recolonize sprayed areas. In a number of publications a maximum field size of about 10 ha, with 150 m to 250 m length and 400 m to 600 m width, surrounded by natural and semi-natural habitats is regarded as an ideal agroecosystem (Jedicke, 1990; Kaule, 1991; Röser, 1995). Taking these data into account, it seems appropriate, to define a field size, which is deemed unfavourable to permit an exchange of organisms between populations and a recolonization of sprayed areas within a reasonable period of time. However, respecting also some general economic conditions (Hempsch & Brinkmann, 1973; Weinschenk & Gebhard, 1985), a field size of 25 ha still seems an appropriate size indicating the need for risk management measures.

Size of field margins

To assess the potential risk for populations living in off-crop habitats it is suggested to consider the width of the habitat concerned. The latter is important for the proportion of the habitat contaminated via spray drift and can be described by pesticide spray drift data (Ganzelmeier et al., 1995; Rautmann et al., 1997). However, Rautmann et al. (1997) did not find any deposits of a tracer, applied in a winter wheat crop (EC65) according to good agricultural practice, on paper strips placed in different heights at a distance of 7.5 m downwind in a grassy headland (Table 1).

Table 1. Average spray deposits (%) in a field margin (application to winter wheat; EC 65; spray nozzles XR 11004; 300 l ·ha^{-1}; wind speed 0.5 to 3.0 m · sec^{-1})(Rautmann et al., 1997).

Distance m	Deposits in different height %				
	0	35	65	120	cm
0.0	26.14	30.09	43.24	-	
1.0	0.63	-	1.05	0.75	
3.0	0.36	-	0.46	0.62	
7.5	0.00	-	0.00	0.00	

According to these data, spray drift of pesticides applied in agricultural crops may cover a strip of up to 7.5 m of a grassy field margin. Therefore field margins of 15 m or wider are required to protect at least 50 % of an evenly distributed population within a particular field margin from any spray drift and thus ensure recovery of affected populations. In contrast, habitats smaller than 15 m are deemed unfavourable and should therefore be protected if a toxicity exposure ratio indicates a potential risk for sensitive species. However, in order to avoid habitat destruction by farmers and to encourage the creation of flowering strips (Nentwig, 1993), risk management restrictions should be advisory for habitats less than 3 m wide.

THE BBA POSITION ON RISK MANAGEMENT IN THE FRAMEWORK OF THE AUTHORIZATION OF PESTICIDES FOR THE GERMAN MARKET

For a number of pesticides it is necessary to implement a risk management to reduce the exposure of non-target arthropods to pesticides in order to avoid unacceptable effects and to fulfil the requirements for the authorization of pesticides as laid down in Directive 91/414/EEC (Forster et al., 1997). However, it does not seem appropriate to calculate buffer strips in the way this is done to protect aquatic organisms, because of the high variability of deposits (i.e. exposure scenarios) found in terrestrial habitats, e.g. covered with weeds of different height. A better approach might be the use of a toxicity exposure ratio (TER) as an indicater of risk for sensitive species in a short distance from the crop, e.g. 1 m. As far as this ratio indicates an unacceptable risk a restriction should be applied, e.g. a buffer zone recommendation. De Snoo & de Wit (1996) demonstrated the reduction of spray drift using buffer zones (Table 2). According to these findings a buffer strip of 6 m can help to significantly reduce spray drift, due to the filtering capacity of the cereal crop. If the TER indicates an unacceptable risk to non-target arthropods it therefore seems appropriate to use a fixed buffer zone of 6 m as far as field crops are concerned. This measure was already implemented for use of pesticides in summer cereals in the UK to protect non-target arthropods from high risk insecticides (Campbell, 1995).

Table 2. Average spray deposits (%) on water sensitive paper at crop edge (cereal field; different spray nozzles; 200 to 600 l $\cdot ha^{-1}$; wind speed 3.0 to 4.5 m $\cdot$ sec^{-1})(de Snoo & de Wit, 1996).

Buffer strip m	Deposits %
0	100.00
3	0.46
6	0.03

Based on a local risk assessment the question, whether certain species or habitats need to be protected, cannot be addressed solely from the faunistical-ecological point of view. Therefore, a simple and pragmatic decision-making procedure is required, using characteristics, such as the size of field margins, landscape structure and the field size, which can be addressed on the local level. It might be advisable to implement *advisory* statements for field margins wider than 15 m, because these habitats will only partly be contaminated through spray drift of pesticides. However, field margins less than 3 m wide should also be protected through *advisory* restrictions in order to avoid habitat destruction. Provided that the proportion of natural and semi-natural habitats exceeds 5 % (e.g. in an area of 100 ha), or the size of sprayed fields is less than 25 ha, *advisory* restrictions are deemed appropriate, because an exchange between populations can be expected within a reasonable period of time. The decision-making procedure reads as follows:

When a comparison of spray drift data with toxicity data of pesticides indicate that non-target arthropods in the off-crop area may be at risk, ***statutory restrictions*** *will be applied:*

"Do not spray within a buffer zone of 6 m adjacent to natural or semi-natural habitats, unless a local risk assessment turns out that

1. *the width of habitats concerned is less than 3 m or more than 15 m or*
2. *the proportion of natural and semi-natural habitats is higher than 5 % (scale 100 ha) or*
3. *the area of the field sprayed is less than 25 ha."*

The ***restrictions*** *listed are* ***advisory****, if one out of these criteria is fulfilled.*

Exceptions from this principle may be necessary with regard to special environments, where buffer zones might allways be regarded essential (e.g. nature reserve) or plant protection issues, where buffer zones might not be applicable (e.g. forestry). Further risk management restrictions in order to enable recovery of populations of non-target arthropod and recolonization of sprayed areas may cover the number of applications, the proportion of a field sprayed and application technique, with regard to spray drift. The appropriate restrictions will be specified within the authorization procedure, while the responsibility of risk managment will be devolved from the regulatory authority to the farmers and the extended service.

Implications for the authorization of pesticides in Germany

Since the end of 1992 the BBA has labelled all pesticides with regard to their potential impact on beneficial arthropod species, mainly to support Integrated Pest Management. In July 1998, 1106 plant protection products had been registered in Germany, of these 1098 were suitable for an analysis of the labels applied. From these a proportion of 77 % were labelled with regard to the effects on non-target arthropods. Pesticides in the high risk class and the very high risk class made up about 30 % of the registered pesticides in Germany. It is very much likely, that for pesticides in the very high risk class, mainly covering insecticides and acaricides (88 %), the acceptability of the effects in accordance with the Uniform Principles will only be provable, when risk mitigation strategies (e.g. buffer zones) are officially recommended for the use of these products.

However, the fact that buffer zones cannot be sprayed, often results in yield losses in this zone. A rough estimate of the total length of field margins in Germany is 1.5 Mio km (Enzian 1998, unpubl. data). Assuming all these margins were protected using buffer zones of 6 m, the area of arable land concerned came to about 900 000 ha, which is 7.6 % of the total arable land. These figures inevitably justify a local risk assessment in order to decide, whether an exception from the statutory buffer zone restriction could be permitted in a particular field situation.

We are certain, that the use of buffer zones in the framework of authorization does not have to be a threat to production but can be considered as a powerful tool for both, granting and maintaining authorizations for high risk pesticides whilst protecting non-target arthropod populations.

REFERENCES

Anonymous (1987). Untersuchung und Bewertung von Belastungen in Ökosystemen. Seminar im Rahmen des BMFT-Projekts "Auffindung von Indikatoren zur prospektiven Bewertung der Belastbarkeit von Ökosystemen" am 4. November 1985 in Berlin. *Mitteilungen aus der Biologischen Bundesanstalt für Land- und Forstwirtschaft* **234**, 71 pages.

Anonymous (1992). Lübecker Grundsätze des Naturschutzes. Eds. Länderarbeitsgemeinschaft für Naturschutz, Landschaftspflege und Erholung (LANA). *Landschaftspflege und Naturschutz in Thüringen* 29 **3**, 57-62.

Barrett K; Grandy N; Harrison E G; Hassan S A; Oomen P (1994). *Guidance document on regulatory testing procedures for pesticides with non-target arthropods*. SETAC, 51 pages.

Bohn U; Bürger K; Mader H J (1989). *Leitlinien des Naturschutzes und der Landschaftspflege. Natur und Landschaft* 64 **9**, Sonderbeilage 1-16.

Campbell P (1995). Position Document: Labelling and risk management strategies for pesticides and terrestrial non-target arthropods: A UK Proposal. From: Third UK Forum on Non-target Arthropods, Chesterford Park, 29-30 March 1995, 10 pages.

Cilgi T (1993). Measurement of pesticide drift into field boundaries. A.N.P.P.-B.C.P.C. - *Second international symposium on pesticides application techniques, Strasbourg - 22nd to 24th September 1993*, 417-424.

Cilgi T; Jepson P C (1995). The risks posed by deltamethrin drift to hedgerow butterflies. *Environmental Pollution* **87**, 1-9.

Environment Schemes, though this is not necessarily intended to be their main purpose (Table 1).

Table 1. Agri-Environment Scheme Options in Great Britain with potential for use as buffer zones.

Option [1]	Schemes [2]	Vegetation
No-spray zone	PASS (insecticide)	arable crop
Conservation headland	SCPS, TC, PASS, certain ESAs	arable crop
Uncropped wildlife strips	TC, PASS, certain ESAs	natural regeneration (cultivated annually/biennially)
Grass margins	CSS, CPS, TC, PASS	natural regeneration or sown grass
Extended hedgerows	CPS, certain ESAs	grassland (or arable crop - some ESAs)
Water margin management	CPS, certain ESAs	grassland
Water Fringe Option	Habitat Scheme	grassland, scrub or wood

1. Main option types. Prescription variations occur in different schemes, and a number of other options could be used to provide buffer zone benefits but are normally implemented on a whole field scale e.g. conversion of arable to grassland. Set-aside strips also have potential as buffer zones, though the minimum width of 20m restricts their use in this role.

2. CSS = Countryside Stewardship Scheme (England); CPS = Countryside Premium Scheme (Scotland); TC = Tir Cymen (Wales); PASS = Pilot Arable Stewardship Scheme; ESA = Environmentally Sensitive Area

CONSERVATION VALUE OF BUFFER ZONES

Buffer zones can provide conservation value in two ways:

i. by reducing pollution of adjacent habitat

ii. by improving resource availability or habitat value within the buffer zone itself.

Thus, whilst buffer zones may have the primary purpose of protecting a vulnerable area such as a watercourse or SSSI, they may also provide valuable habitat in their own right. Conversely, areas such as field margins managed primarily to provide habitat or landscape features may also buffer adjacent hedges, ditches etc.

BENEFITS ARISING FROM POLLUTION CONTROL

Buffer zones have the potential to influence three major types of pollutants: sediments (aquatic systems only), nutrients and pesticides (aquatic and terrestrial systems). The effects of each are briefly described with further references for the interested reader.

Aquatic habitats

Sediment

The impacts of sediment in the aquatic environment have been recently reviewed by Wood & Armitage (1997). Sediments affect plants in various ways, including reduction in light penetration, and hence photosynthesis, direct damage to stems and leaves caused by abrasion, and smothering. Some species, e.g. *Ranunculus penicillatus*, are more susceptible than others, e.g. *Nasturtium officinale* (Brookes, 1986). Damage to or elimination of algae and macrophytes also affects invertebrate and fish communities, since plants are at the base of the food chain.

Direct effects on invertebrates can result from clogging of respiratory or filter feeding structures, low oxygen concentration, reducing prey availability, and reduced substrate stability and/or suitability. Although sedimentation generally reduces invertebrate abundance and diversity, the situation is complex and some taxa prefer sediment-rich substrates.

Effects on fish are likely to be of greatest interest in most instances, due to their economic importance and amenity value. These can arise indirectly, by affecting their food supply or directly by reducing their ability to find food, by clogging gill membranes, changing migration patterns, degradation of spawning habitats and suffocation of eggs. The latter is particularly important in the case of salmonids (salmon and trout), whose eggs are particularly susceptible to silt deposition (e.g. Olsson & Petersen, 1986). Sediments can also carry other pollutants such as nutrients and pesticides. Although buffer zones have the potential to limit pollution of water courses by sediment they should be viewed as a secondary measure to in field "best management practices" for the protection of what is, after all, a vital agricultural resource (Dillaha III & Inamdar, 1997)

Nutrients

The effects of high concentrations of nutrients in water, leading to eutrophication, have received a considerable amount of study. Detailed consideration is beyond the scope of this paper; a recent text is by Harper (1992). Phosphate generally has most impact; high levels in fresh water cause algal blooms, which can deoxygenate the water and kill fish and other organisms. Nitrate concentrations are of less environmental importance, and the considerable research and regulatory activity devoted to reducing the nitrate content of ground and surface waters, arising from the EU Drinking Water Directive, are aimed at minimising the small potential risk to human health rather than preventing entrophication.

Even where major impacts such as fish kills do not occur, eutrophication generally reduces species richness and wildlife conservation value, though mild eutrophication can benefit some species, e.g. certain birds (Harper, 1992). Buffer zones can be effective in reducing both phosphate and nitrate in surface runoff and sub surface flows; a range of types of buffer strip have been found successful. Mander *et al.*(1991) reported alder and willow to be the most effective vegetation types; 10 metre wide strips removed almost 100% of incoming phosphorous. A Norwegian study of a wetland system planted with reeds found similar levels (average 97%) of P removal (Jenssen *et al*, 1994). However in some cases, e.g. where native vegetation was allowed to grow, the buffer strip itself was found to be a source of dissolved phosphate (Uusi-Kamppa *et al.*, 1997).

Buffer zones can also remove up to 90% of nitrate, though there is tremendous variation in efficiency, and no clear agreement as to whether trees or grass are best. Gilliam *et al.* (1997) considered a 29m buffer to be a desirable goal for wildlife and stream health, though conceding that much could be achieved with narrower buffers, considerable reductions in nitrate concentration occurring over the first 10m width.

Pesticides

Pesticides can reach water via surface runoff, sub-surface flow, particulate transport (absorbed onto sediments) and spray drift (Harris & Forster, 1997). Other possible sources include industrial effluent, sewage, atmospheric fallout and spillage (Puder *et al.*, 1993). Many of the worst pollution incidents are caused by point sources, and linear buffer zones are unlikely to prevent such incidents, though targeted buffers (i.e. positioned where point source contamination could occur) may have a role where risks can be predicted (Muscutt *et al.*, 1993). Buffer zones have limited impact on movement via sub-surface flow, unless additional measures are taken to restrict drainage and introduce absorbent materials into the drainage system (Harris & Forster, 1997).

Although herbicides can potentially cause ecological damage by killing or inhibiting growth of algae and macrophytes, with consequent effects on the food chain. (e.g. Hamala and Kollig, 1985; Peterson *et al.*, 1994), most attention has focused on direct toxicity to aquatic invertebrates and fish. Fish poisoning is usually related to acute point-source pollution incidents; Williams *et al.*(1987) concluded that the risk to fish from spray drift was slight. The risk to invertebrates is considerably greater however, and damage to aquatic populations of a number of species following insecticide spraying has been documented (e.g. Muirhead-Thompson, 1978; Crossland *et al.*, 1982; Pinder *et al.*, 1983).

Although it is relatively easy to demonstrate the potential for damage, particularly by pesticides such as the pyrethroids which are highly toxic to aquatic fauna, the determination of risk in the field is much more difficult. Relevant factors influencing outcomes include solubility in water, tendency to bind to organic particles, and ecological niche of the organism concerned, as well as its innate susceptibility. For example, surface dwelling insects are most at risk from oil-based formulation which form a surface film, whereas sediment-dwelling species may be more at risk from compounds which are readily absorbed into organic material (Pinder *et al.*, 1993).

In the UK, the Pesticides Safety Directorate has imposed "no-spray" buffer zones on a large number of pesticides when applied close to water courses (Croxford, 1998). These are based on Toxicity: Exposure Ratios (TER's) which relate the Predicted Environmental Concentration (PEC) to toxicity data for test organisms (Tooby, 1997). The success of this approach depends on the validity of assumptions used in calculating the PEC and the selection of test species representative of the range of susceptibilities present in surface water habitats. Peterson *et al.* (1994) argue for the inclusion of an "uncertainty factor" in hazard evaluation to allow for the wide range of sensitivities among naturally occuring taxa. The mechanism for determining and applying no-spray zones is currently under review in the UK (Croxford, 1998).

Terrestrial Habitats

Nutrients

The potential damage to natural or semi-natural terrestrial habitats and wildlife from nutrients arising from agricultural sources is arguably of far less significance than that which may occur in aquatic habitats. The concern of conservationists is more often aroused by the effects of direct application of nutrients e.g. to a previously unfertilised and species-rich hay meadow.

However, buffer strips may have a role in preventing misplacement of fertilisers into adjacent habitats. Whilst pneumatic and liquid fertiliser applicators are highly accurate, the more commonly used spinning disc applicators often spread beyond the edge of the crop, as do oscillating spout spreaders (Rew *et al.*, 1992; Tsiouris & Marshall, 1998). Misplaced nitrogen fertiliser can reduce species richness (Kleijn & Snoeijing, 1997), and may encourage nitrophilous weeds such as *Bromus sterilis*, at the expense of benign or desirable species (Boatman *et al.*, 1994; Theaker *et al.*, 1995).

Pesticides

Cooke (1993) noted that there were remarkably few studies on the effects of pesticide drift, as opposed to the extent of drift. A number of relevant papers have been published since then, but large gaps in our knowledge remain. Most attention has been payed to effects of herbicides and insecticides, with very little information on possible effects of fungicides (Cooke 1993).

The most common approaches to studying the effects of pesticide drift on terrestrial fauna and flora have been combining toxicity data with spray drift models to predict risks (e.g. Breeze *et al.*, 1992), and bioassays to determine effects of drift in the field (e.g. Marrs *et al.*, 1992). The former has greater predictive ability but is limited by the number of factors which can be incorporated without the model becoming unwieldy, and the artificial nature of the experimental environment. The latter suffers from being empirical but offers opportunities to study the effects of a wide range of factors under realistic conditions. Both approaches are therefore needed to give a full evaluation of potential effects.

Factors which can influence effects of herbicide drift on non-target plants include plant species, herbicide used, age of plant and nature of surrounding vegetation (Marrs *et al.*, 1991a, b; 1993). These authors recommend buffer zones of 6-10m for established perennials and 20m for establishing seedlings, where herbicides are applied by tractor-mounted sprayers (Marrs *et al.*, 1992, 1993).

Factors affecting the risk to butterfly larvae from insecticide drift include intrinsic susceptibility of the species to pesticides, active ingredient, bio-availability, habitat complexity and larval food plant, diel activity and feeding behaviour (Longley & Sotherton, 1997). Pyrethroids are particularly toxic to butterflies, with rates of deltamethrin as low as $^{1}/_{520}{}^{th}$ of field rates being lethal to larvae of *Pieris brassicae* in the laboratory (Cilgi & Jepson, 1995).

A series of trials including laboratory toxicity testing (Sinha *et al.*, 1989) and field bioassays (Davies *et al.*, 1991; 1993) using the sensitive species *Pieris brassicae*, led to recommended buffer strip widths of 12-24m for ground-based hydraulic insecticide spraying (up to 32m for diflubeuzuron), and 50m for air assisted orchard spraying. These "safe" distances were based on LD_{10} data, but sub-lethal effects may also be important (Cilgi & Jepson, 1994). Samu *et al.* (1992) showed that webs of the spider *Araneus diadematus* were efficient collectors of agrochemical spray drift, which can then affect the spiders web-building ability (Samu & Vollrath, 1992). The herbicide glyphosate reduced numbers of spiders in field margins, probably by reducing habitat suitability through changes in vegetation structure and microclimate (Haughton *et al.*, 1998). Effects on these and other predatory invertebrates could lead to reductions in bioloical control of aphids and other pest species, increasing the need for application of insecticide sprays to crops.

BENEFITS ARISING WITHIN BUFFER ZONES

A large range of vegetation/habitat types have been used as buffer zones, including ponds, wet meadows, wetlands and forests (see papers in Haycock *et al.* 1997), sometimes of considerable widths, e.g. 25 to 75m in Illinois (Dickson & Schaeffer, 1997), 10-30m under the Habitat Scheme Water Fringe Option in the UK (Tytherleigh, 1997). Consideration here will be confined to within-field buffer zones, generally ranging between two and ten metres in width, except in the case of set-aside, where the minimum strip width allowed is 20m under European Union Regulations (MAFF, 1996).

Most within-field buffer-zones fall into one or more of the following categories.

i. No-spray zones or Conservation Headlands. These are cropped as in the rest of the field but with modified pesticide or fertiliser use

ii. Naturally regenerated herbaceous vegetation

iii. Sown grass strips, with or without dicotyledonous species (forbs)

No-spray/conservation headlands

The simplest form of buffer zone is a "no-spray zone", applied as a statutory restriction in the UK by the Pesticides Safety Directorate (PSD) for certain pesticides in order to protect watercourses or non-target arthropods in field margins. In many cases, the pesticide in question may be substituted by an alternative without a buffer zone requirement, but where the buffer is simply left untreated, some conservation benefits may ensue. These are most likely where an insecticide is withheld. Apart from the implications of reduced drift into non-crop habitats, the buffer zone itself may act as a reservoir of beneficial or benign non-target invertebrates which can subsequently re-colonise the field. Spatial dynamics of recovery from insecticide applications have been described by Duffield & Aebischer (1994), Jepson & Thacker (1993) and Thomas *et al.* (1990). The benefits of such insecticide-free zones were perceived to justify the payment of grant aid for 10-12m wide "crop margins with no summer insecticide" under the pilot Arable Stewardship Scheme (MAFF, 1998).

Where herbicides are also withheld, or confined to the use of selective products, wider biodiversity benefits may accrue. A system of crop margin management incorporating this approach has been developed by The Game Conservancy Trust, termed "conservation headland". Broad-spectrum herbicides and summer insecticides are not applied to the outer few metres of crop (usually from the outer tramline to the field edge), but certain selective herbicides are used to control grass weeds and *Galium aparine*, and fungicides are also applied as for the rest of the crop (Boatman & Sotherton, 1988). Originally developed to provide feeding areas rich in invertebrates eaten by gamebird chicks, conservation headlands also provide nectar resources for butterflies and hoverflies, and refuges for rare arable flora (Sotherton, 1991). The diversity of rare arable flora is increased by withholding of nitrogen fertiliser (Wilson, 1994). De Snoo *et al* (1994) recorded an increased number of visits by blue-headed wagtail (*Motacilla flava flava*) to crop margins where herbicides and insecticides were not used, and such areas were also preferred feeding habitat for woodmice, *Apodemus sylvaticus* (Tew *et al.*, 1992). Conservation headlands are generally implemented only in cereal fields, but their potential use in sugar beet and potatoes has been studied in the Netherlands (de Snoo, 1997) and in linseed in the UK (Tree & Boatman, 1993).

Naturally regenerated herbaceous vegetation

Naturally regenerated vegetation in uncropped field margin strips is supported under various Agri-Environment Scheme options (see Table 1), but can be separated into "Uncropped Wildlife Strips", which are cultivated annually or biennially, and grass strips established by natural regeneration which are not cultivated.

Uncropped wildlife strips (UWS), first pioneered in the Breckland Environmentally Sensitive Area and now adopted also into the Pilot Arable Stewardship Scheme, are primarily designed to conserve arable flora by providing an agrochemical and competition free disturbed environment. A similar prescription is available in the Countryside Stewardship Scheme. They are hence most appropriate where plant communities of conservation interest exist, usually (but not always) on sandy or chalky soil. Implementation in other situations may simply encourage common and even noxious weeds to increase. However, monitoring and feedback to modify management prescriptions has helped reduce undesirable infestations of *Bromus* sterilis in Breckland UWS (Critchley, 1996). Critchley (1994) found that soil ph, overhanging trees, broadleaved shelterbelts and previous cropping with sugar beet were the most important factors affecting plant community composition in UWS, and recommended that sites following sugar beet, and those with overhanging broadleaved trees be avoided.

Where grassland establishment is the long-term aim, the outcome of natural regeneration clearly depends on species already present, either as plants or in the seed bank. Smith *et al* (1993, 1994) found that, on their site at Wytham near Oxford, sowing a grass/wild flower mixture produced better control of annual grass weeds, *Elymus repens* and *Urtica dioica*, and increased butterfly abundance and overall invertebrate abundance. Predatory liniphiid spiders and staphylinid beetles were not however significantly affected by sowing as opposed to natural regeneration (Feber *et al.*, 1995) and effects of management (mowing regime, herbicide application) were generally of greater importance than whether the sward was sown. Smith *et al.* (1994) concluded that where a diverse and attractive flora is present and pernicious weed populations are small, natural regeneration with mowing is the preferred option, but where the potential for natural establishment of species-rich and agriculturally acceptable swards is low, the sowing of carefully designed mixtures is an attractive option.

Sown grass strips

Where grass strips are sown, conservation value will depend on species mixture and management (Smith *et al.*, 1997). Insect diversity tends to be greater on tall grass species than shorter ones (Tscharntke & Greiler, 1995). A number of highly ranked polyphagous predatory Coleoptera overwinter in field boundary vegetation (Sotherton, 1984); greater numbers are found and survival is higher beneath tussocky grasses such as *Dactylis glomerata* (Thomas *et al.*, 1991; Dennis *et al.*, 1994). Grey partridges (*Perdix perdix*) prefer tall vegetation for nesting (Aebischer *et al.*, 1994, and similar habitat is used by nesting yellowhammers (*Emberiza citrinella*) and whitethroats (*Sylvia communis*) (Stoate & Szczur, 1994).

Mowing is a common method of management, used to encourage establishment of sown grasses and control weeds (Smith *et al.*, 1993), but can reduce value for wildlife. For example, mowing reduced numbers of butterflies (Feber *et al.*, 1996), liniphiid spiders and staphylinid beetles (Feber *et al.* 1995). Grey partridges prefer to nest in field boundaries containing dead grass remaining from the previous year (Rands, 1986). There is also some evidence that tall vegetation can give greater protection from pesticide drift to seedlings (Marrs *et al.*, 1993) or hedgerows (Longley *et al.* 1997) than short vegetation. In some situations, it may be possible to control weed species by selective use of herbicides, thus avoiding the need to cut the vegetation (Boatman, 1993).

Inclusion of dicotyledonous flowering species in grass seed mixtures can provide nectar resources for a wider range of taxa e.g. butterflies (Dover, 1996), hoverflies (Cowgill *et al.*, 1993) and bumblebees (Dramstad & Fry, 1995). Although many studies have investigated the requirements of different species and guilds, there is a need for further work to design optimum seed mixtures and management practices to maximise the potential for biodiversity conservation. By imaginative design based on sound research, buffer zones could themselves become a refuge for many threatened forms of farmland wildlife as well as serving their primary purpose of protecting watercourses, hedgerows and other sensitive non-crop habitats.

CONCLUSION

Although considerable attention has been devoted to the design of buffer strips and their effectiveness in protecting non-crop habitats, their benefits in terms of conservation value are not always clearly defined. This paper attempts to summarise briefly some of the information available in the literature; whilst the importance of buffer zones cannot be denied, in many areas, further research is urgently needed if they are to be used effectively to enhance farmland biodiversity without imposing unnecessary costs on agricultural businesses.

REFERENCES

Aebischer N J (1994). Field margins as habitats for game. In: *Field margins - integrating agriculture and conservation.* BCPC Monograph No. 58, ed N.D. Boatman, pp. 95-104, BCPC: Farnham.

Anon (1996). *Understanding Buffer Strips.* The Environment Agency: Bristol.

Boatman N D (1993). Selective control of *Bromus sterilis* in field boundaries with fluazifop-P-butyl. In: *1993 Brighton Crop Protection Conference - Weeds,* pp. 349-355. BCPC:Farnham.Boatman N D; Rew L J; Theaker A J; Froud-Williams R J (1994). The impact of nitrogen fertiliser on field margin flora. In: *Field margins - integrating agriculture and conservation.* BCPC Monograph No. 58, ed N D Boatman, pp. 209-214 BCPC: Farnham.

Boatman N D; Sotherton N (1988). The agronomic consequences and costs of managing field margins for game and wildlife conservation. *Aspects of Applied Biology,* **17**, 47-56.

Breeze V; Gavin T; Butler R (1997). Use of a model and toxicity data to predict the risks to some wild plant species from drift of four herbicides. *Annals of Applied Biology* **121**, 669-677.

Brookes A (1986). Response of aquatic vegetation to sedimentation downstream from river channelisation works in England and Wales. *Biological Conservation* **38,** 352-367.

Cilgi T; Jepson P C (1994). The risks posed by deltamethrin drift to hedgerow butterflies. *Environmental Pollution* **87**, 1-9.

Cooke A S (1993). Conservation and pesticide drift. In: *The environmental effects of pesticide drift,* ed A.S. Cooke, pp. 76-89. English Nature: Peterborough.

Cowgill S E; Wratten S D; Sotherton N W (1993). The selective use of floral resources by the hoverfly *Erisyrphus balteatus (Diptera: Syrphidae)* on farmland. *Annuals of Applied Biology* **122**, 223-231.

Critchley N (1994). Relationships between vegetation and site factors in uncropped wildlife strips in Breckland Environmentally Sensitive Area. In: *Field margins - integrating agriculture and conservation.* BCPC Monograph No. 58, ed N D Boatman, pp 283-288. BCPC: Farnham.

Critchley N (1996). Monitoring as a feedback mechanism for the conservation management of arable plant communities. *Aspects of Applied Biology* **44**, 239-244.

Crossland N O; Shires N W; Bennett D (1982) Aquatic toxicology of cypermethrin III. Fate and biological effects of spray drift deposits in fresh water adjacent to agricultural land. *Aquatic Toxicology* **2**, 253-270.

Croxford A C (1998) Buffer zones to protect the aquatic environment. In: 1998 Brighton Crop Protection Conference - Pests and Diseases. BCPC: Farnham.

Davis B N K; Lakhani K H.; Yates T J; Frost A J (1991). Bioassays of insecticide spray drift: the effects of wind speed on the mortality of *Pieris brassicae* larvae (lepidoptera) caused by diflubenzuron. *Agriculture, Ecosystems and Environment* **36,** 141-149.

Davis B N K; Brown M J; Frost A J; Lakhani K J; Plant R A; Yates T J (1993). Effects of insecticides on terrestrial invertebrates. In: *The environmental effects of pesticide drift,* ed A.S. Cooke, pp.47-63 English Nature: Peterborough.

Dennis P; Thomas M B; Sotherton N W (1994). Structural features of field boundaries which influence the overwintering densities of beneficial arthropod predators. *Journal of Applied Science* **31,** 361-371.

Dickson B C; Schaeffer D J (1997). Ecorestoration of riparian forests for non-point source pollution control policy and ecological considerations in agroecosystem watersheds In: *Buffer Zones: their processes and potential in water protection,* eds N.E. Haycock, T.P. Burt, K.W.T. Goulding & G Pinay, pp. 221-227 Quest Environmental: Harpenden.

Dillala T A III; Inamdar S P (1997). Buffer zones as sediment traps or sources In: *Buffer Zones: their processes and potential in water protection* eds N.E. Haycock, T.P. Burt, K.W.T. Goulding & G. Pinay, pp 33-42 Quest Environmental: Harpenden.

Dover J W (1996). Factors affecting the distrubution of satyrid butterflies on farmland *Journal of Applied Ecology* **33**, 723-724.

Dramstad W; Fry G (1995). Foraging activity of bumblebees (*Bombus)* in relation to flower resources on arable land. *Agriculture Ecosystems & Environment* **53**, 123-135.

Duffield S; Aebischer N J (1994). Effect of plot size on recovery of populations of beneficial insects following dimethoate application. *Journal of Applied Ecology* **31**, 263-282.

Feber E; Johnson P J; Smith H; Baines M; MacDonald D W (1995). The effects of arable field margin management on the abundance of beneficial arthropods. In: *Integrated Crop Protection - towards sustainability?* BCPC Symposium Proceedings No. 63, ed R.G. McKinlay & D.Atkinson. pp 261-269. BCPC: Farnham..

Feber R E; Smith H; MacDonald D W (1996).The effects on butterfly abundance of the management of uncropped edges of arable fields. *Journal of Applied Ecology* **33**, 1191-1205.

Gilliam J W; Parsons J E; Mikkelsen R L (1997). Nitrogen dynamics and buffer zones. In: *Buffer Zones: their processes and potential in water protection,* eds N E Haycock, T P Burt, K W T Goulding & G Pinay, 54-61. Quest Environmental: Harpenden.

Hamala J A; Kollig H P (1985). The effects of atrazine on periphyton communities in controlled laboratory ecosystems *Chemosphere* **14**, 1391-1408.

Harris G L; Forster A (1997). Pesticide contamination of surface waters - the potential role of buffer zones. In: *Buffer Zones: their processes and potential in water protection,* eds N E Haycock, T P Burt, K W T Goulding & G Pinay pp.62-69. Quest Environment: Harpenden.

Harper D (1992). *Entrophication of freshwaters.* Chapman & Hall: London.

Haughton A J; Bell J R; Boatman N D; Wilcox A (1988). The effects of different rates of the herbicide glyphosate on spiders in arable field margins (to be completed).

Haycock N E; Burt T P; Goulding K W T; Pinay G (1997). *Buffer Zones: their processes and potential in water protection.* Quest Environmental: Harpenden.

Jenssen P D; Maehlum T; Roseth R; Braskerund B; Syversen N; Njs A and Krogstad T (1994) The potential of natural ecosystem self-purifying measures for controlling nutrient inputs. *Marine pollution Bulletin,* **29** (6-12), 420-425.

Jepson P C; Thacker J R M (1990). Analysis of the spatial component of pesticide side-effects on non-target invertebrate populations and its relevance to hazard analysis. Functional Ecology **4**, 349-355.

Kleijn D; Snoeijing G I J (1997). Field boundary vegetation and the effects of agrochemical drift: botanical change caused by low levels of herbicide and fertilizer. *Journal of Applied Ecology* **34**, 1413-1425.

Longley M; Cigli T; Jepson P C & Sotherton N W (1997). Measurements of pesticide spray drift deposition into field boundaries and hedgerows. *1. Summer applications. Environmental Toxicology and Contamination*, **16**, pp 165-172.

Longley M; Sotherton N W (1997). Factors determining the effects of pesticides upton butterflies inhabiting arable farmland - a review. *Agriculture, Ecosytems & Environment* **61**, 1-12.

MAFF (1996). Arable Area Payments Explanatory Guide. PB 2592.

MAFF (1998). Arable Stewardship. PB 3210.

Mander U; Matt O and Nugin U (1991) Perspectives on vegetated shoals, ponds and ditches as extensive outdoor systems of wastewater treatment in Estonia. In: Etnier, C. and Guterstam, B. (Eds.) *Ecological Engineering for wastewater treatment.* Proceedings of the International Conference at Stensund Folk College, Sweden. pp. 271-282.

Marrs R H; Frost A J; Plant R A (1991a). Effects of herbicide spray drift on selected species of nature conservation interest: the effects of plant age and surrounding vegetation structure. *Environmental Pollution* **69**, 223-235.

Marrs R. H; Frost A J; Plant R A; Lunnis P (1992). The effects of herbicide drift on semi-natural vegetation: the use of buffer zones to minimise risks. Aspects of Applied Biology **29**, 57-64.

Marrs R H; Frost A J; Plant R A; Lunnis P (1993). Determination of buffer zones to protect seedlings of non-target plants from the effects of glyphosate spray drift. *Agriculture, Ecosystems & Environment* **45**, 283-293.

Muirhead - Thompson R C (1978). Lethal and behavioural impact of chlorpyrifos methyl and temephos on select stream macro invertebrates: experimental studies on down stream drift. *Archives of Environmental Contamination and Toxicology* **7**, 139-147.

Muscatt A D; Harris G L; Bailey S W; Davies D B (1993). Buffer zones to impove water quality: a review of their potential use in UK agriculture. *Agriculture, Ecosytems and Environment* **45**, 59-77.

Olsson T I; Peters en B (1986). Effects of gravel size and peat material on embryo survival and alevin emergence of brown trout, *Salmo trutta. Hydrobiologia* **135**, 9-14.

Peterson H G; Bontin C; Martin P A ; Freemark K E; Ruecker N J; Moody M J (1994). Aquatic phyto-toxicity of 23 pesticides applied at expected environmental concentrations. *Aquatic toxicology* **28**, 275-292.

Pinder L C V; House W A; Farris (1993). Effects of insecticides on freshwater invertebrates. In: *The environmental effects of pesticide drift*, ed A S Cooke, pp 64-75. English Nature: Peterborough.

Rands M R W (1986). Effect of hedgerow characteristics on partridge breeding densities. *Journal of Applied Ecology* **23**, 479-487.

Rew L J; Theaker A J; Froud-Williams R J; Boatman N D (1992). Nitrogen fertiliser misplacement and field boundaries. *Aspects of Applied Biology* **30**, 203-206.

Samu F; Matthews G A; Lake D; Vollrath F (1992). Spider webs are efficient collectors of agrochemical spray. *Pesticide Science* **36**, 47-51.

Samu F; Vollrath F (1992). Spider orb web as bioassay for pesticide side effects. *Entomologia Experimentalis et Applicata* **62**, 117-124.

Sinha S N; Lakhani K H; Davis B N K (1990). Studies on the toxicity of insecticidal drift to the first instar larvae of the large white butterfly *Pieris brassicae* (Lepidoptera: Pieridae). *Anuals of Applied Biology* **116**, 27-41.

Smith H; Feber R E; Johnson P S; McCallum K; Plesner Jensen S; Younes M; MacDonald D W (1993). *The conservation management of arable field margins (English Nature Science Series No. 18)* English Nature: Peterborough.

Smith H; Feber R E; MacDonald D W (1994). The role of wild flower seed mixtures in field margin restoration. In: *Field Margins: integrating agriculture and conservation*, BCPC Monograph No. 58 ed N D Boatman, pp 289-294. BCPC: Farnham.

Smith H; McCallum K; MacDonald D W (1997) Experimental comparison of the nature conservation value, productivity and ease of management of a conventional and a more species-rich grass ley. *Journal of Applied Ecology* **34**, 53-64.

Snoo G R de (1997). Arable flora in sprayed and unsprayed crop edges. *Agriculture, Ecosystems and Environment* **66**, 223-230.

Snoo G R de, Dobbelstein R T J M; Koelewijn S (1994). Effects of unsprayed crop edges on farmland birds In: *Field Margins- integrating agriculture and conservation.* BCPC Monograph No. 58, ed N D Boatman, pp.221-226. BCPC: Farnham.

Sotherton N W (1984). The distribution and abundance of predatory arthropods overwintering on farmland. *Annals of Applied Biology* **105**, 423-429.

Sotherton N W (1991) Conservation Headlands: a practical combination of intensive cereal farming and conservation In: *The Ecology of temperate cereal fields,* eds L G Firbank, N Carter, J F Darbyshire & G R Potts, pp. 373-397. Blackwell Scientific Publications: Oxford.

Stoate C; Szczur J (1994). Nest site selection and territory distribution of yellowhammer (*Emberiza citrinella)* and whitethroat *(Sylvia communis)* in field margins. In: *Field margins - integrating agriculture and conservation*, BCPC Monograph No. 58, ed N D Boatman, 129-132. BCPC: Farnham.

Tew T E; MacDonald D W; Rands M R W (1992). Herbicide application affects micro habitat use by arable wood mice (*Apodemus sylvaticus) Journal of Applied Ecology* **29,** 532-540.

Theaker A J; Boatman N D; Froud-Williams R J (1995). The effect of nitrogen fertiliser on the growth of *Bromus sterilis* in field boundary vegetation. *Agriculture, Ecosystems and Environment* **53**, 185-192.

Thomas M B; Wratten S D; Sotherton N W (1991). Creation of "island" habitats in farmland to manipulate populations of beneficial arthropods: predator densities and emigration *Journal of Applied Ecology* **3**, 906-917.

Tooby T E (1997). Buffer zones: their role in managing environmental risk In: *1997 Brighton Crop Protection Conference* - Weeds, pp. 435-442. BCPC: Farnham.

Tree J A; Boatman N D (1993). The potential for conservation headlands in linseed. In: *1993 Brighton Crop Protection Conference - Weeds,* pp. 355-363. BCPC: Farnham.

Tscharntke T; Greiler H J.(1995). Insect communities, grasses, and grasslands. *Annual Review of Entomology* **40**, 535-558.

Tytherleigh A (1993). The establishment of buffer zones - the habitat scheme water fringe option, UK. In: *Buffer zones their processes and potential in water protection,* eds N E Haycock, T P Burt, K W T Goulding & G Pinay, pp. 225-264. Quest Environmental: Harpenden.

Uusi-Kamppa J; Turtula E; Hartihainen H; Ylaranta T (1993). The interactions of buffer zones and phosphorus run off. In: *Buffer zones:their processes and potential in water protection,* eds N E Haycock, T P Burt, K W T Goulding & G Pinay,pp 43-53. Quest Environmental: Harpenden.

Williams C T; Davies B N K; Marrs R H; Osborn D (1987). Impact of pesticide drift. *NERC Contract report to Nature Conservancy Council.* Institute of Terrestrial Ecology: Huntingdon.

Wilson P J (1994). Managing field margins for the conservation of the arable flora. In: *Field margins - integrating agriculture and conservation,* BCPC Monograph No. 58 ed N D Boatman, pp. 253-258. BCPC: Farnham.

Wood P J; Armitage P D (1997). Biological effects of fine sediment in the lotic environment. *Environmental Management* **21**, 203-217.

The role and practical management of buffer strips in crop production

J H Orson
Morley Research Centre, Morley St. Botolph, Wymondham, Norfolk, NR18 9DB, UK

ABSTRACT

Pesticides and chemical fertilisers decrease the impact of food production on the global environment through helping to reduce the area of land required to meet demand. On a national scale, these inputs are essential for UK farmers to compete in international markets but measures are required to control any pollution resulting from their use and to help to offset the effects of the intensification of crop production that they have facilitated. This requires their responsible use whilst achieving optimum economic yields and, in many situations, the adoption of buffer strips. However, there are practical problems with the management of buffer strips because machinery and labour has to be rationalised to ensure that crop production is internationally competitive. More guidance is required on the form, size and location of buffer strips in order that they meet their objectives.

INTRODUCTION

The main functions of buffer strips are to reduce the movement of pesticides and nutrients to field side water courses and vegetation and/or to provide a refuge and a habitat for flora and fauna in order to increase the biodiversity of the countryside. It is inevitable that they occur in varying forms, according to individual circumstances and objectives. In some cases there may be no or only minor change to the management of the outer few metres of the crop. However, in other cases the outside of the field may be sown with species which will provide habitat and refuge, reduce the surface run-off of soil and water containing pesticides and nutrients to water courses and intercept spray drift (Boatman, 1998). Buffer strips can be of varying widths, again depending on their objectives. This paper sets out the essential role of such areas in the context of current agriculture and discusses some practical aspects of their management in the context of pesticide use.

THE ROLE OF BUFFER STRIPS

Consumers do not support traditional systems

History shows that as economies develop there is a migration from the countryside to the cities. This process of urbanisation occurred in the UK during the industrial revolution in particular. Wheat consumption rose significantly, despite the fact that rotations at that time could produce wheat only one year in four. Hampered by low yields and the necessity of a rotation, production could not meet consumption and prices rose rapidly, particularly after the poor harvest in 1845. This was a very wet summer, when blight decimated the Irish potato crop and disease riddled the UK wheat crop. The high price of wheat resulted in the Repeal of the Corn Laws, which protected home wheat production but despite this, prices were healthy for another twenty-five to thirty years. However, the introduction of a new technology, namely steam engines, resulted in the cheap production of wheat in North America and its economical transport to the UK. Wheat imports trebled and prices halved over a ten-year period in the latter part of the 19th century.

Urbanisation is still occurring at a rapid rate in some parts of the world. The urban population in Asia, Latin America and Africa is expected to rise from 37% of the total in 1990, to nearly 50% in the year 2000. As in the UK in the mid-19th century, this is likely to result in a further increase in the demand for wheat. For example, a Senegalese farmer consumes three kg of wheat a year, whereas an inhabitant of the capital city consumes 30 kg (UNO, 1996).

Hence, the lessons of history show that:

- consumers, once they become detached from production, have a diet that does not reflect the output of traditional systems.
- technology has a significant impact on the competitiveness of crop production of individual farmers and countries.
- environmental damage can be exported or imported in the guise of food. For instance, large tracts of the natural vegetation of the North American prairies were destroyed in the last century because low yields and the need for a regimented rotation restricted European production of wheat.

The role of technology

UK farmers are now becoming competitive in an expanding world wheat market, not by reducing inputs but by wise investment in the technologies of plant breeding, plant nutrition and pesticides (Table 1). This has enabled a fuller exploitation of a climate and soils, which can sustain high yields and thereby has allowed the costs of production to be spread over a greater physical output. In contrast, much of North America does not have such a favourable climate and drought limits the ability of its farmers to exploit these technologies. In addition, UK farmers have been enabled to adopt intensive cereal systems by the availability of effective pesticides and plant nutrition. Unlike the situation in the middle of the last century, it is now no longer necessary to grow crops and produce livestock which are not profitable nor in demand by the urban population or in order to 'weed and feed' cereals and other cash crops. This intensification of production, along with higher yields, has resulted in the UK becoming a major exporter of grain.

Table 1. Wheat yields and total production costs/tonne – an international comparison.

	UK	France	Germany	US	Ireland
Yield (t/ha)	8.1	7.4	7.6	2.4	7.8
Total production costs/tonne (£)	98.8	102.2	109.9	114.8	103.1

Source: M C Murphy, Dept. of Land Economy, University of Cambridge - personal communication

Notes

1. Winter Wheat in UK, France, Germany and Ireland; Winter and Spring Wheat in the US
2. Based on input levels, prices and volumes between 1994-1996 in each country.
3. Exchange rate £ per ECU - 0.677353

Balancing consumer requirements and concerns

The message is clear. In developed economies and open world food markets, consumers will not support traditional systems in their own country because they are not prepared to pay for and/or balance their diet in accordance with the production from the crops and livestock involved. Open world markets mean that farmers have to concentrate on only those crops, which are in demand and which they can grow competitively. Secondly, the competitiveness of North European agriculture depends on high yields made possible by investing wisely in technology. These are not only lessons from history but also the key to how the UK farmer must compete in the future. The Government sees as an objective that our agriculture should be competitive in world markets. Competitiveness will not only be influenced by factors such as communications and exchange rates but, as in the past, by the technological battle between our agriculture and that of our international competitors. It requires acceptance by the government and by consumers that the current technologies involved in crop production should continue to be used and that new technologies should be introduced when safe and robust.

On the other hand, it has to be accepted by the farming community that the intensification of production in the UK has led to environmental damage. This has resulted in consumer pressure to reduce the environmental impact of arable production. Central to the issue is the key fact that the biggest impact of a crop on the environment is its very presence. This is because in order to establish arable crops, the natural vegetation has to be destroyed and the land cultivated annually, as occurred in the American prairies last century. This fact provides another clue to the way forward. It is essential on a global scale that economic yields are optimised in the long-term, by using current and new technologies sensitively in order to reduce to a minimum the land in arable production. With world markets come global issues and responsibilities and the UK has to decide how much environmental damage it is prepared to import or export in the guise of food.

There is no doubt that pesticides and nitrogen also have an impact on the environment but on a significantly lower scale than do the destruction of the natural environment and the cultivations necessary to establish the crop. However, they can have an impact on the species that use arable crops as a habitat or food source, such as some farmland birds, beetles and spiders. With greater knowledge, new technologies and more rigorously evaluated pesticides, this impact will be minimised along with a reduction in the risk of pollution.

Whilst it is clear that the area cropped will determine the main effect of arable production on the environment, it is also slowly being realised that a relatively small proportion of the land area can support a significant proportion of the natural biodiversity (Halley *et al.*, 1996). This provides the final clue to the way forward and defines the role of buffer strips. Leave farmers to optimise economic yields by the responsible use of current and new technologies, whilst ensuring that non-cropped areas and buffer strips are managed in such a way as to minimise pollution and to encourage biodiversity and retain the integrity of the landscape. In this way, a competitive agriculture can be maintained and the environmental value of the countryside improved.

THE PRACTICAL MANAGEMENT OF BUFFER STRIPS

Setting objectives

The first stage of any management plan is to have clear objectives based on an analysis of the circumstances. This process has been sadly missing in many cases where landowners have sought to increase the environmental and landscape value of the land. For instance, examples abound of where valuable vegetation has been destroyed in order to dig a pond. It is also absolutely essential that any introduction of buffer strips in order to reduce pollution is done is such a way as to maximise their contribution to the environmental objectives of the farm.

There are now clearer biodiversity objectives as a result of the Biodiversity Plan introduced by the Department of the Environment (Anon., 1995). This was the result of an objective appraisal of the then current status and trends in populations of individual species within the UK and Europe. The national plan has been rolled down to a more local level and expert advisers can now provide individual farmers with information on which species need to be encouraged within their locality and for which habitats can be provided on their land.

The conflict between an efficient agriculture and reducing pollution and improving the environmental value of arable land

It has to be accepted that, whilst it is possible to farm successfully and at the same time to improve the environmental value of land, there are inevitably conflicts. Farmers in the UK are preparing to produce food at world prices: this necessitates optimising economic yields with the use of chemical fertilisers and the most cost-effective pesticides, reducing labour and machinery to a realistic minimum and increasing the size of farms to take advantage of the economies of scale. This business environment not only reduces the time and machinery available to manage buffer strips but also has implications on their form and size. For instance, there is a desire to increase field size and/or to grow the same crop in blocks of neighbouring fields. It can be argued that these factors should influence the size and form of buffer strips around individual fields to ensure that there is sufficient biodiversity in the countryside.

Field size

There is no doubt that large fields have always had advantages in terms of the efficiency of machinery and labour, particularly with the higher forward speeds (Figure 1) and working widths (Sturrock *et al.*, 1977). They also minimise the losses in yield associated with the cropping near the edge of a field, due to competition from field boundary vegetation (Figure 2) and the impact on soil structure from machinery turning (Sparkes *et al.*, 1998). In addition, large fields reduce the proportion of the field that is adjacent to water or field boundary vegetation (Figure 3). Purely from an economic view, farmers perceive this as an advantage of larger fields because of the reduction in the loss of crop or of inconvenience associated with buffer strips. However, larger fields are often associated with a lower proportion of non-cropped land, which has consequences on both biodiversity and the landscape.

Figures 1-3 all indicate that the optimum field size is above 30 ha. Cereal farmers who have discussed field size with the author have suggested that 30 ha is the optimum size when practical considerations such as rotation and product storage are taken into account. Where such field sizes are adopted, the area of non-cropped land in field boundaries could form a very low proportion of land cover, perhaps less than one percent.

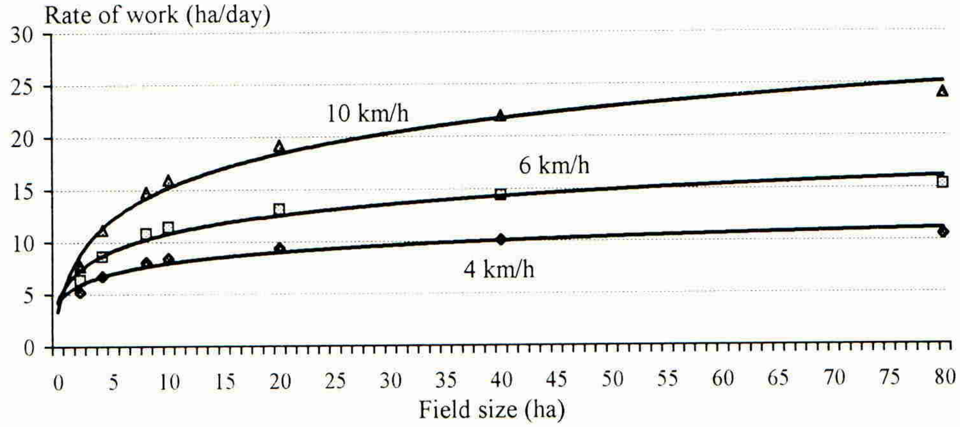

Figure 1. Rate of work in ha/day of a machine with a 5m working width according to forward speed (kilometres/h) and field size (Sturrock *et al.*, 1977).

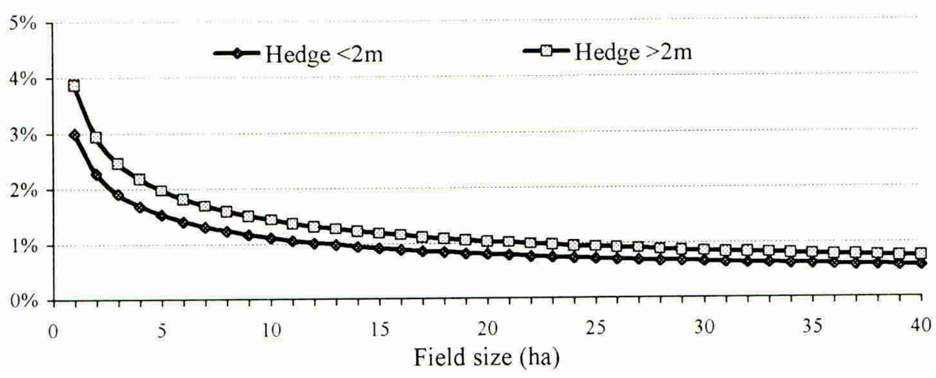

Figure 2. Percentage loss of field yields of winter wheat due to competition from field boundary vegetation according to its height and the area of square fields (based on field data provided by Dr. Sarah Cook, ADAS Boxworth, UK).

There is research that clearly indicates that a relatively small area devoted to natural vegetation can make a disproportionally high contribution to natural biodiversity (Halley *et al.*, 1996). The challenge for researchers is to define the forms, area (both in terms of individual units and as a proportion of the land area) and distribution of natural vegetation required in order to meet the specific objectives set in local biodiversity plans. Where there are large fields or where blocks of neighbouring fields have the same crop, particularly in the absence of other non-cropped land such as woods, it may be necessary to have wider buffer strips than would be required for water protection in order to provide sufficient refuge and habitat. For instance, to set aside 5% of the field area would result in a three metre wide buffer strip in a five ha field but a seven metre wide buffer strip in a 30 ha field (Figure 3). The added advantage of wider non-cropped buffer zones is that, where desirable, hedges can be allowed to grow to a very large size with less fear of them affecting crop yield. Where the objective is to provide a refuge for less mobile fauna which live in the crop or a specialised habitat for some bird species, the alternative to wider buffer strips on the edge of the crop is to split large fields with non-cropped strips such as 'beetle banks' (Thomas *et al.*, 1991). This will have to be done with care in order that the efficiency of labour and machinery is maintained.

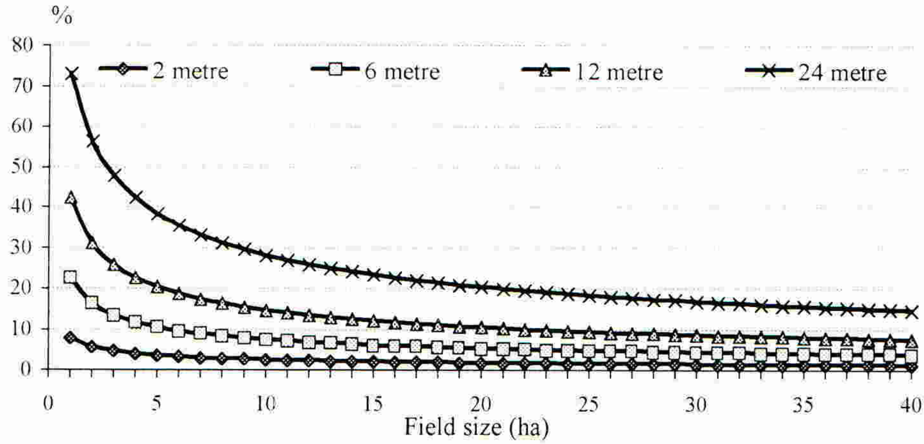

Figure 3. Percentage of a square field within 2m, 6m, 12m and 24m of the field boundary, according to field size.

The current no-spray zones imposed on field crops in order to reduce the pollution of surface water in the UK (Croxford, 1998) have resulted in restrictions in pesticide choice in the crop within six metres of surface waters or ditches which may transport water. The restrictions still apply to ditches that do not contain water at the time of application. This often results in less effective products being applied to the whole field or the outer spray width of the crop. This is because farmers still need to protect the outer six metres of the crop from pests, diseases and weeds but also want to avoid the inconvenience of having to treat the rest of the same spray bout or field separately. The inconvenience and potential financial loss experienced by a farmer having to change product for this area of the field is minimised by having large fields. For example, the direct financial implications of having to use a less effective fungicide mixture applied to the flag leaf of a disease susceptible wheat cultivar on the outer 24 metres of fields was calculated by the author, based on the Morley farm for 1998. It took into account the practical experience of restrictions in product choice close to dry ditches and prices during 1998, along with response to fungicides in experiments on the farm of Morley Research Centre in 1998. This shows, with wheat valued at £70/tonne, that a reduction in the margin over input costs for the whole field from this single spray operation alone was £80 in a 10 ha field and £140 in a 30 ha field.

It is unfortunate that the outer metre or two of crops, in addition to usually having higher numbers of desirable fauna, often contain the highest populations of weeds and some pests and diseases. Hence, with no-spray zones, pesticide use can be encouraged on the crop edge because restrictions in choice may lead to the more intensive use of less effective products. However, due to their impact on fauna, there are statutory or advisory restrictions on the use of some products near the edge of crops.

Management of small areas

There is a need to increase the efficiency of labour and machinery as world markets open up and competition intensifies. This inevitably results in farmers having less time, labour and relevant machinery to manage separately small areas, such as buffer strips. Simple operations can become major challenges, such as applying a different pesticide to the outer six metres of the crop. The desirability to cut and remove vegetation from sown buffer strips in order to deplete soil reserves of nutrients and to prevent the cuttings smothering the sward is causing problems in arable areas. There are two options: to forage harvest the area after the field crop is harvested and blow the cut mature vegetation into the body of the field where the seeds may result in a weed risk, or to try to bale the grass as either hay or silage. In arable areas there may not be the equipment available for such a small-scale operation.

Local Environmental Risk Assessments for Pesticides (LERAP)

The objectives of LERAP, the factors involved in the risk assessment and the potential difficulties of farmers carrying out and recording the process are outlined by Croxford (1998). These new proposals to protect surface waters remain subject to further consultation. However, on the basis of current ideas, the use of all products may be allowed more than two metres from potentially water-bearing ditches that are dry at the time of application. This may result in farmers choosing not to crop the area next to ditches. For the majority of farms, this provision alone will dramatically reduce the inconvenience involved with the current no-spray zones. In addition, under certain conditions, LERAP may allow some of the pesticides that currently have a six metre no-spray zone to be used up to two metres away from ditches which contain water. In the situation where a slightly wider buffer zone may have to be observed, it may not be worth the time and inconvenience of changing from the most effective pesticide being applied to the rest of the field, thus leaving the outer edge of the crop untreated. However, in some instances, untreated insects, diseases or weeds in this area of the crop may threaten to re-infect the body of the field. On the other hand, this is often the area of the crop with the highest number of desirable fauna and where weeds provide the most environmental benefit.

Modern sprayers have made it easier to comply with LERAP. It is now possible, with little inconvenience or increase in operator exposure, to avoid the application of pesticides to the outer two or three metres of crop. In addition, it is now easy to use different nozzles to apply pesticides to the outer few metres of the crop in order to reduce spray drift into the field boundary vegetation or watercourses, which may be a key requirement of this procedure.

Hence, LERAP may prove to have less direct influence on product choice than the current no-spray zones. This may also have the advantage of decreasing the risk of pesticide resistance. On the other hand, it may have more influence on product timing because farmers may attempt to apply pesticides at a time when the ditches are dry. For instance, weed control

The impact of differing climate change downscaling methodologies on entomological risk assessments

C H Jarvis, D Morgan
Central Science Laboratory, Sand Hutton, York, YO41 1LZ, UK

ABSTRACT

A common feature of climate change studies involving insects is the provision of statistics describing potential alterations to the spatial distributions of insect phenologies or populations. Often these relate to one particular estimate of future outputs of potential global climate change agents such as CO_2 (emissions scenarios), perhaps projected to multiple dates. That alternative estimates of CO_2 and other agents of change exist is widely appreciated. However, the uncertainty in moving from global predictions of global change to national estimates and the implications for insect outbreaks has received little attention. Focusing on spatial uncertainty, the work draws on the capabilities of the British Climatic Research Unit SPECTRE software to demonstrate that multiple spatial configurations of changes may arise.

Predictions of changes to distributions of the codling moth (*Cydia pomonella*) and accumulated temperatures are used to illustrate the effects of using different climate change scenarios. This paper highlights uncertainties surrounding the underlying climatology that should be considered when interpreting climate change predictions.

INTRODUCTION

Forecasts of the medium term effects (e.g. 2033, 2100) of global warming are frequently reported in the scientific literature. These data must be translated to statistics of potential climate change for a specific nation or region in order to determine the effects on insect outbreaks. In Britain, climate circulation models produced at the UK Meteorological Office include for example the UK high resolution transient experiment (UKTR) and the Hadley Centre Unified Model greenhouse gas experiment (HadCM) series. These studies however inform potential monthly changes, rather than daily, and are projected only to broad spatial resolutions (e.g. 2.5 * 3.75°, HADCM2). Such temporal and spatial scales contrast with that of the daily data of UK meteorological stations more commonly used in modelling pest populations and development. This discrepancy, between scales at which climate circulation and change is modelled and the scale at which estimates of climate change are needed for assessing ecological risk, is currently being addressed by climate research under the title 'downscaling'. Meanwhile, the impact assessment process is subject to a large number of abiotic uncertainties, in addition to those of a biotic nature, that are often not acknowledged within applied climate change studies published in entomological and related disciplines.

The purpose of this study is to highlight the potential effects of alternative climate change methodologies on predictions of pest outbreaks. Uncertainties arise, both spatially and temporally, that have the potential to alter applied agricultural assessments in a significant way (e.g. Semenov *et al.*, 1996). For the purpose of this study, the spatial component forms a particular focus. The insect modelled is the codling moth (*Cydia pomonella*), an important insect pest of apples in the UK. In order to show the wider implications of the study for other pests, accumulated temperature changes are also discussed.

METHODOLOGY

To assist in the production of applied climate impact assessments the Climatic Research Unit (CRU), in conjunction with MAFF, compiled a selection of current climate modelling predictions within a software suite known as SPECTRE (Barrow *et al.*, 1997). This comprises pre-processed data for a variety of emissions scenarios (e.g. IPCC 95), the effects of which have been forecast for Britain using general circulation model (GCM) experiments such as the UKTR and HadCM. Digital data for one reference year (2100), derived from the Composite (aggregated results from seven models) and UKTR climate model results, were output from SPECTRE and converted using proprietary GIS software to the Ordnance Survey National Grid. These represent equilibrium and transient climate modelling projections respectively.

A spatial environmental modelling system which calculates daily maximum and minimum temperatures in locations between meteorological stations was reported by Jarvis *et al.* (1998). In previous studies a number of field validated models, such as that developed for *C. pomonella* (Morgan, 1992), have been integrated with the system. This allows surfaces of important phenological stages, as opposed to more commonly found discrete point estimates, to be mapped over the landscape of England and Wales at a spatial resolution of $1km^2$ for a variety of pests. Geographical simulations were run using daily UK Meteorological Office temperature records over 30 years (1961-1990), from 60-180 meteorological sites depending on year, as their base. Monthly spatial estimates of temperature changes for 2100 as produced by SPECTRE were then added to the interpolated daily maximum and minimum temperatures in order to identify the year to year fluctuations in the pest phenology and accumulated temperature (8.6°C base) for the two different climate models. Julian date and accumulated temperature results were modelled and mapped at a spatial resolution of $10km^2$.

RESULTS

Preliminary analysis using the package revealed considerable spatial differences between the model derived spatial patterns of climate change in temperature terms, not only in terms of overall magnitude within the warming trends but also in the relative spatial distribution of these effects. These are also reflected within the phenological results. The mean Julian date for the period 1960-1991 at which codling moth larvae reach 50% emergence of first generation for England and Wales (Figure 1(a)) is compared with projections of the average expected reduction of the lifecycle under the two estimates of climate change for 2100 (Figure 1(b),(c)). When aggregated over the entire country, as is common practice, statistics showing expected change as a proportion of the overall landscape for the two GCMs are similar. However, there are considerable underlying differences in the spatial distribution of the climate change effects. In the case of UKTR projections (Figure 1(b)), warming is greatest in northern regions while the composite model (Figure 1(c)) predicts that the greatest changes

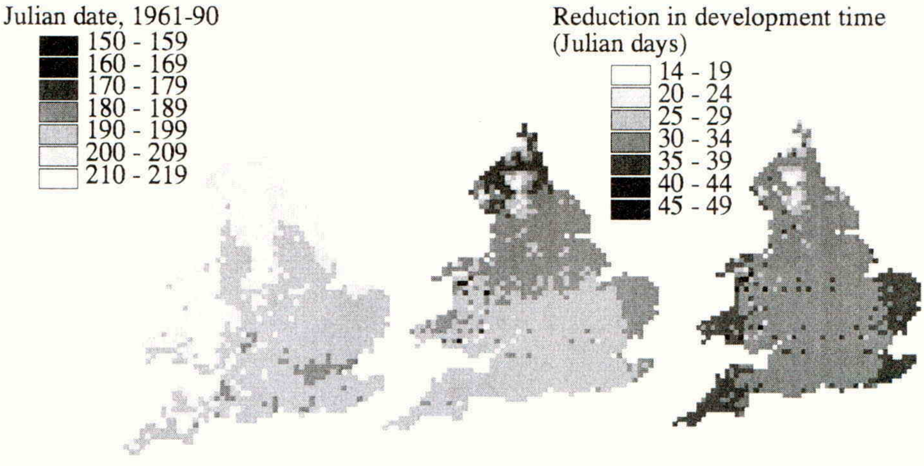

Figure 1. Julian date of 50% emergence of first-instar larvae of codling moth under: (a) current conditions; (b) expected reduction in development time, UKTR model, year 2100; (c) expected reduction in development time, composite model, year 2100.

will be found in southern coastal areas, reflecting differences between the underlying climate models.

Considering the magnitude of change in Julian dates between the two projected scenarios for Britain as whole (Figure 2), differences of up to one month occur at the margins of

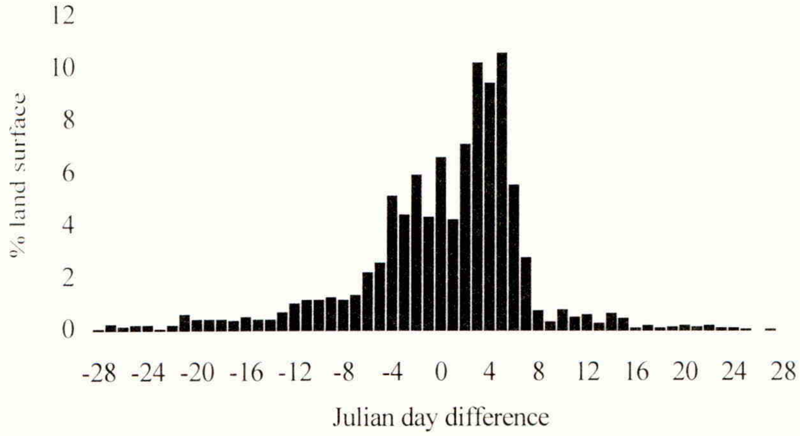

Figure 2. Difference in projected Julian dates for codling moth first-generation larvae (50%).

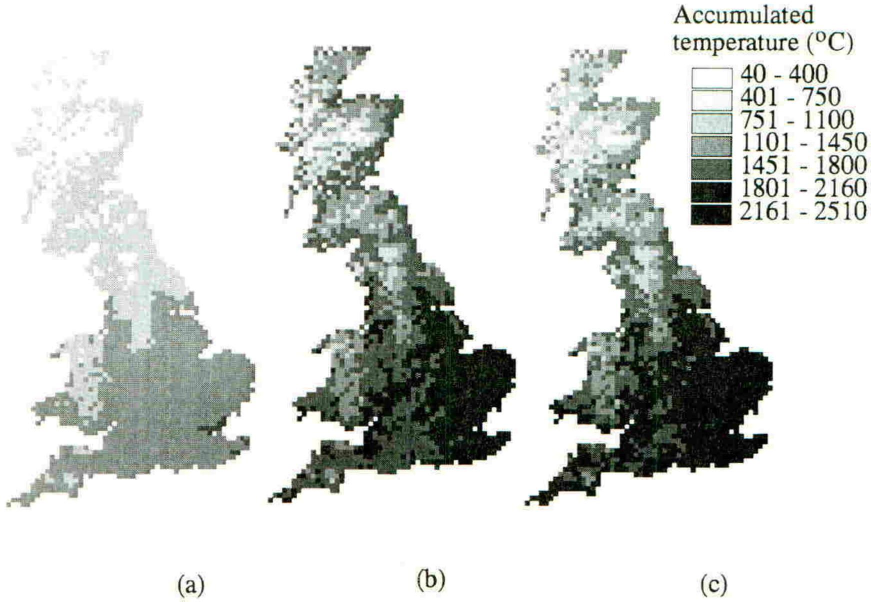

Figure 3. Accumulated temperature above 8.6°C threshold for (a) current conditions, (b) 2100, as adjusted by the UKTR model, (c) 2100, as adjusted by the composite model.

geographical distribution. In the case of second generation larvae of codling moth, both range and the revised number of generations differ even more markedly over the landscape between scenarios. The UKTR experiment indicates that codling moth has the potential, by the year 2100, to occur throughout Scotland. In contrast, the composite climate projections indicate that multiple generations in southern Britain are more likely than an extension to range.

Similar trends in the effects of climate change on accumulated temperatures may also be observed (Figure 3). Both projections show a consistent north-south shift in temperature sum, but the differences between modified accumulated temperature maps are highly significant when compared with the degree of change between current and projected conditions. For up to 43% of the British land surface, the difference between the two scenarios is between 100-200% of that between the original and revised climate estimate. For a further 2% of the land area, this proportion rises to 200-300%. These figures relate to changes relative to 1997, rather than the standard 30-year average baseline, and so reflect a snapshot of the likely overall outcome.

DISCUSSION

The effects of climate change on pest distributions in Britain may be considerable. The degree to which differences in spatial configuration of insect phenology will occur varies according to the climate-warming scenario and downscaling technique used in its construction. The latter for example is reflected in the underlying broad scale grid clearly apparent within Figures 1(b) and (c), which indicates the dangers of over-reliance on regional or sub-regional temperature change data in applied studies unless generated by an explicitly regional climate model. The ways in which differences in temperatures under climate change will differ locally in their relative distribution from the current position at local scales are relatively unknown. Gaussian kernel estimators are currently used in a pragmatic bid to create more detailed grids from the initial crude GCM results (Barrow *et al.*, 1997), but these do not reflect underlying climate processes. For these reasons, over-detailed grid resolutions should be avoided in applied studies until such time as the underlying climatological science has matured.

The difference between two different mapped assessments of phenology or accumulated temperature change, as a proportion of changes relative to current conditions, may be significant even where the apparent effects appear slim on the basis of visual comparison. The distribution of the pest presented in this study may not represent the most dramatic extremes, which are more likely to occur where over-wintering of pests becomes possible (Leather *et al.*, 1993) and the pest's geographical margins of development lie within central Britain. Nevertheless, they illustrate that climate warming assessments and pest predictions need to consider multiple possible outcomes, not only of original emissions scenarios and their global translations to warming, but also the variety of ways in which climatologists model these. Any attempts to project the economic implications of climate change as a result of alterations to insect behaviour may be skewed according to whether differences in pest distributions and development are reflected in modifications of range or by altering the number of possible generations, or both. Treating changes in temperature alterations in isolation from CO_2 and ozone effects on both pest and crop environment reflects only one small component of the overall change possibilities.

Driving phenological models with modified temperature estimates over 30 years allows the possibility of assessing year to year fluctuations in climate change effects. Aggregated estimates of change reflect a mean value relative to the 1961-90 baseline temperatures, as do those of alternative approaches such as the use of CLIMEX, but in this case the underlying variability and extremes may be explored. The use of monthly average change over daily fluctuations introduces temporal discrepancies, which should be much improved with the availability of daily temperature change expected by the year 2000 as part of the HadCM3 experiments. Meanwhile, since the monthly pattern of temperature change appears stable throughout most of the annual cycle, and given the lack of alternative information, the current approach was considered viable. It should be noted however that changes in variance in day to day fluctuations in temperature from those of the climatic 'normal' period (1961-1990) may also have a material effect upon impact assessments.

The results presented reflect only one particular emissions scenario and one assessment of sensitivity of the climate to these emissions. The UKTR and composite models used to project climate-warming effects over Britain belong to two different stages of development in climate modelling. However even among projections from the most recent model HadCM2 (e.g. Baker *et al.*, 1998), that similarly to UKTR uses ocean-atmospheric interactions, there is evidence from other disciplines (e.g. Viner & Hulme 1997) that regional assessments of the effects of climate change will differ. While a consensus is being reached that, on a nation wide basis, climate models are becoming increasingly reliable (Viner & Hulme 1997) caution is still advised in interpreting the results for particular regions too literally. This suggests a greater focus is needed by the entomological community at large on computer simulations investigating 'what if...' type scenarios to determine critical thresholds, and further biological experimentation regarding the rate of adaptation of both individual pests and agricultural systems to changes on CO_2 and temperature.

In conclusion, climate warming impact assessments are by their very nature uncertain. While it is essential that information for policy use is obtained, care should be taken in the interpretation of single mapped outcomes. Maps of pest distribution can provide strong visual impressions. However, given the geographical uncertainties surrounding their production they should not be used in isolation from a fuller pest risk assessment (Baker *et al.*, 1998) and outputs from a range of modelling methods should be compared and assessed on their relative significance. Examples using codling moth and accumulated temperature show that the magnitude of uncertainty in regional assessments of climate warming effects may be higher than the degree of warming itself.

ACKNOWLEDGEMENTS

This work was supported by the Plant Health Division of MAFF. The paper was substantially improved by discussions with colleagues at CSL, in particular Dr R H A Baker.

REFERENCES

Baker R H A; MacLeod A; Cannon R J C; Jarvis C H; Walters K F A; Barrow E M; Hulme M (1998). Predicting the impacts of a non-indigenous pest to the UK potato crop under global climate change: reviewing the evidence for the Colorado beetle, *Leptinotarsa decemlineata* (this volume).

Barrow E; Hulme M; Jiang T (1997). *SPECTRE: Spatial and Point estimates of Climate change due to Transient Emissions (Version 2.0)*, Software User Manual, Climatic Research Unit: Norwich.

Jarvis C H; Stuart N; Morgan D; Baker R H A (1998). To interpolate and thence to model, or vice versa? In Gittings, B. (Ed.) *Innovations in GIS VI*, Taylor & Francis: London (In press).

Leather S R; Walters K F A; Bale JS (1993) *The ecology of insect overwintering*, Cambridge University Press: Cambridge, pp255.

Morgan D (1992). Predicting the phenology of lepidopteran pests in orchards in SE England, *Acta Phytopathologica et Entomologica* **27**, 473-477.

Semenov M A; Porter J R (1995). Climatic variability and the modelling of crop yields, *Agricultural and Forest Meteorology* **73**, 265-283.

Viner D; Hulme M (1997) *The Climate Impacts LINK Project: Applying results from the Hadley Centre's Climate Change Experiments for Climate Change Impacts Assessments*, Report prepared for the UK Department of the Environment, 24pp.

Aphid pest potential increases at elevated CO_2

C S Awmack, R Harrington
Department of Entomology & Nematology, IACR-Rothamsted, Harpenden, Herts, AL5 2JQ, UK

ABSTRACT

Aphid population development often increases at elevated CO_2 but the interactions with changed plant physiology are not known. When a single fourth instar aphid (either *Acyrthosiphon pisum* or *Aulacorthum solani*) was added to bean plants grown at elevated CO_2 and a population was allowed to develop for 20 days there was a greater decrease in plant growth compared to ambient CO_2. *A. pisum* decreased shoot growth by 24% at ambient CO_2 but by 34% at elevated CO_2. *A. solani* had no effect on shoot growth at ambient CO_2 but at elevated CO_2 shoot growth decreased by 20%, suggesting that *A. solani* has the potential to cause serious yield loss in beans if atmospheric CO_2 concentrations continue to increase. Aphids had no effect on the number of flowers open at harvest at ambient CO_2, while at elevated CO_2 *A. pisum* and *A. solani* decreased flowering by 73% and 60% respectively. These data imply that aphids will cause greater losses in yield of bean plants under elevated CO_2 than in our current climate.

INTRODUCTION

Global atmospheric CO_2 is likely to reach double current ambient concentrations by the end of the next century if emissions continue at their current rate (Houghton *et al.*,1996). Elevated CO_2 could affect agricultural production in two ways; by contributing to global warming and by increasing the rate and efficiency of photosynthesis (Parry, 1992). Although an increase in photosynthetic carbon fixation would appear to be beneficial for agriculture, as yields of most crops increase, it is not known how the pest status of insects will be affected. Chewing insect herbivores are generally adversely affected by elevated CO_2 atmospheres because of the effects of increased photosynthesis on the quality of their host plants (Watt *et al.*,1995). Considerably less is known about the performance of aphids at elevated CO_2. Although the performance of some species of aphids is improved (Awmack *et al.*,1996; 1997) it is not yet known whether enhanced plant growth at elevated CO_2 will be adequate to compensate for increased damage caused by larger aphid populations.

Aphids cause damage to crops in two main ways; by transmission of viruses and by direct feeding. As aphid populations have the potential to increase exponentially from a single individual by parthenogenesis small changes in fecundity or development times early in the growing season can have large effects on yield after only a few weeks. This

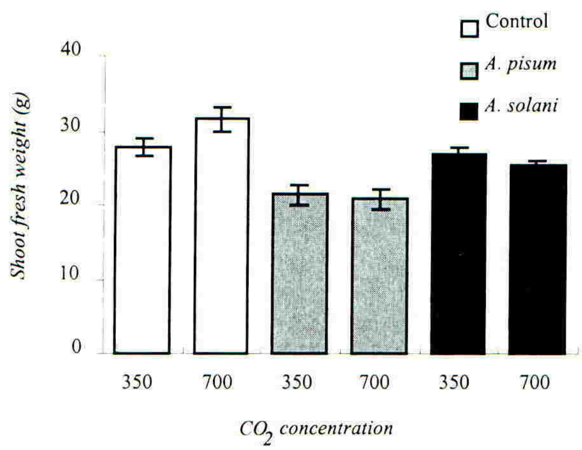

Figure 1. Shoot fresh weight of bean plants grown at ambient (350 µl l^{-1}) and elevated (700 µl l^{-1}) CO_2. All data are the means of ten replicates and are shown ± one standard error.

paper summarises the results of an experiment to investigate the effects of an increase in atmospheric CO_2 concentrations to levels equivalent to those predicted to occur by the end of the 21st century if emissions continue to increase at their current rate, on the pest status of the pea aphid, *Acyrthosiphon pisum,* and the glasshouse and potato aphid, *Aulacorthum solani,* feeding on broad bean, *Vicia faba*.

MATERIALS AND METHODS

Experimental conditions, growth of plant material and aphid rearing

All experiments were done in the "Envirocon" facility at Rothamsted (Lawlor, 1993) in four chambers, two running at 350 µl l^{-1} CO_2 ("ambient") and two running at 700 µl l^{-1} CO_2 ("elevated"). All four chambers were maintained at a constant temperature of 18 °C with a 16 h daylength provided by natural daylight supplemented with artificial lighting when required. Plants were grown from seed in the appropriate CO_2 concentration in 1 litre pots containing a nutrient-free potting medium (Terra-Green, Oil Dri, Chicago) and 1.6 g slow release fertiliser (Osmacote mini, Sierra UK) to provide levels of nutrients similar to field conditions (about 80 kg ha^{-1}). All aphids were clones, derived from a single parthenogenetic female of either *A. pisum* or *A. solani* and reared at ambient CO_2 at 18 °C with a 16 h daylength. All aphid cultures had been maintained on *V. faba* for several years before the experiments started.

Measurement of the effects of aphid infestation on plant yield at ambient and elevated CO_2

Bean plants were grown from seed at ambient and elevated CO_2 as described above. The seedlings were transplanted into 1 litre pots when they were ten days old and left for two

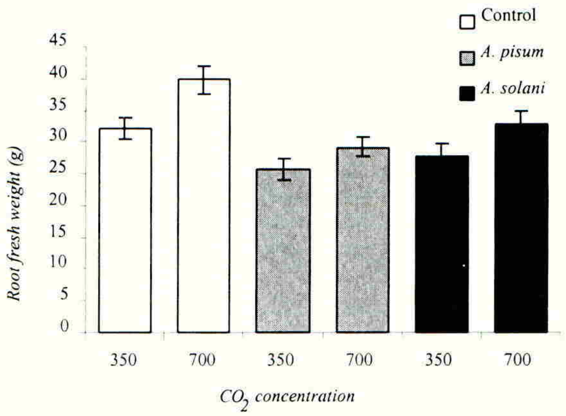

Figure 2. Root fresh weight of bean plants grown at ambient (350 µl l^{-1}) and elevated (700 µl l^{-1}) CO_2. All data are the means of ten replicates and are shown ± one standard error.

days to minimise stress due to transplanting. A single late 4th instar wingless aphid was then added to each plant and the whole plant was enclosed in a cage made of fine mesh and plastic. Ten control plants of each species were treated in the same way except that no aphids were added.

The plants in each CO_2 treatment therefore comprised;
10 *Vicia faba* with 1 *Aulacorthum solani*
10 *Vicia faba* with 1 *Acyrthosiphon pisum*
10 *Vicia faba* with no aphids

The plants were divided between the four CO_2 rooms (two at ambient, two at elevated) so that there were 15 plants in each.

Twenty days later the plants infested with *A. pisum* at elevated CO_2 were starting to show signs of necrosis and the experiment was stopped. The aphids were removed and the plants were separated into shoot and root tissue and weighed (roots were washed, patted dry with a towel to removed surface water and then weighed). The number of open flowers with the standard petals separating, beyond Stage 2 (Osborne *et al.,* 1997) on each plant was counted.

Data analysis

Data were analysed using Genstat for Windows 5, Release 3.22 (Rothamsted Experimental Station) using ANOVA with CO_2 as a main effect and the presence or absence of aphids (and aphid species) as blocks. Individual means were compared using two-tailed t-tests where justified by ANOVA.

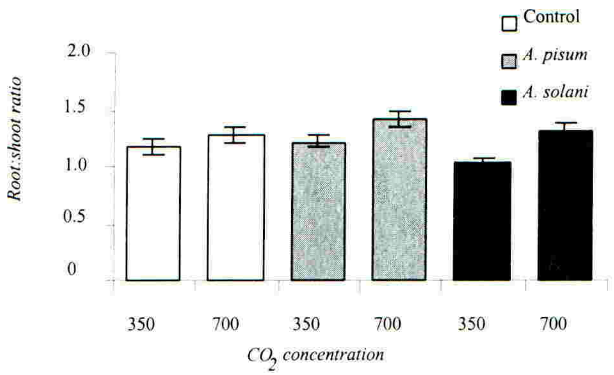

Figure 3. Root:shoot ratios of bean plants grown at ambient (350 $\mu l\ l^{-1}$) and elevated (700 $\mu l\ l^{-1}$) CO_2. All data are the means of ten replicates and are shown ± one standard error.

RESULTS

The effects of elevated CO_2 on uninfested bean plants

Elevated CO_2 had a significant effect on the growth of bean plants. Mean shoot weight was 14% greater at elevated CO_2 than at ambient ($P < 0.05$, Figure 1) and root weight was 24% greater ($P < 0.01$, Figure 2) but the root:shoot ratio was unaffected by elevated CO_2 ($P > 0.05$, Figure 3). Elevated CO_2 had no effect on the number of flowers open at the time of harvest (Figure 4).

The interactions between aphids and bean plants at ambient and elevated CO_2

When a single fourth instar *Acyrthosiphon pisum* was added to the bean plants there were significant reductions in shoot fresh weight at both ambient and elevated CO_2 (Figure 1). Shoot weight decreased by 20% relative to the control at ambient CO_2 ($P < 0.01$) and by 27% at elevated CO_2 ($P < 0.001$), with the net effect being that the addition of a single aphid and its progeny negated the effects of elevated CO_2 on shoot growth. Root weight was decreased by the addition of *A. pisum* (Figure 2), by 24% at ambient CO_2 ($P < 0.01$) and by 34% at elevated CO_2 ($P < 0.001$). The root:shoot ratio of the plants was unaffected by *A. pisum* at both ambient and elevated CO_2 ($P > 0.05$, Figure 3). *A. pisum* had no effect on the number of open flowers at ambient CO_2 but at elevated CO_2 the number of open flowers decreased by 73% ($P < 0.001$, Figure 4).

When a single fourth instar *A. solani* was added to each bean plant there were also interactions with CO_2 concentration and plant growth. At ambient CO_2 *A. solani* had no effect on bean plants; none of the comparisons were significantly different from the controls. At elevated CO_2, however, *A. solani* caused a decrease in shoot fresh weight of 20% ($P < 0.001$, Figure 1) and root fresh weight decreased by 18% ($P < 0.01$, Figure 2) but the root:shoot ratio was unaffected by elevated CO_2 (Figure 3). The number of flowers on bean plants infested with *A. solani* at elevated CO_2 decreased by 60% ($P < 0.001$, Figure 4).

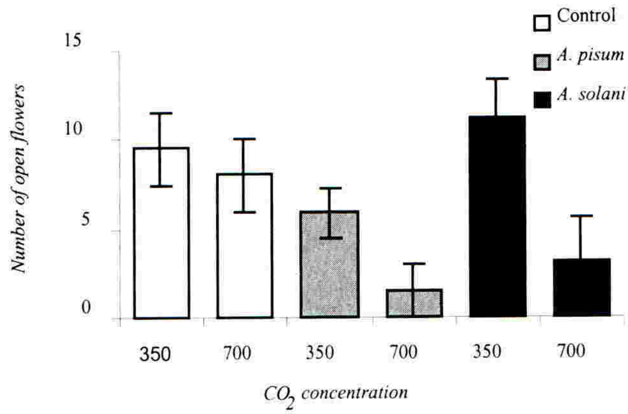

Figure 4. Number of open flowers on bean plants grown at ambient (350 µl l^{-1}) and elevated (700 µl l^{-1}) CO_2. All data are the means of ten replicates and are shown ± one standard error.

DISCUSSION

Elevated CO_2 atmospheres are likely to have a large impact on the pest status of aphids. Although it has been demonstrated that aphids reared on plants growing at elevated CO_2 have higher reproductive rates (Awmack *et al.,* 1996;1997), the effects of increases in

aphid reproduction on plant yield at elevated CO_2 have not previously been investigated. When bean plants were grown without aphids the effect of elevated CO_2 was to increase both shoot and root fresh weight. Elevated CO_2 atmospheres equivalent to those predicted to occur by the year 2100 would therefore seem to be beneficial for bean plants and could lead to an increase in yield.

Elevated CO_2 magnified the effects of aphid infestation on bean plants. A single *A. pisum* added to a twelve day old plant growing at elevated CO_2 was sufficient to cause a decrease in shoot fresh weight of 34% after 20 days because of direct feeding damage by its progeny. These data highlight the importance of aphids as pests for UK agriculture for even if only one nymph survives after spraying its potential to cause damage is immense. The addition of a single aphid was enough to negate the effects of elevated CO_2 on shoot and root fresh weight. Flowering was unaffected by *A. pisum* at ambient CO_2 yet it was reduced by 73% at elevated CO_2 suggesting that the plant is allocating more of its photosynthate to somatic growth than to reproduction. This in turn implies that the aphids are extracting more phloem sap from the plant (both because the percentage decrease in fresh weight is greater at elevated CO_2 and because the plants resource allocation has changed) and this is consistent with the observations that insects increase their intake of food when reared on plants grown at elevated CO_2 to compensate for the increased C:N ratio of the plant tissue (Watt *et al.,*1995).
When *A. solani* was added to the plants there was a major change in its importance as a pest of beans at elevated compared to ambient CO_2. At ambient CO_2, *A. solani* had no significant effects on plant growth compared to the control plants. Although large

populations of *A. solani* are able to develop on bean plants at ambient CO_2 the plant may compensate for the phloem sap lost by their feeding and, at least for 20 days, *A. solani* has no direct effect on yield. However, at elevated CO_2 there was a dramatic shift in the pest status of *A. solani* on beans. Shoot and root fresh weights were significantly less than the control plants, again suggesting that aphids can negate the beneficial effects of elevated CO_2 on the yield of bean plants and reduce the number of open flowers by 60%.

In conclusion, these data suggest that the pest status of the aphids *A. pisum* and *A. solani* could increase if atmospheric CO_2 concentrations continue to rise, and that aphid species such as *A. solani* which do not cause yield losses in our current environment could become serious pests.

ACKNOWLEDGEMENTS

This work was funded by NERC grant GR3/R9675. IACR Rothamsted receives grant-aided support from the Biotechnology and Biological Sciences Research Council of the United Kingdom. CSA would also like to acknowledge the support of the glasshouse staff at IACR Rothamsted.

REFERENCES

Awmack, C S; Harrington, R; Leather, S R; Lawton, J H (1996). The impacts of elevated CO_2 on aphid-plant interactions. In: *Implications of Global Environmental Change" for Crops in Europe.* Aspects of Applied Biology **45,** 317-322

Awmack, C S; Harrington, R; Leather, S R (1997). Host plant effects on the performance of the aphid *Aulacorthum solani* (Homoptera:Aphididae) at ambient and elevated CO_2. *Global Change Biology* **3,** 545-549.

Houghton, J T; Meirs Filho, L G; Callander, B A; Harris, N; Kattenberg, A; Maskell, K (1996). Climate Change 1995: The Science of Climate Change. Cambridge University Press, Cambridge.

Lawlor, D W (1993). Facility for studying the effects of elevated carbon dioxide concentration and increased temperature on crops. *Plant, Cell and Environment* **16,** 603-608.

Osborne, J L; Awmack, C S; Clark, S J; Williams, I H; Mills, V C (1997). Nectar and flower production in *Vicia faba* L. (field bean) at ambient and elevated carbon dioxide. *Apidologie* **28,** 43-55.

Parry, M. L. (1992). The potential effect of climate changes on agriculture and land use. *Advances in Ecological Research* **22,** 63-91.

Watt, A D; Whittaker, J B; Docherty, M; Brooks, G; Lindsay, E; Salt, D T (1995). The impact of elevated atmospheric CO_2 on insect herbivores. In: *Insects in a changing environment.* eds R Harrington & N E Stork, pp. 198-219. Academic Press: London

The effect of elevated atmospheric carbon dioxide on aphids and Collembola: an ecotron experiment

T H Jones, T M Bezemer, K J Knight, J E Newington, L J Thompson
NERC Centre for Population Biology, Imperial College at Silwood Park, Ascot, Berkshire, SL5 7PY, UK

ABSTRACT

Model terrestrial ecosystems were set-up in the Ecotron controlled environment facility. The effects of elevated CO_2 (ambient + 200 μmol mol^{-1}) on (i) the abundance *of Myzus persicae* and one of its parasitoids *Aphidius matricariae*, and (ii) soil-dwelling Collembola species were studied. Aphid abundance was enhanced by elevated CO_2 but parasitism rates remained unchanged. These results suggest that *M. persicae* might increase its abundance under conditions of climate change. There were marked changes in the abundance and species composition of Collembola. These results imply that enhanced atmospheric CO_2 concentrations may have major impacts on soil food chains.

INTRODUCTION

Global levels of atmospheric carbon dioxide (CO_2) are predicted to double in the next century and may consequently increase global temperatures by 2-5 °C (Houghton *et al.*, 1996). Considerable effort has been made to investigate the impact of these changes on the biotic environment and there is now useful information available on how the individual components of ecosystems (e.g. plants, herbivores and decomposers) will respond to predicted climate changes (Bazzaz, 1990; Watt *et al.*, 1995; Ball, 1997; Bezemer & Jones, 1998). Rarely, however, have several key components been studied within one single ecological and interacting system; accordingly it is questionable how adequate these single-species studies are for predicting the long-term impacts of climate change on complex systems (Lawton, 1995; Körner, 1995; Weiner, 1996). The work presented here was a component part of a series of climate change experiments carried out in the Ecotron controlled environment facility where the effects of elevated CO_2 and temperature were studied both separately and in combination. In this study we investigate the effects of elevated CO_2 on above- and below-ground insects (aphids and Collembola) growing within a complex, multi-species model ecosystem.

METHODS AND MATERIALS

The experiment used 16 terrestrial microcosms, each $1m^2$, maintained in the Ecotron controlled environment facility at Silwood Park. Environmental conditions were the same for all chambers: a photo-period of 18 hours, including a gradual dusk and dawn of two hours; average light intensity at canopy (1m from lights) was 294 $\mu ms^{-1}m^{-2}$, temperature varied smoothly between a maximum of 20°C during the day and a minimum of 12°C at night; and relative humidity varied smoothly between a maximum of 70% after watering and minimum of 58%. Eight chambers were maintained at ambient external atmospheric CO_2 concentrations, which fluctuated naturally between 350 and 400 μmol mol^{-1}, and eight were dynamically maintained at 200 μmol mol^{-1} above ambient. The community, established in previously fumigated soil that was relatively poor in nutrients (41.61 ppm nitrogen, 17.63 ppm phosphorus, 12.45 ppm potassium), consisted of primary producers, herbivores, secondary consumers (parasitoids) and soil micro- and macro-organisms (Table 1). All chambers were initiated with the same community and several ecosystem processes were measured over three plant generations. For details see Bezemer *et al.*, (1998), Jones *et al.*, (1998) and Kampichler *et al.*, (1998).

Table 1. Composition of the Ecotron community (cf. species very similar, but not exactly like type-specimen).

Plant species	**Herbivore and parasitoid species**
Cardamine hirsuta	*Helix aspersa* (mollusc)
Poa annua	*Brevicoryne brassicae*, *Myzus persicae* (aphids)
Senecio vulgaris	*Phytomyza* (*Chromatomyia*) *syngenesiae* (leafminer)
Spergula arvensis	*Trialeurodes vaporariorum* (whitefly)
	Aphidius matricariae, *Dacnusa sibrica*, *Encarsia formosa* (parasitoids)
Soil biota	
Lumbricus terrestris (earthworm)	
Porcellio scaber (wood louse)	
Folsomia candida, *Proisotoma minuta*, *Protaphorura cf. armata*, *Pseudosinella alba*, *Sphaeridia cf. pumilis* (Collembola)	
Plus soil bacteria, fungi, protists and nematodes seeded into each chamber by means of a filtered soil leachate (see Jones *et al.*, 1998)	

RESULTS AND DISCUSSION

Aphids

During the period when aphid measurements were being taken (Plant Generation 3), *P. annua* dominated all communities, comprising 93 and 99% of total plant abundance for ambient and elevated CO_2 treatments, respectively. Total final above-ground plant biomass was unaffected ($p > 0.05$) by CO_2 treatment as were leaf carbon and nitrogen contents ($p > 0.05$). Leaves grown in both ambient and elevated CO_2 conditions contained 0.8% nitrogen. Because of the high relative abundance of *P.annua*, insect densities were only recorded on this plant species. Population counts of *M. persicae* were, on average, 300% greater in elevated CO_2 at the start of recording and remained significantly ($p < 0.05$) higher throughout the recording period (Figure 1).

Rates of parasitism were relatively high in both ambient and elevated CO_2. Five weeks after releasing the parasitoid, approximately 30 to 40% of the aphids were parasitised. However, parasitoid efficiency (measured as percentage parasitism) was not affected by the CO_2 treatment.

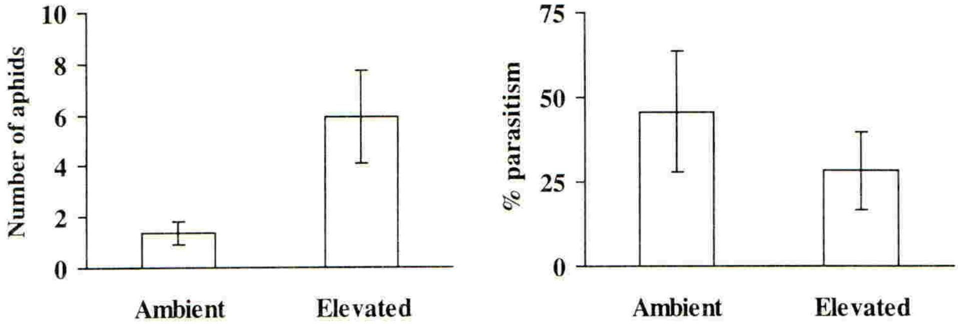

Figure 1. Mean number (±SE) of *Myzus persicae* and mean percentage parasitised (±SE) by *Aphidius matricariae* at the end of the experiment in ambient and elevated CO_2.

M. persicae is an important pest of many agricultural crops. The results suggest that this aphid might increase its abundance under conditions of climate change. We speculate that in elevated CO_2, *M. persicae*, which feeds mainly on young and senescent leaves (van Emden *et al.*, 1969), benefited from enhanced rates of photosynthesis and leaf senescence. The precise change in foliage nutritional quality responsible remains unclear. Other data collected during the course of the Ecotron climate change experiments showed the prevalence of species-specific changes: *Brevicoryne brassicae* populations, for example, at the end of Plant Generation 2 was higher in ambient CO_2 than in elevated CO_2 (T M Bezemer, unpublished data). Further studies, encompassing not only species-specific but also both long-term and community-wide effects, are necessary before we will be able to attempt to move towards general predictions on how global environmental change will affect aphids, and other insect/herbivore, populations.

Collembola

More marked, and previously unreported, effects were observed in the soil biota. At the end of Plant Generation 3, total numbers of Collembola were significantly higher in elevated CO_2. Species composition also changed (Figure 2). *Proisotoma minuta* dominated communities in ambient CO_2, while *Folsomia candida* dominated in elevated CO_2.

That key environmental variables influence soil micro-arthropods is well established (Klironomos *et al.*, 1996). Of these, temperature, water content and pH of soil showed no significant differences between treatments. Nor can change in the collembolan community be attributed to changes in root biomass (Kampichler *et al.*, 1998), or in root quality (as assessed by C:N ratios). Soil microbial biomass was unaffected by elevated CO_2; similar results have been obtained in most (Rice *et al.*, 1994), but not all (Hungate *et al.*, 1996) other studies. Enzymes involved in carbon- and nitrogen-cycling in the soil also showed no significant treatment effects (Kampichler *et al.*, 1998). Only minor differences were found in bacterial taxonomic composition between chambers, and there were no consistent differences between treatments.

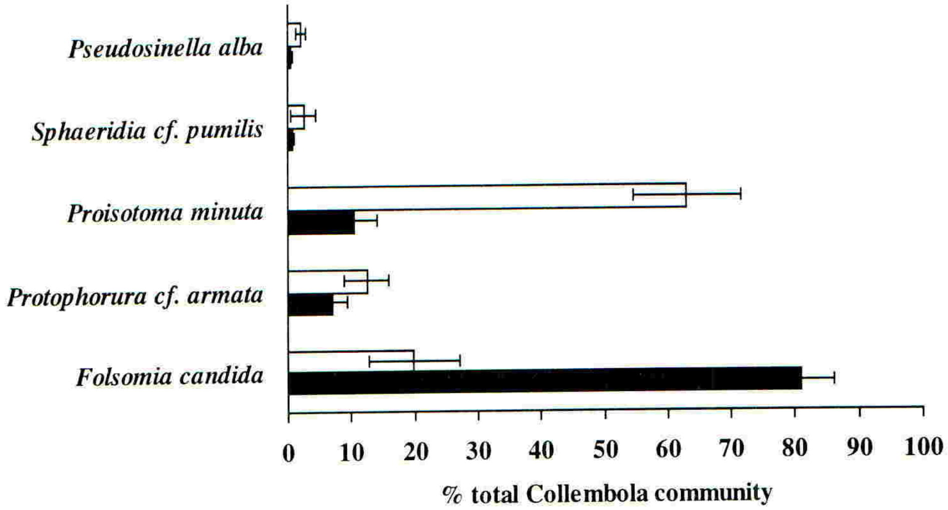

Figure 2: Composition of Collembola community at the end (after 9 months) of an Ecotron experiment. data are given as mean (±SE). There is a significant differences ($p << 0.05$) in the proportion (arc-sine transformed) of each of the five species. Shaded bars represent elevated CO_2 chambers, open bars represent ambient CO_2 chambers.

Fungi, in contrast showed differences between ambient and elevated atmospheric CO_2 treatments. One functional group, cellulose decomposers, had higher biomass in elevated CO_2 treatments (mean (SE) number of colonies (x 10^2 g^{-1} soil) recovered, 17.2 (9.4) (ambient), 35.0 (14.8) (elevated); $p < 0.05$). This probably accounted for the increased decomposition rates of cotton strips placed in the soil (measured as cotton rotting rate, this value was 36.5 cotton strips per year ± 3.53 (elevated) and 26.2 cotton strips per year ±4.20 (ambient); $p < 0.05$). Moreover, fungal taxonomic composition differed between treatments: 14 of the 33 species isolated were common to both, whereas 9 and 10 species were restricted to the ambient and elevated treatments, respectively, a pattern extremely unlikely by chance. These results imply that enhanced atmospheric CO_2 concentrations will have major impacts on soil food chains.

A significant proportion of photosynthetically-fixed carbon is allocated below ground (Ågren *et al.*, 1996); after release much of this carbon becomes available to rhizosphere micro-organisms (O'Neill, 1994). Levels of dissolved organic carbon (DOC) in soil were significantly higher in elevated CO_2 ($p < 0.05$), and soil-water dissolved organic nitrogen (DON) concentrations were higher, almost reaching statistical significance ($p = 0.06$).

These changes are probably sufficient to drive the observed differences in soil fungi. Collembola are major consumers of, and selective grazers on, different species of fungi. We suggest that differences in the collembolan community were driven by differences in the soil fungal assemblages, which in turn were driven by differences in organic substrates derived from higher plants.

These results should not be over-generalized. The Ecotron controlled environment facility houses model ecosystems. Published studies (see above) provide conflicting data on soil microbial responses to elevated CO_2, with the possibility that responses are specific to particular plant species, communities, or ecosystems. Considerably more attention must however be paid to the long-term impact of increasing atmospheric CO_2 concentrations on soil ecosystem processes and soil biota.

Future work

Single species studies, be they on plant or insect, above- and below-ground, are unlikely to provide adequate predictions of the effects of climate change on complex multi-species communities. This study clearly illustrates how many ecosystems interactions and feed-backs, involving fungi, bacteria, meso-fauna, herbivores and nutrients become subject to both direct and indirect effects of CO_2, leading to complex spatially and temporally variable effects. Further experiments designed to predict the effects of enhanced CO_2 on whole communities and ecosystems should abandon the use of small-scale, short-term, single species experiments and instead, go either directly to field manipulation of real ecosystems (Billing *et al.,* 1983; Tissue & Oechel, 1987; Arp *et al.*, 1993) or if this is not possible for reasons of cost or time, to more realistic (and complex) model systems.

ACKNOWLEDGEMENTS

These experiments were partially funded by the NERC TIGER Initiative (GTS/02/646) and could not have been carried out without the invaluable help of the whole Ecotron Team (1994 – 1997).

REFERENCES

Ågren G I; Johnson D W; Kirschbaum M U E; Bosatta E (1996). Ecosystem physiology-soil organic matter. In: *Effects of climate change on grasslands and coniferous forests,* eds: J M Melillo & A Breymeyer, pp. 207-228. Wiley: Chichester.

Arp W J; Drake B G; Pockman W T; Curtis P S; Whigham D F (1993). Interactions between C_3 and C_4 salt marsh plant species during four years of exposure to elevated atmospheric CO_2. *Vegetatio* **104/105**, 133-143.

Ball A S (1997). Microbial decomposition at elevated CO_2 levels: effect of litter quality. *Global Change Biology* **3**, 379-386.

Bazzaz F A (1990). Response of natural ecosystems to rising CO_2 levels. *Annual Review of Ecology and Systematics* **21**, 167–196.

Bezemer T M; Thompson L J; Jones T H (1998). *Poa annua* shows inter-generational differences in response to elevated CO_2. *Global Change Biology* **4**, 687-692.

Billing W D; Peterson K M; Luken J O; Mortensen D A (1984). Interaction of increasing atmospheric carbon dioxide and soil nitrogen on the carbon balance of tundra microcosms. *Oecologia* **65**, 26-29.

Emden H F van; Eastop V F; Hughes R D; Way M J (1969). The ecology of *Myzus persicae*. *Annual Review of Entomology* **14**, 197-270.

Houghton J T; Meiro Filho L G; Callander B A; Harris N; Kattenburg A; Maskell K (eds) (1996). *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment of the Intergovernmental Panel on Climate Change.* 584 pp. Cambridge University Press.

Hungate B A; Holland EA; Jackson R B; Chaplin F S III; Mooney H A; Field C B (1996). The fate of carbon in grasslands under carbon dioxide enrichment. *Nature* **388**, 576-579.

Jones T H; Thompson L J; Lawton J H; Bezemer T M; Bardgett R D; Blackburn T M; Bruce K D; Cannon P F; Hall G S; Hartley S E; Howson G; Jones C G; Kampichler C; Kandeler E; Ritchie D A (1998). Impacts of rising atmospheric carbon dioxide on model terrestrial ecosystems. *Science* **280**, 441-443.

Kampichler C; Kandeler E; Bardgett R D; Jones T H; Thompson L J (1998). Impact of elevated atmospheric CO_2 concentrations on soil microbial biomass and activity in a complex, weedy field model ecosystem. *Global Change Biology* **4**, 335-346.

Klironomos J N; Riling M C; Allen M F (1996). Below-ground microbial and microfaunal responses to *Artemisia tridenta* grown under elevated atmospheric CO_2. *Functional Ecology* **10**, 527-534.

Körner C (1995). Towards a better experimental basis for upscaling plant responses to elevated CO_2 and climate warming. *Plant Cell and Environment* **18**, 1101-1110.

Lawton J H (1995). The response of insects to environmental change. In: *Insects in a changing environment: 17th Symposium of the Royal Entomological Society of London, 7–10 September 1993*, eds: R Harrington & N E Stork, pp. 4-26. Academic Press: London.

O'Neill E G (1994). Responses of soil biota to elevated atmospheric carbon dioxide. *Plant Soil* **165**, 55-65.

Rice C W; Garcia F O; Hampton C O; Owensby C E (1994). Soil microbial response in tallgrass prairie to elevated CO_2. *Plant and Soil* **165**, 67-74.

Tissue D T; Oechel W C (1987). Physiological responses to CO_2 enrichment of *Eriophorum vaginatum* to elevated CO_2 and temperature in Alaskan tussock tundra. *Ecology* **68**, 401-410.

Watt A D; Whittacker J B; Docherty M; Brooks G; Lindsay E; Salt D T (1995). The impact of elevated atmospheric CO_2 on insect herbivores. In: *Insects in a changing environment: 17th Symposium of the Royal Entomological Society of London, 7–10 September 1993*, eds: R Harrington & N E Stork, pp. 198–217. Academic Press: London.

Weiner J (1996). Problems in predicting the ecological effects of elevated CO_2. In: *Carbon dioxide, populations and communities*, eds: C Korner & F A Bazzaz, pp. 431-441. Academic Press: London.

Predicting the impacts of a non-indigenous pest on the UK potato crop under global climate change: reviewing the evidence for the Colorado beetle, *Leptinotarsa decemlineata*

R H A Baker, A MacLeod, R J C Cannon, C H Jarvis, K F A Walters
Central Science Laboratory, Sand Hutton, York, YO41 1LZ, UK

E M Barrow, M Hulme
Climatic Research Unit, University of East Anglia, Norwich, NR4 7TJ, UK

ABSTRACT

Substantial increases in the potential distribution of the Colorado beetle (*Leptinotarsa decemlineata*) were predicted using CLIMEX, a computer program which estimates potential geographical distribution based on climate, loaded with climatic scenarios for 2050 derived from the HadCM2 global climate model greenhouse gas only experiments. In Great Britain, this pest could extend its potential range by 120% with a 400 km extension of its northerly limit to cover over 99% of registered potato production. The difficulties of converting these potential increases in distribution to assessments of economic impact are discussed.

INTRODUCTION

Trade in plants and plant products is regulated to ensure that damaging pests are not introduced to new areas. The World Trade Organisation requires all phytosanitary regulations to be based on risk assessment and various national and international schemes for pest risk analysis (PRA) are now under development, e.g. EPPO (1998). The assessment of climatic suitability, based on current or historical climatic data, is a key element in PRA. Although these data are critical for determining the likelihood of initial establishment, the economic damage caused by a pest introduction to a new area will depend on the degree to which the organism can thrive and spread over time. Future changes in climate should thus also be considered in order to evaluate a pest's long term economic impact.

The Colorado beetle (*Leptinotarsa decemlineata*), which is absent from the UK due to the effective application of plant health policy, is a highly suitable pest for studying the effects of climate change on PRA due to the wealth of information and models which accurately describe its environmental responses and pest potential. Baker *et al.* (1996) compared the establishment potential of this pest in Great Britain (GB) at 10 km resolution for 1961-90 and 2060-70, under the 1.7 - 1.8°C warming predicted by the Hadley Centre global climate model (GCM) transient experiment (UKTR), using a geographical information system (GIS) and CLIMEX, a computer program which estimates potential distribution based on phenology and climatic conditions in a pest's natural distribution (Sutherst & Maywald, 1985). It was shown that the beetle could enlarge its potential range by 102% and that, in the 79,500 km^2 where establishment is already possible, suitability would increase by 76%, reaching levels comparable to areas in Eastern Europe where damage levels are currently high.

This paper updates these predictions using data derived from the second Hadley Centre coupled ocean-atmosphere GCM (HadCM2) and an enhanced version of CLIMEX (Skarratt *et al.*, 1995). HadCM2 is an improvement over UKTR primarily because historical climate is modelled over several centuries, ensuring a steady state between oceanic and atmospheric systems and a "warm start" for the climate change experiments (Johns *et al.*, 1997).

Whichever climate change scenario is used, an increase in thermal budget during the growing season is likely to favour the development of warmth-loving pests, increasing their potential economic impacts. However, the precise nature and extent of this impact is very difficult to quantify. This paper reviews the data and analyses required to prepare climate change impact scenarios for *L. decemlineata* in the key regions where potatoes are cultivated in GB.

MATERIALS AND METHODS

We selected the HadCM2 experiments in which a 1% per year compound increase in greenhouse gas forcing was applied. Four equally valid experiments (HCGG1-4) were conducted, varying only in their initial start date. The scenarios predict climate change at 2050, representing a mean for the 30-year period, 2035-64, with global mean CO_2 concentrations reaching 515 ppm*V*. Compared to the 1961-90 period, an average global mean warming for HCGG1-4 of 1.91°C (range 1.88-1.97) is predicted, with Europe warming on average by 2.30°C (range 2.09-2.57). The HadCM2 experiments which incorporated the direct effects of sulphate aerosols on climate and indicated a reduced rate of warming (Mitchell & Johns, 1997) were not used because the level of sulphate forcing is most likely incorrect. The rise in sulphur dioxide emissions was overestimated and predictions of both the direct and indirect influence of sulphate aerosols in climate cooling have now been revised (Hulme & Jenkins, 1998).

The HadCM2 results, at an original spatial resolution of 2.5° latitude x 3.75° longitude, were interpolated using a simple Gaussian space-filtering routine to a 0.5° x 0.5° resolution for the European area. In order to represent locations where potatoes are cultivated, the scenario data were applied to the 1961-90 minimum altitude climate data (Hulme *et al.*, 1995) for those grid cells representing land in Europe. Vapour pressure was converted to relative humidity and, together with mean monthly rainfall and temperature minima and maxima, reformatted for input to CLIMEX. Standard CLIMEX parameters for *L. decemlineata* were applied, with the day length and temperature triggering diapause set at 15 h and 6°C respectively. An ecoclimatic index (EI), a measure of climatic suitability estimated by CLIMEX, was calculated for each scenario grid cell and imported to a GIS for display. Data from GB were analysed in detail.

RESULTS

Figures 1 and 2 show European EIs for *L. decemlineata* under current (1961-90) and future climate (2035-64), represented as HCGGX, which is a separately derived mean of the four greenhouse gas forcing experiments (HCGG1-4). Table 1 summarises the results for GB.

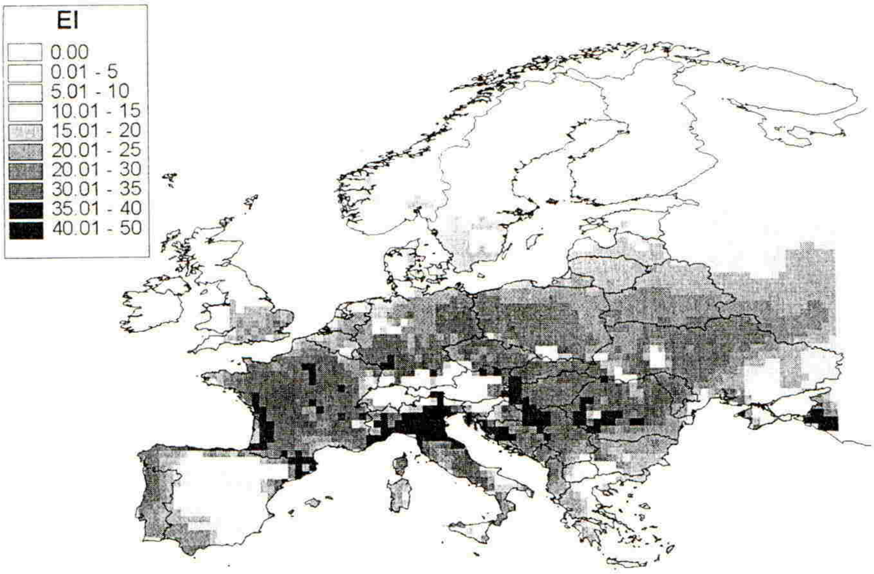

Figure 1. *Leptinotarsa decemlineata* potential distribution predicted by CLIMEX under current (1961-90) climate. The Ecoclimatic Index (EI) is a measure of the climatic suitability of the location for permanent colonisation. Thus temporary, economically damaging, outbreaks may occur even where the EI is zero.

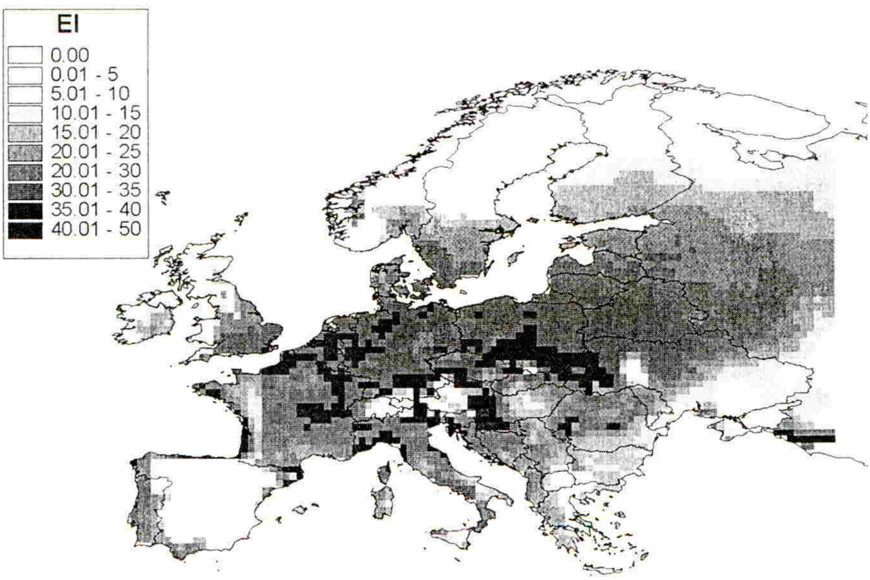

Figure 2. *Leptinotarsa decemlineata* ecoclimatic indices (EI) predicted by CLIMEX under the mean HadCM2 greenhouse gas climate change scenario.

Table 1. The effect of climate change on the suitability of 0.5° latitude x 0.5° longitude grid cells in Great Britain for *Leptinotarsa decemlineata* establishment expressed as ecoclimatic indices (EI)

	Climate Change Scenarios (see text for abbreviations)					
	Base	HCGG1	HCGG2	HCGG3	HCGG4	HCGGX
Number of cells with EI = 0	144	66	69	81	54	65
Number of cells with EI > 0	66	144	141	129	156	145
Number of cells with EI ≥ 20	21	70	68	71	79	73
Maximum EI	25	37	34	35	36	36
Mean EI	5	13	12	14	13	12

DISCUSSION

Climate change and potential distribution

Under the HCGG scenarios, the CLIMEX predictions show that, by 2050, there will be 63-90 (mean 79) additional grid cells climatically suitable for *L. decemlineata* colonisation in GB - potentially extending its range by 95 - 136% (mean 120%). This represents a mean increase of 3.5° latitude (approximately 400 km) in the northern limit of its distribution to include the substantial areas of potato production in Eastern Scotland. Under these scenarios, only conditions where the potato crop is grown in the extreme north of Scotland and the islands (0.6% of the area under registered potato production) are likely to be unsuitable.

Economic impact

L. decemlineata "remains worldwide the most devastating defoliator of potatoes" (Hare, 1990) and its potential to become widespread throughout the main potato growing areas of GB is cause for considerable concern. There are two main methods which can be used to quantify the potential economic impact of this pest. The first is based on crop yield loss models, the second on comparisons with areas where the high EIs predicted for GB under climate change currently occur.

Nault & Kennedy (1998) showed that reliable relationships cannot readily be established between the defoliation caused by *L. decemlineata* and yield loss because of wide variations between potato varieties and crop yield, the difference in vulnerability of each crop phenological stage and the paucity of data. These problems will have to be overcome before a biologically-realistic, statistically-robust model can be constructed.

Variations in the effectiveness of control, particularly in the USA where insecticide resistance is widespread, make comparisons of high EIs with reports of economic damage difficult to make. The most detailed recent European studies have been made in Poland, where EIs range from 20-29 and yield losses from *L. decemlineata* were reported to be 5% with control and 40% without, though there was considerable annual variation (Oerke *et al.*, 1994). The HCGG scenarios produced substantial increases in EI for GB, with a mean of 73 grid cells exceeding 20, including almost all of southern and eastern UK where the majority of the potato crop is grown. In 23 of these cells, there are sufficient degree days for two generations to develop. Such increases cannot readily be compared with previous studies (Baker, 1996; Baker *et al.*, 1996) which used the earlier version of CLIMEX without the improved representation of diapause. The new version calculates much higher values of EI in southern UK and central Europe but predicts the same northern limit of permanent *L. decemlineata* establishment. This limit is dependent on the mean 1961-90 thermal budget during development. A sequence of warm summers would still enable temporary establishment and serious economic damage to occur in areas further north, such as Scotland and southern Finland.

Translating predicted yield loss estimates to measures of economic impact, whether derived from yield loss models or EI comparisons, requires detailed data on seed and ware potato production, consumption and trade. Some of these data can be obtained with considerable accuracy from crop protection literature and producer gross margin budgets, whereas other data have to be estimated with a wide margin for error. Thus, based on 1979 prices, Bartlett (1980) calculated that, living with *L. decemlineata*, producers in England and Wales would incur additional labour, pesticide and application costs of £16/ha. However, the number of sprays and the area covered would vary according to region and the weather, so annual direct costs could range from £0.4 - £2.7 million. Non-commercial and indirect costs were even more difficult to assess and were estimated as 70% of direct costs.

The difficulties faced by those estimating economic impacts are compounded under climate change. Even if the errors inherent in the HadCM2 and CLIMEX models are ignored, substantial changes can be expected in potato crop distribution and production (Davies *et al.*, 1997) and in pest management, including the more effective implementation of IPM and the development of potato varieties resistant to *L. decemlineata* or containing genes coding δ-endotoxins of *Bacillus thuringiensis* (Whalon & Ferro, 1998).

The implications of these results for the quarantine (Plant Health) services in the UK, are that *L. decemlineata* will become an even greater threat. The increased suitabilities for permanent occupation under the different climate change scenarios, suggest that the probabilities for the survival and persistence of a colonising population of *L. decemlineata* in the UK will increase substantially. Thus, there will be a requirement for even more vigilance, coupled with an ability to respond rapidly to any outbreaks. The likelihood of colonisation events occurring, through migration as well as introduction by man, could also increase as a result of larger populations to the south of the UK.

ACKNOWLEDGEMENTS

We thank A W Pemberton, P W Bartlett and S A Hill for comments on this paper which was funded by MAFF, Plant Health Division. The HadCM2 GCM data used to construct the climate change scenarios described here were supplied by the Climate Impacts LINK

Project, funded by the UK Department of the Environment, Transport and the Regions (Contract Reference EPG 1/1/16). The climate change scenarios were originally constructed for the CLIVARA project (Climate Change, Climatic Variability and Agriculture in Europe) which was funded by the Commission of the European Communities Environment Programme (Contract number: ENV4-CT95-0154).

REFERENCES

Baker R H A (1996). Developing a European pest risk mapping scheme. *EPPO Bulletin* **26**, 485-494.

Baker R H A; Cannon R J C; Walters K F A (1996). An assessment of the risks posed by selected non-indigenous pests to UK crops under climate change. *Aspects of Applied Biology* **45**, 323-330.

Bartlett P W (1980). Interception and eradication of Colorado beetle in England and Wales, 1958 – 1977. *EPPO Bulletin* **10**, 481-189.

Davies A; Jenkins T; Pike A; Shao J; Carson I; Pollock C J; Parry M L (1997). Modelling the predicted geographic and economic response of UK cropping systems to climate change scenarios: the case of potatoes. *Annals of Applied Biology* **130**, 167-178.

EPPO (1998). Pest risk assessment scheme. *EPPO Bulletin* (In Press).

Hare J D (1990). Ecology and management of the Colorado potato beetle. *Annual Review of Entomology* **35**, 81-100.

Hulme M; Conway D; Jones P D; Jiang T; Barrow E M; Turney C (1995). Construction of a 1961-1990 European climatology for climate change modelling and impact applications. *International Journal of Climatology* **15**, 1333-1363.

Hulme M; Jenkins G J (1998) *National climate change scenarios for the UK*. A report for the UK Climate Impacts Programme, Climatic Research Unit, University of East Anglia, Norwich, UK, (In Press).

Johns T C; Carnell R E; Crossley J F; Gregory J M; Mitchell J F B; Senior C A; Tett S F B; Wood R A (1997). The second Hadley Centre coupled ocean-atmosphere GCM: model description, spinup and validation. *Climate Dynamics* **13**, 103-134.

Mitchell J F B; Johns T C (1997). On modification of global warming by sulphate aerosols. *Journal of Climate* **10**, 245-267.

Nault, B A; Kennedy G G (1998). Limitations of using regression and mean separation analyses for describing the response of crop yield to defoliation: a case study of the Colorado potato beetle (Coleoptera: Chrysomelidae) on potato. *Journal of Economic Entomology* **91**, 7-20.

Oerke E-C; Dehne H-W; Schönbeck F; Weber A (1994). *Crop Production and Crop Protection. Estimated Losses in Major Food and Cash Crops*. Elsevier: Amsterdam.

Skarrat D B; Sutherst R W; Maywald G F (1995). *CLIMEX for Windows Version 1.0. User's Guide*. CSIRO and CRC for Tropical Pest Management. St. Lucia. Australia

Sutherst R W; Maywald G F (1985). A computerised system for matching climates in ecology. *Agriculture, Ecosystems and Environment* **13**, 281-299.

Whalon M; Ferro D (1998). Bt-potato resistance management. In: *Now or never: serious new plans to save a natural pest control*, eds M Mellon & J Rissler, pp. 107-135. UCS Publications: Cambridge, Massachusetts, USA.