PHYSICO-CHEMICAL PROPERTIES OF FUNGICIDES IN RELATION TO EFFECTS ON TAKE-ALL

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ABSTRACT

Some ergosterol biosynthesis inhibitors are among the most toxic fungicides to the take-all fungus (*Gaeumannomyces graminis* var. *tritici*) *in vitro*, but as soil treatments they performed inadequately in the field, mainly because of inappropriate distribution in soil. In agar plate tests the order of toxicity and also lipophilicity of three of these fungicides was penconazole > nuarimol >> PP969. In tests which measured fungitoxicity of vapour alone, penconazole was ten times more toxic than PP969 when evaporating from a treated glass surface and twenty times as toxic when evaporating from treated soil; nuarimol was not active, being involatile. In pot tests where the chemicals were uniformly distributed throughout the soil the three fungicides were similarly effective against take-all on the roots of living wheat plants. Where alternate, 2 cm deep, layers of treated and untreated soil were used, the order of effectiveness was PP969 >> nuarimol > penconazole. Hence the dominant property where fungicides were unevenly distributed in the soil, was not volatility but polarity. The greater availability of PP969 for redistribution in soil water, due to its lower adsorption by soil, outweighed its poorer intrinsic toxicity.

INTRODUCTION

Take-all, caused by *Gaeumannomyces graminis* var. *tritici*, is the most important U.K. cereal disease which is not presently controlled commercially by fungicides. During a series of experiments the ergosterol biosynthesis inhibitor (EBI), nuarimol, emerged as the best of a number of fungicides applied to soil for controlling the disease in wheat (Bateman 1984). While nuarimol consistently decreased take-all and sometimes increased yields, it appeared to be phytotoxic at the higher rates tested (2.2 to 4.4 kg/ha) and had doubtful economic benefits at lower rates (up to 1.1 kg/ha). Improvements in the performance of soil-applied fungicides are now being sought by studying EBI fungicides with different physical properties.

The most effective soil fungicides for take-all control are likely to be those with physical properties which allow them to redistribute through the soil and reach the pathogen or infection site with maximum efficiency. Diffusion coefficients of fungicides in the soil air phase are approximately 10^4 times greater than those in soil water (Hartley 1976). Provided that the water-air partition coefficient is less than 10^4, then air phase diffusion is expected to be more important than water phase diffusion. Initially, therefore, the behaviour in soil of relatively volatile fungicides was examined.

MATERIALS AND METHODS

Chemicals

The fungicides nuarimol, penconazole and PP969 were used as technical grade material (97.9, 98.5 and 91.2% pure respectively) and as wettable powders with, respectively, 8%, 10% and 50% active ingredients. PP969 is (5RS, 6RS)-6-hydroxy-2,2,7,7-tetramethyl-5-(1,2,4-triazol-1-yl) octan-3-one.

Physical properties

Lipophilicity was measured as the octan-1-ol water partition coefficient (K_{ow}) by the method of Fujita *et al.* (1964). Technical grade fungicide was dissolved in octanol saturated distilled water (20 ml: pH 7.45) at 4 μg/ml. Water saturated octanol (0.2 ml) was added, the mixture gently inverted fifty times and then centrifuged. Fungicide concentrations in both aqueous and octanol phases were measured by h.p.l.c. and further compared with concentrations in aqueous solutions treated similarly but without octanol. Values given are the mean of three replicates.

The vapour pressure of PP969 was determined by the method of Dobbs & Grant (1980) from the rate of evaporation from glass microscope slides, calibrated with the given vapour pressure and rate of evaporation of penconazole. Fungicides were quantitatively analysed using h.p.l.c.

Soil adsorption coefficients (k_d) were calculated from octanol-water partition coefficient and soil organic matter content (2.6%) using the equation of Briggs (1981). Air-wet soil partition coefficients were calculated as those in Nicholls *et al.* (1981).

TABLE 1

Physical properties of fungicides

	Vapour pressure (μPa)	Lipophilicity $\log_{10} K_{ow}$	Adsorption kd.(calculated)	Air/wet soil partition (calculated)
PP969	2.1×10^3 @ 20°C	1.74 (1.95)[c]	0.9	2.7×10^{-7}
Nuarimol	<2.6 @ 25°C[a]	2.98	4.0	1.6×10^{-9}
Penconazole	2.1×10^2 @ 20°C[b]	3.20	5.2	6.5×10^{-8}

[a] Worthington (1979)
[b] Eberle *et al.* (1983)
[c] Shephard, M.C. (1985)

Intrinsic toxicities *in vitro*

Toxicities of the fungicides to *G. graminis* var. *tritici* were compared by growing colonies from 4 mm agar culture discs placed on potato dextrose agar (PDA) containing the fungicides. The technical grade materials were incorporated by dissolving in methanol and mixing with molten PDA cooled to 50°C, at 1 ml methanol per 100 ml PDA, before pouring into plastic Petri dishes. Agar without fungicide was treated only with methanol. By measuring colony growth after 4 to 6 days at 20°C on up to five concentrations of each fungicide in threefold dilutions between 0.01 and 0.81 μg/ml, with fifteen replicate colonies for each fungicide concentration, the concentration required to decrease growth in colony diameter by 50% (EC_{50}) was determined using Wadley's analysis after transformation to probits or logits. Average EC_{50}s were calculated from eleven experiments, all of which included nuarimol; penconazole and PP969 were each used in four. Standard errors were always less than x/÷ 1.4 of the EC_{50} value.

Vapour activity *in vitro*

Vapour activity of the fungicides was determined in similar experiments in which the fungal colonies were grown on PDA in glass Petri dishes. Each fungicide dissolved in acetone was placed in the lids of five of the dishes at 20 ml per lid. The acetone was then evaporated off in a sterile air flow and the lids replaced on the dishes, each already inoculated with three culture discs. Acetone alone was used in control plates. In some experiments the acetone solutions were applied to soil placed in a layer in the lid of each Petri dish (20 g moist sterile clay loam per dish). All dishes were sealed with plastic tape and incubated, inverted, for 4 to 6 days, when growth in colony diameters were measured.

Pot experiments with uniformly treated soil

Fungicidal activity in soil was determined in two experiments by growing wheat plants, cv. Avalon, in plastic pots, measuring 10 cm in diameter and 10 cm deep, containing a 1:1 loam-sand mixture. Each treatment had five replicate pots, each sown with seven seeds. The pots were inoculated throughout (except for control pots) with cultures of *G. graminis* var. *tritici* on sterilised oat grains at 7.5 g inoculum per kg soil. The soil was treated with fungicides by mixing either with wettable powder fungicides or with technical grade fungicide dissolved in acetone. With the latter method an acetone solution was mixed with a small quantity of dry soil and the acetone evaporated off, before mixing with the bulk of the soil.

Pot experiments with layered fungicide treatments

Two 2-cm-deep bands of treated soil were placed in each pot, separated by a 2 cm band of untreated soil. The uppermost treated band was 1.5 cm below the seed, which was sown 1 cm below the surface of a covering layer of untreated soil, in all pots. All treated pots contained fungicides at a concentration of 3 mg a.i./kg. Pots with untreated soil only were used for comparison. The sown pots were kept in a growth room, with 10 h day length and day/night temperatures of 15°/10°C, for 5 weeks, when the plants were removed and the root systems washed free of soil and examined under water against a white background to determine take-all infection. The percentages of seminal roots infected were calculated.

RESULTS AND DISCUSSION

In agar plate tests the order of toxicity was penconazole > nuarimol >> PP969 (Fig. 1) with penconazole being seventeen times more active than PP969. This is also the same order as that of lipophilicity (Table 1), although the very different structures of the chemicals prevent conclusions being drawn directly from this coincidence, but penconazole was the most intrinsically active chemical tested.

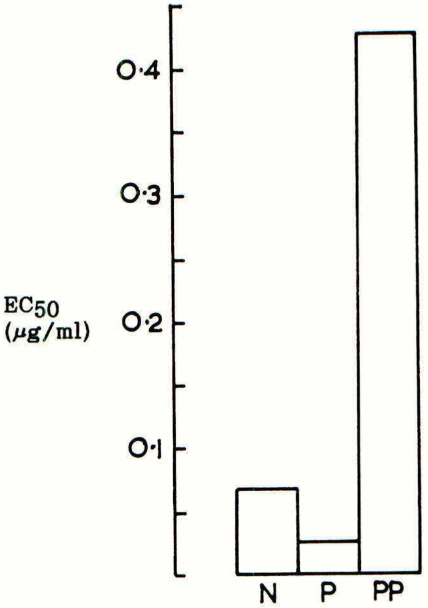

Fig 1. Concentration of nuarimol (N), penconazole (P) and PP969 (PP)in agar required to cause 50% suppression of colony growth (EC_{50}) of *Gaeumannomyces graminis* var. *tritici*.

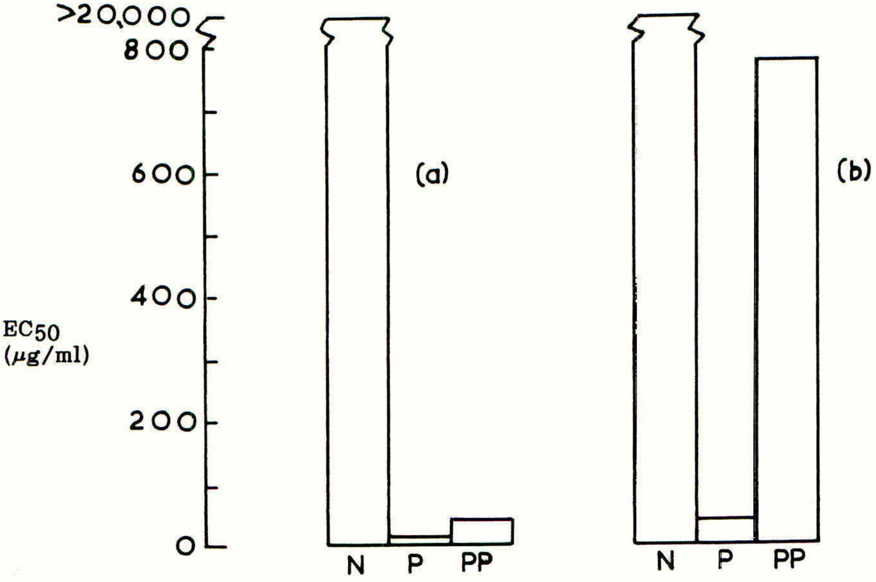

Fig. 2. Concentrations of nuarimol (N), penconazole (P) and PP969 (PP) required to cause 50% suppression of colony growth (EC_{50}) of *Gaeumannomyces graminis* var. *tritici* in Petri dishes, by vapour activity from (a) glass and (b) moist soil.

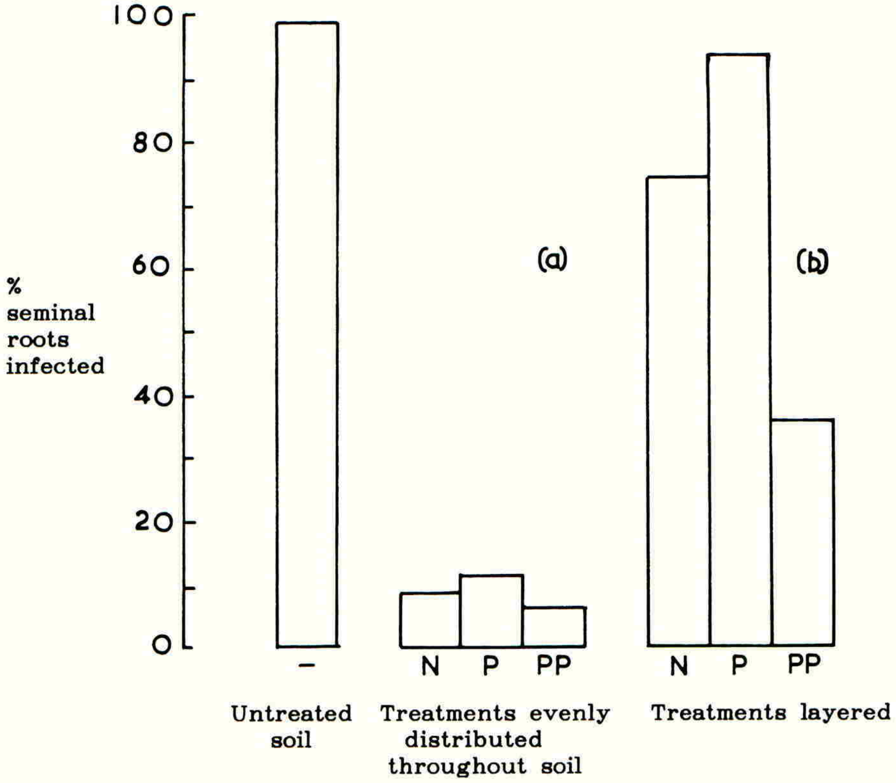

Fig. 3. Effects on take-all of uniform or layered distribution of nuarimol (N), penconazole (P) and PP969 (PP) in soil in pot tests.

Toxicity measured after uptake of vapour alone from a treated glass surface (Fig. 2a) showed penconazole to be only ten times more active than PP969, the vapour pressure of the latter being greater than that of penconazole (Table 1). When toxicity was measured after uptake of vapour alone from treated moist soil, penconazole was twenty times more active than PP969. The effectiveness of PP969 relative to penconazole was greater after uptake from glass than from moist soil. This is because evaporation from glass is determined solely by vapour pressure, which for PP969 is ten times that for penconazole, whilst the relevant physical property in evaporation from soil is the air/wet soil partition coefficient, which is only four times that for penconazole (Table 1). The greater lipophilicity of penconazole resulted not only in more adsorption by soil but also a greater tendency to partition into the air phase from water, the latter effect outweighing the former. In these tests nuarimol was not active, being involatile.

In pot tests where the fungicides were initially uniformly distributed throughout the soil, all compounds were equally effective, probably because *in vitro* activity, which increased with lipophilicity, was balanced by adsorption to soil which also increases with lipophilicity (Fig. 3a and Table 1). Not surprisingly, because the fungicides were uniformly distributed to begin with, volatility was not an advantageous property in this test.

In the field it is difficult to obtain uniform distributions of fungicides. Uneven distribution was simulated in pot tests by having alternate layers of treated and untreated soil. The order of toxicity was PP969 > nuarimol > penconazole, the reverse of *in vitro* activity and lipophilicity. The results are averages of three experiments, in each of which the results of individual treatments were statistically significant (at $\underline{P} = 0.05$) when analysed as percentages transformed to arcsines. The same order was found whether the chemical was applied in a formulation or as technical grade material. The least intrinsically active compounds which are least strongly adsorbed by soil were most effective. Penconazole, which was most active by fumigant action was less effective than the involatile nuarimol; hence fumigant action is probably not the dominant effect where fungicides are unevenly distributed. The most polar chemical (PP969) was most effective indicating that its greater availability for redistribution in soil water outweighed a lesser intrinsic toxicity to the fungus. Graham-Bryce (1969) has shown that diffusion of involatile polar chemicals in soil water increases markedly with increasing soil water content, but diffusion of volatile chemicals is insensitive to such changes. Water contents were high in the above pot experiments and will usually be close to field capacity in the field during autumn and winter in the U.K. The high vapour pressure of PP969 and its polarity might be effective in relatively dry periods in autumn and spring, provided sufficient fungicide persists.

These fungicides are currently treatments in rigorous field experiments (Hornby *et al.*, 1984) which should test the predictions made from this laboratory work, and highlight any lack of persistence of the compounds.

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INTERACTION OF FLUORESCENT PSEUDOMONADS, HYPHAE OF THE TAKE-ALL FUNGUS AND GROWTH OF WHEAT ROOTS IN SOIL

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ABSTRACT

The effect of seed treatment with fluorescent pseudomonad bacteria on growth of wheat roots and length of black runner hyphae of the take-all fungus on wheat roots was measured using a line intercept method. In natural soil, the length and density of hyphae and the length and proportion of root colonized by hyphae all increased with time. In steamed soil where root growth was more rapid, the total length of hyphae and total length of root colonized by hyphae increased with time while the density of hyphae and proportion of the root system colonized by hyphae decreased. Treating seed with fluorescent pseudomonad bacteria reduced the density of hyphae and proportion of root system colonized by hyphae in both natural and steamed soil.

INTRODUCTION

Take-all is a serious wheat disease caused by the soil-borne fungus *Gaeumannomyces graminis* var. *tritici* (Ggt). Fluorescent pseudomonad bacteria applied to soil (Smiley 1978), wheat roots (Sivasithamparam & Parker 1978) or wheat seed (Weller & Cook 1983) can reduce the severity of the disease. The effect of these bacteria on Ggt is usually determined by examining the interaction between the two organisms *in vitro* using a dual culture agar assay or by measuring changes in expression of symptoms of take-all in wheat plants *in vivo*. Direct evaluations of the response of the pathogen to the bacteria can be made using the *in vitro* assay, but agar tests do not necessarily indicate how two organisms will interact in the complex environment of the wheat rhizosphere. *In vivo* assays do not distinguish between disease reduction caused by changes in host susceptibility and reduction caused by suppression of growth of the pathogen.

Measurements of growth of the black runner hyphae (brh) of Ggt on wheat roots in relation to suppression of disease have been made by Smiley (1978) who measured the linear extension of hyphae from a fixed inoculum source, and Wildermuth & Rovira (1977), who calculated the density of hyphae on sections of seminal roots using the line intercept method. The first method does not allow for branching of hyphae and it cannot be used to measure colonization of roots from inoculum distributed throughout soil. The second method overcomes these problems, but as only small sections of the roots are examined, the density of hyphae on the root system as a whole is not measured, nor is there any indication of the proportion of the root system colonized by hyphae. Neither method measures the length of the roots and so treatment effects on root growth and the effect of root growth on the extent of colonization of roots by hyphae cannot be assessed.

Smiley (1978) measured the effect of fluorescent pseudomonad bacteria applied to soil on the growth of hyphae of Ggt down roots from an agar plug placed below the wheat seed. Application of bacteria to seed will probably be necessary if they are to be used as commercial biological control agents (Weller & Cook 1983), and because take-all inoculum in the field is distributed throughout the soil. It is therefore important to determine how bacteria seed coatings will affect colonization of wheat roots by hyphae of Ggt growing from inoculum dispersed throughout soil.

In this paper we describe a method of estimating the length and density of brh of Ggt on roots of wheat grown in infested soil. The method encompasses the examination of the whole root system and enables root growth to be calculated. It was used to examine the effect of two isolates of fluorescent pseudomonad applied to wheat seed grown in natural and steamed soil.

MATERIALS AND METHODS

Organisms

Pseudomonas fluorescens Isolate 2-79 (NRRL-B15132) was obtained from D. Weller (USDA, Pullman, Washington). Isolate D018 was supplied by N. Charigkapakorn of the University of Western Australia. It was isolated from take-all lesions on roots of wheat grown in soil from Lake Grace, Western Australia. The Ggt isolate used (WUF-2) was isolated from roots of wheat grown in soil from Gabalong, Western Australia (Fang & Parker 1981).

The bacteria were grown for 48 h on King's Medium B Agar (KMB) (King *et al.* 1954), suspended in 1.0% methylcellulose and applied to surface sterilized wheat seed (cv. Gamenya). This resulted in approximately 10^8 colony forming units (cfu) of bacteria/seed. Control seeds were treated with methylcellulose alone as described by Weller & Cook (1983). The inoculum of the pathogen was prepared by inoculating sterilized millet seeds (50 cm^3 of seeds in 40 ml water) with agar pieces from an actively growing colony of Ggt. The millet seeds were incubated at room temperature (22-25°C) for 21 d, dried in a laminar flow cabinet and stored at 4.4°C until use.

Soil

Soil from Gabalong (a sandy loam soil with a pH of 5.9 (2 parts soil to 5 parts water by weight) was used in both experiments. The soil was air-dried and sieved (4.0 mm). Natural, untreated soil was used in Experiment I, while in Experiment II it was steamed (60°C for 1 h) and redried before use. Each pot received 250 g of soil and soil moisture was maintained at 60% of water-holding capacity throughout both experiments. The pots were placed in a temperature-controlled bath at 17°C.

Experimental Design

Experiment I was a factorial combination of two seed treatments (isolate D018 v. no bacteria), three levels of Ggt inoculum (0, 5 and 10 millet seeds/pot) and four harvest dates (14, 21, 28 and 42 d after sowing). Five wheat seeds were planted in each pot and there were four replications of each treatment. The infested millet seed was placed 5 cm below the surface of natural (untreated) soil.

Experiment II was a factorial combination of three seed treatments (isolate D018, isolate 2-79 and uninoculated control), two levels of Ggt inoculum (0 and 8 millet seeds/pot) and four harvest dates (16, 24, 32 and 40 days after sowing). Three wheat seeds were planted in each pot. There were three replications of treatments without inoculum of Ggt and seven of treatments with Ggt inoculum, which was mixed throughout the soil.

Assessment

At each harvest the roots were washed and stored in 70% ethanol at 4.4°C until they could be examined. In Experiment I the roots of all five plants were bulk and examined together, while in Experiment II the roots of each plant were examined separately. The roots were cut into segments (c 1.0 cm) and dispersed in the bottom of a rectangular dish (12.5 x 7.0 cm). Twenty-five randomly-placed fields of view had been marked on the bottom of the dish. A blue background made counting roots and brh on roots easier. Each field was examined at 31.5x magnification using a dissecting microscope with a hairline in the eyepiece. Numbers of roots, brh on roots, roots with brh and roots with blackened stele which intercepted the hairline in each field were counted. The numbers for all 25 fields were summed and the total length of root, brh, roots with brh and roots with blackened stele was calculated using Newman's (1966) formula for estimating root length; $L = NA/2H$, where N = number of intercepts, A = area of dish, H = total length of hairline. The density of hyphae on each root system was calculated using the formula L brh/L of root. The proportion of root system colonized by hyphae and the proportion with blackened stele were calculated using the formulae: L of root with brh/L of root and L of root with blackened stele/L of root.

The data were transformed where necessary using a square root transformation and Genstat V (Anonymous 1977) used for analysis of variance.

RESULTS

Effects on the host

Germination of seeds was not affected by the bacteria in natural soil. In steamed soil seeds treated with bacteria had lower % germination ($p < 0.05$) than untreated seeds. Seeds treated with methylcellulose alone, methylcellulose containing isolate D018 or isolate 2-79 had 100%, 76.2% and 91.7% germination respectively. Increase in root length with time was greater in steamed soil than in natural soil (Fig. 1). Root length decreased ($p < 0.05$) with increasing levels of Ggt inoculum in natural soil. The average root length was 969, 936 and 904 mm/plant for plants grown in soil with 0, 5 and 10 millet seeds/pot respectively. Ggt inoculum did not ($p < 0.05$) affect root length in steamed soil. Coating seeds with bacteria did not affect ($p < 0.05$) root length in natural soil (Fig. 1). In steamed soil, however, plants grown from seeds coated with bacteria had longer roots ($p < 0.05$) at 40 d than plants grown from seed treated with methylcellulose alone (Fig. 1).

Hyphal length and hyphal density

The total length and density (mm hyphae/mm root) of hyphae increased ($p < 0.01$) with time in natural soil (Fig. 2A & C). In steamed soil, the total length of hyphae in all treatments increased until day 32 ($p < 0.01$) (Fig. 2B), while the density of hyphae on roots from seed coated with bacteria decreased with time and the density of hyphae on roots grown from control seed varied (Fig. 2D). In natural soil, both the total length of hyphae and the density of hyphae increased ($p < 0.01$) with increasing levels of millet-seed inoculum. Treating seed with bacteria reduced ($p < 0.05$) the total length of hyphae in steamed soil but not in natural soil (Fig. 2A & B). Treating seed with bacteria reduced ($p < 0.05$) the density of hyphae, the effect being greatest at 28 and 32 d in natural and steamed soils respectively (Fig. 2C & D).

Root length colonized by hyphae

The total length of root colonized by hyphae and the proportion of root length colonized by hyphae increased ($p < 0.01$) with time in natural soil (Fig. 3A & C). In steamed soil the total length of root colonized by hyphae increased ($p < 0.01$), while the proportion of root length colonized decreased ($p < 0.01$). Both the total length of root colonized by hyphae and

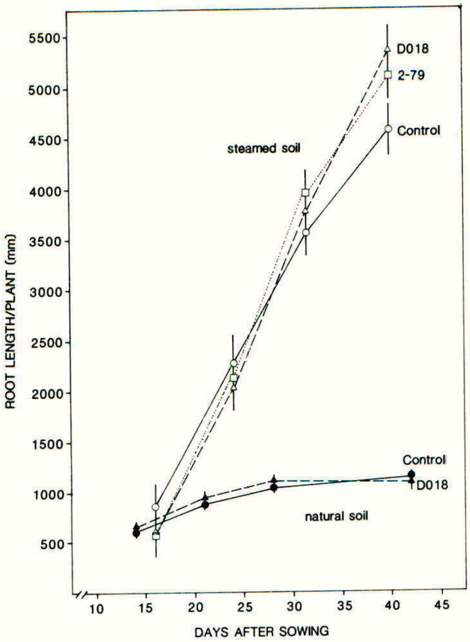

Fig. 1. Effect of fluorescent pseudomonads on the growth of wheat roots in natural or steamed soil.

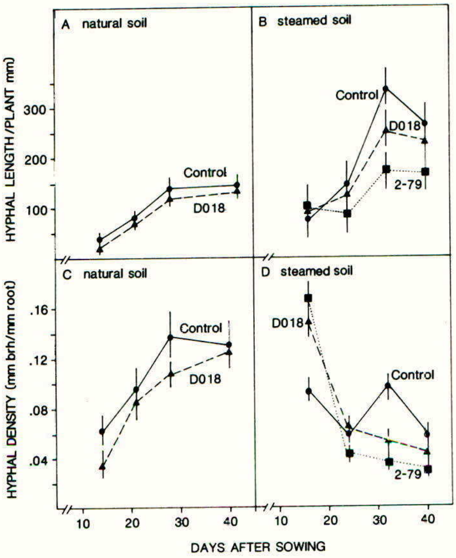

Fig. 2. Effect of fluorescent pseudomonads on the growth of black runner hyphae (brh) on roots of wheat grown in natural or steamed soil.

the proportion of root colonized by hyphae increased with increasing levels of Ggt inoculum in natural soil. The total length of root colonized by hyphae was reduced ($p < 0.05$) by treating seed with bacteria in steamed soil (Fig. 3B) but not in natural soil (Fig. 3A). The proportion of root length colonized was reduced ($p < 0.05$) by treating seed with bacteria in both soils (Fig. 3C & D).

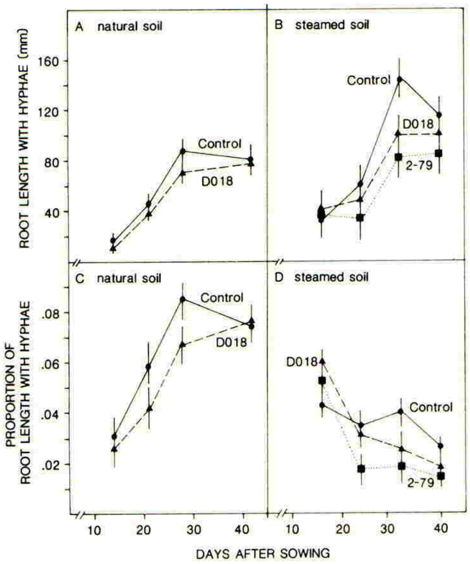

Fig. 3. Effect of fluorescent pseudomonads on the colonization of wheat roots by black runner hyphae (brh) in natural or steamed soil.

Root length with blackened stele

The extent of stelar blackening was low (< 10%) in both soils. Roots with blackened stele did not become apparent until day 28 in natural soil and day 32 in steamed soil. The extent of blackening was reduced in both soils by treating seed with bacteria. The most marked reduction occurred in steamed soil where the length of root with blackened stele was reduced from 52.7 mm in the controls to 24.9 and 29.5 mm (SED 9.41) in plants grown from seed coated with D018 and 2-79 respectively.

DISCUSSION

Coating seed with bacteria reduced germination in steamed but not natural soil. As the initial population of bacteria on the seeds was similar in both soils, the difference is probably due to soil treatment. Steaming soil reduces the microbial population and therefore competition, and it can increase the availability of inorganic nutrients (Warcup 1957). Either or both of these changes could allow bacteria on the seed to increase more rapidly in steamed soil leading to depletion of oxygen levels around the seed and inhibiting or delaying germination (Kommedahl & Windels 1981).

Increase in root length with time was greater in steamed soil. As Experiment I (in natural soil) was conducted in autumn (April-May) and Experiment II (in steamed soil) in winter (July-August), it is unlikely that differences in day length, light intensity or air temperature are responsible for observed differences in root growth because they would have been most favourable in Experiment I. It is more likely that reduced microbial activity, elimination of minor pathogens and increased soil nutrition brought about by steaming were the cause of the rapid increase in root length in steamed soil.

Root length decreased with increasing levels of Ggt inoculum in natural soil, but was not affected by the pathogen in steamed soil. Infection by Ggt can affect root length by reducing growth, as phloem translocation does not occur past severe take-all lesions (Asher 1972), or by root pruning where root tissue which is severely affected breaks off when plants are removed from soil. It is possible, however, for plants infected with take-all to form new roots to compensate for damaged roots (Asher 1972). Plants grown in steamed soil may have been more able to produce new roots than plants grown in natural soil.

Coating seed with bacteria had no effect on root length in the natural soil, but appeared to increase root length in steamed soil. The difference in root length between plants grown from seed treated with bacteria and those grown from seed treated with methylcellulose alone was significant only at 40 days, when most of the plants were beginning to show signs of nutrient deficiency. It is uncertain whether the observed increase in root length was mediated by this stress or if it is a normal occurrence in older plants. Bacteria on the seed in steamed soil may have multiplied faster than in natural soil and reduced the effect of any minor pathogens not eliminated by steaming.

The difference in the rate of root growth in the two soils illustrates the importance of measuring both host and pathogen growth in order to interpret any studies of colonization of roots by Ggt. In natural soil the total length of hyphae, density of hyphae, total root length colonized by hyphae and proportion of root length colonized by hyphae all increased with time. This indicates that the rate of hyphal growth was greater than the rate of root growth. In steamed soil, however, while both the total length of hyphae and the total length of root colonized by hyphae increased with time, the density of hyphae and the proportion of root colonized by hyphae decreased, indicating that the rate of root growth was greater than the rate of pathogen growth. This suggests that a plant with a rapidly growing root system could tolerate more pathogen growth than a plant with a slow growing root system.

Measurements of external colonization of roots by black runner hyphae do not give information about the extent of internal colonization of roots by hyaline hyphae. The effect of the pathogen on plant growth is determined by the position of infection on the roots (Asher 1972) and the extent of disruption of vascular tissue by Ggt as it invades the root (Manners & Myers 1975). Therefore the extent of colonization of roots by black runner hyphae may not be related to decrease in yield.

Treating seed with bacteria reduced both the density of hyphae on roots and the proportion of root colonized by hyphae in both natural and steamed soil. Weller (1985) proposed that bacteria which reduce pathogen growth by antibiosis are more effective after lesions have formed, as nutrients from the lesions would provide nutrients necessary for antibiotic production. Bacteria which limit the pathogen by producing siderophores should be more active on the root surface (Weller 1985). In these experiments the greatest effect on the pathogen occurred when lesions (areas of blackened stele) began to appear on the roots and when only a few were visible. Isolate 2-79 is known to produce both a phenazine antibiotic (Gurusiddaiah *et al.* 1986) and a siderophore (Weller 1985). It is unlikely that competition for iron is operating in Gabalong soil which is an acid soil, because inhibition of pathogens by siderophores would operate only in alkaline soils (Wong 1985). The bacteria may produce enough antibiotic in the absence of macroscopic lesions to limit pathogen growth or the fluorescent pseudomonads used in this study reduce growth of Ggt by a mechanism other than antibiotic or siderophore production. The absence of visible lesions on roots does not eliminate the possibility that there are enough nutrient rich areas on the root surface to support multiplication of bacteria and for antibiotic production. Weste (1972) reported that extensive cellular damage and exudation of a granular diffusate from damaged cells occurred on wheat roots infected with Ggt several days before macroscopic lesions were evident. Healthy roots also leak nutrients, especially in intercellular spaces where both bacteria and fungi proliferate (Foster 1985). Thus, while our data show that bacteria can limit pathogen growth on the root surface even before many lesions are visible, the mechanism of this inhibition is yet to be defined. In addition to reducing growth of hyphae on the surface, bacteria may also reduce pathogenesis by reducing the number of penetrations of root tissue by hyphae and decreasing the growth of hyphae within the root. They may also increase the resistance of the host root to the pathogen.

Differences in the density of hyphae between control plants and treated plants decreased at the end of both experiments. This seemed to be related to a reduction in the density of hyphae on the controls rather than a loss of bacterial effectiveness. Where the vascular tissue has been destroyed by Ggt, roots may die and break off when the plants are pulled from soil. These roots remaining in the soil will probably be heavily colonized by hyphae of Ggt and their loss would result in an apparent decrease in infected root length and in density of hyphae on the root system as a whole. Detailed study using large volumes of soil with adequate nutrition are needed to show how long bacteria applied to seed will limit growth of the pathogen.

Neither our experiments nor previously published work distinguishes between effects related to reduced microbial activity and increased inorganic nutrition of plants. Varying levels of soil nutrients may enable us to differentiate between the two factors.

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TIMING OF PROCHLORAZ SPRAYS FOR CONTROL OF CEREAL STEM-BASE DISEASES

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ABSTRACT

In trials during the 1984-86 period, cereal fungicides based on prochloraz have shown greater effectiveness and flexibility in application timing for the control of eyespot than the previous standard, carbendazim.

GS 30-31 is, in general, the best timing for a single prochloraz treatment for stem-base disease control but in some crops earlier or later timings have proved equally or more effective.

This paper also discusses the results of novel two-spray sequences of the same fungicides with each spray of less than normal dose which have achieved even higher levels of eyespot control and yield. Two-spray sequences have particular relevance in seasons with early or prolonged eyespot infection and attack.

INTRODUCTION

Prochloraz, a novel imidazole fungicide, was introduced in the UK in 1981 for the control of a wide range of stem-base, foliar and ear diseases in cereals (Harris *et al* 1979).

Prior to this introduction and since 1974 benzimidazole fungicides were applied to winter cereal crops at growth stage (GS) 30-31 (Zadoks *et al* 1974) to control eyespot caused by *Pseudocercosporella herpotrichoides*. Recommendations for the control of eyespot and other stem-base diseases with prochloraz and later with a prochloraz + carbendazim formulation kept to this traditional timing.

Since 1974 farming practices have changed. Winter cereals, especially winter barleys, are drilled earlier in the autumn, often following a cereal crop. Under these conditions eyespot and other stem-base diseases can often be found in the crop in the late winter or early spring, long before the traditional time for applying eyespot fungicides. Neither the effects on disease control and yield of delaying fungicide applications until GS 30-31 in such situations nor the efficacy of eyespot fungicides in the winter or early spring appear to have been investigated.

In autumn 1983 twelve trials were established to investigate the effect of spray timing on the control of stem-base diseases of winter cereals with a prochloraz + carbendazim co-formulation and with carbendazim. This paper describes the results of these trials and of a further twenty-two trials in the period 1984-86, which led to recommendations for the use of prochloraz formulations for eyespot control at times other than GS 30-31 and in 2-spray programmes at reduced doses.

MATERIALS AND METHODS

In the period 1983 to 1986 spray timing trials with prochloraz formulations were conducted in winter wheat and winter barley crops in the major arable crop areas of the UK. Formulations used were prochloraz emulsifiable concentrate (400 g a.i./l) 'Sportak' and prochloraz + carbendazim suspension concentrate (prochloraz 266 g a.i./l + carbendazim 100 g a.i./l) 'Sportak Alpha'. In some experiments these formulations were compared with carbendazim s.c. (511 g a.i./l).

Trials were of randomized block design with 6 replicates. Plots, arranged across the crop rows, were 10 m long x 2 m wide.

Treatments were applied using Drake and Fletcher knapsack sprayers calibrated to deliver 200 l/ha through Tee Jet 8001 nozzles at 285 k Pa.

Timing trials in 1983-1984 compared single sprays of prochloraz + carbendazim co-formulation or carbendazim applied in December, February, April, early May and late May with two-spray programmes of prochloraz + carbendazim for stem-base disease control and yield. Details of treatments are given in Table 1.

In 1984-85, following reports of widespread mbc resistance in the eyespot fungus (Griffin and Yarham 1983), experiments examined the effects on stem-base disease and yield of prochloraz + carbendazim applied in December, February, April, May and end-May. Comparison with carbendazim was made only at the April spray timing. Details of treatments are given in Table 2.

A parallel series of trials compared prochloraz + carbendazim, prochloraz or carbendazim treatments applied in April with a two-spray programme (February and April) of prochloraz 300 g a.i./ha. Details of treatments are given in Table 3.

This protocol was repeated in 1985-86 season and was extended to include a further two-spray programme; prochloraz 300 g a.i./ha applied in March and May. Details of treatments are given in Table 4.

All experimental plots were oversprayed with a 'blanket' fungicide programme to minimise the effects of foliar diseases on yields.

Assessments of stem-base diseases were made on the plots to be sprayed at each spray timing and at the grain milky ripe - dough stage (GS 75-80). Early season assessments scored the number of tillers showing stem-base browning. Later assessment scored the incidence and severity of stem-base diseases on 10 main tillers per plot using a disease key (Clarkson and Polley 1981). These scores were then used to calculate a Disease Index and percentage control compared to untreated plots.

The centre 1.25 m of each plot was harvested using a Hege small plot combine and plot yields were corrected to 15% moisture.

RESULTS

In the 1983-84 trials most crops showed stem-browning symptoms from early November. The percentage of tillers infected increased steadily in untreated plots through the winter and early spring, peaking in April (Table 1). Numbers of infected tillers decreased in May, following a dry April. At the grain milky-ripe stage (GS 75) eyespot (Pseudocercosporella herpotrichoides) was the predominant disease but sharp eyespot (Rhizoctonia cerealis) and Fusarium foot rot (Fusarium spp.) were also present, at low levels, in most trials.

Prochloraz + carbendazim treatments gave good control of eyespot and suppression of Fusarium foot rot at all timings but control of sharp eyespot and yield benefits proved variable (Table 1). In all trials best control of eyespot, assessed at the grain milky-ripe stage, and best mean yields from a single spray were achieved with April (GS 30-31) sprays of prochloraz + carbendazim. This treatment also gave good suppression of sharp eyespot and Fusarium foot rot. Earlier and later treatments of prochloraz + carbendazim also gave good control of eyespot but were less effective against sharp eyespot. In some trials plots receiving sprays in November or February had higher levels of sharp eyespot than untreated plots.

Two-spray programmes applying prochloraz + carbendazim in December and April or December and May gave similar results, good control of eyespot but increased levels of sharp eyespot. Mean yields were no better than from a single spray in April or May. In contrast two-spray programmes applied in April and late May gave best overall control of eyespot, some control of sharp eyespot and highest mean yield.

Carbendazim treatments gave less effective control of eyespot and lower overall yields than prochloraz + carbendazim at any timing. Differences were most marked for sprays applied in December or February, under cold conditions, and least marked during May.

Prochloraz + carbendazim gave good suppression of sharp eyespot only at GS 30-31 but good suppression of Fusarium foot rot at all timings.

In the 1984-85 season stem-base disease levels were similar in the winter and early spring to 1983-84 but increased steadily until the end of May, favoured by prolonged wet conditions (Table 2). By harvest stem-base disease levels were the highest recorded for several years. Under these conditions prochloraz + carbendazim sprays applied in April or May (GS 30-49) gave very effective control of eyespot and good yields (Table 2). Sprays applied in December or February gave less effective control of eyespot and again appeared to encourage sharp eyespot.

Carbendazim, applied in April at GS 30-32, gave poor control of eyespot and a lower mean yield than the equivalent prochloraz + carbendazim treatment. A similar trend was seen in the parallel series of trials which compared single sprays with two-spray programmes (Table 3). In these trials a two-spray programme of prochloraz at 300 g a.i./ha, applied in February and April, gave better control of eyespot and sharp eyespot than single sprays of prochloraz, prochloraz + carbendazim or carbendazim applied in April and a better yield.

A similar trend was recorded in trials in 1985-86 season, when again eyespot attacks occurred in late spring (Table 4).

DISCUSSION

In the past three seasons eyespot was the dominant stem-base disease of cereals, both in our trials and nationally, despite very different weather conditions. Disease levels were higher than in the recent past. During the same period sharp eyespot and Fusarium foot rot occurred less frequently and with less severity, perhaps because of the dominance of eyespot.

There is little to suggest that this situation will change until cereal varieties with better eyespot resistance are introduced. Earlier drilling of cereals has increased the risk of eyespot appearing in the winter or early spring before GS 30-31, as in 1983-84 and 1984-85. Later infections in May or June have become increasingly common, especially on winter barley. This is possibly the result of an increase in the rye (R)-type of *P. herpotrichoides*, which can attack late, following the widespread use of benzimidazole fungicides for eyespot control (King and Griffin 1985).

Early, late or prolonged attacks test severely the efficacy of fungicides applied at the traditional timing for eyespot control (GS 30-31). Whilst lodging and yield loss is less after spraying the levels of eyespot control can be quite modest (Griffin 1984) and yield benefits less than optimum (Tables 2, 3). There is clearly a need for a more flexible approach to fungicide timing, determined by the appearance of eyespot at low levels in the crop, rather than by crop growth stage.

Such an approach was not possible with the benzimidazole fungicides, even before the appearance of benzimidazole-resistant *P. herpotrichoides*, since they were not effective in cold conditions (Table 1). It is possible with fungicides containing prochloraz which give good control of eyespot whenever it appears (Tables 1 and 2).

The flexibility of timing allowed by prochloraz can give better control of eyespot by matching spray timing to infection, but it is not without problems. Sprays in the winter, or very early spring, will give good control of eyespot but can encourage sharp eyespot and may give lower yields than a spray at the traditional timing. There is also a risk that later eyespot infections will not be controlled. For these reasons autumn/winter sprays of prochloraz fungicides for eyespot control are not recommended. In our trials and those of ADAS (Griffin - personal communication) a two-spray programme with prochloraz fungicides, with each spray of less than normal dose, has given excellent control of eyespot, better than any single spray, and has improved suppression of sharp eyespot (Tables 3, 4). Mean yields also showed a slight improvement.

Based on the results reported here and in ADAS trials the following recommendations for the control of eyespot and other stem-base diseases with prochloraz fungicides were introduced in autumn 1985.

1. General situation. Apply prochloraz at 400 g a.i./ha or prochloraz at 400 g a.i./ha + carbendazim at 150 g a.i./ha at GS 30-31.

2. If after the above treatment eyespot infection pressure remains high a follow-up spray of prochloraz at 300 g a.i./ha or prochloraz at 266 g a.i./ha + carbendazim at 100 g a.i./ha should be applied approximately 4-6 weeks later.

3. Where early season eyespot infection occurs prochloraz at 300 g a.i./ ha or prochloraz at 266 g a.i./ha + carbendazim at 100 g a.i./ha should be applied in February and repeated 4-6 weeks later.

TABLE 1

Fungicides, spray timing, % tillers with stem browning at spraying, % control of stem-base diseases and yields in winter cereals* 1983-84

	Spray Timing		% tillers	Mean % Control at GS 75			Mean yield as
Treatment	Month	GS	infected at spraying (12 sites)	Eyespot (8 sites)	Sharp eyespot (1 site)	Fusarium (7 sites)	percent of untreated (12 sites)
prochloraz + carbendazim	Dec	21-24	18	61	5	48	103
carbendazim	Dec	21-24	18	5	19	17	101
prochloraz + carbendazim	Feb	22-30	25	60	1	47	104
carbendazim	Feb	22-30	25	37	8	16	102
prochloraz + carbendazim	April	30-31	39	71	49	38	106
carbendazim	April	30-31	39	49	18	43	103
prochloraz + carbendazim	May	32-34	25	62	26	36	104
carbendazim	May	32-34	25	54	18	51	103
prochloraz + carbendazim	End-May	37-55	28	56	31	38	105
carbendazim	End-May	37-55	28	50	30	33	104
prochloraz + carbendazim	Dec + April	21-24 + 30-31	ND	74	-48	55	104
prochloraz + carbendazim	Dec + End-May	21-24 + 37-55	ND	67	- 4	34	105
prochloraz + carbendazim	April + End-May	30-31 + 37-55	ND	83	26	45	107
Untreated: Disease Index % and (Mean yield)			-	45	21	13	(7.7 t/ha)

Doses: prochloraz at 400 g a.i./ha + carbendazim at 150 g a.i./ha,
carbendazim at 255 g a.i./ha

* 6 winter wheat + 6 winter barley
ND no data

TABLE 2

Fungicides, spray timing, % tillers with stem browning at spraying, % control of stem-base diseases and yields in winter cereals* 1984-85

Treatment	Spray Timing		% tillers**	Mean % Control at GS 75		Mean yield as
	Month	GS	infected at spraying (9 sites)	Eyespot (9 sites)	Sharp eyespot (6 sites)	percent of untreated (9 sites)
prochloraz + carbendazim	Dec	21-24	26	45	-69	106
prochloraz + carbendazim	Feb	23-25	28	39	-21	104
prochloraz + carbendazim	April	30-32	36	58	14	109
carbendazim	April	30-32	36	33	9	105
prochloraz + carbendazim	May	33-37	44	56	26	113
prochloraz + carbendazim	End May	37-49	40	53	1	112
Untreated: Disease Index % and (Mean yield)				56	19	(6.8 t/ha)

Doses: prochloraz at 400 g a.i./ha + carbendazim at 150 g a.i./ha, carbendazim at 255 g a.i./ha

* 5 winter wheat and 4 winter barley

TABLE 3

Fungicides, spray timings, % control of stem-base diseases and yields in winter cereals* 1984-85

Treatment	g a.i./ ha	Spray Timing		Mean % control at GS 75			Mean yield
		Month	GS	Eyespot (4 sites)	Sharp Eyespot (1 site)	Fusarium (1 site)	as percent of untreated (6 sites)
prochloraz	400	April	30-32	45	59	77	109
prochloraz + carbendazim	400 150	April	30-32	38	54	77	109
carbendazim	255	April	30-32	20	35	38	103
prochloraz	300	Feb + April	15-24 + 30-32	60	66	61	111
Untreated: Disease Index % and (Mean yield)				79	81	-	(6.1 t/ha)

* 3 winter wheat, 3 winter barley

TABLE 4

Fungicides, spray timing, % control of eyespot and yields in winter cereals* 1985-86

Treatment	g a.i./ha	Spray Timing		Mean % control	Mean yield
		Month	GS	at GS 75 Eyespot (7 sites)	as percent of untreated
prochloraz	400	April	30-31	61	103
prochloraz + carbendazim	400 150	April	30-31	58	104
prochloraz	300	March + End-May	22-30 + 33	76	106
Untreated: Disease Index % and (Mean yield)				40	(7.7 t/ha)

* 4 winter wheat and 3 winter barley

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SAVING SEPTORIA FUNGICIDE SPRAYS: THE USE OF DISEASE FORECASTS

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ABSTRACT

It is calculated that a good forecast-guided Septoria management system in winter wheat should be able to achieve a saving of at least one fungicide spray on average every third year. Further savings would accrue if it became possible to forecast actual disease levels. However, reliable forecasts depend on a sound biological understanding of the epidemiology of the disease.

An epidemiological framework is outlined within which a forecast scheme for *Septoria tritici* is being developed. The scheme relies on assessing inoculum levels in fields in spring and then monitoring upward rainsplash during the period from early stem extension until anthesis. Good disease control was achieved from sprays guided by the scheme in 1986 but a wet spring prevented its value for saving sprays from being tested. The scheme should be applicable also to *S. nodorum* if conditions preclude rapid pathogen multiplication late in the season. Implementation of a forecast-based management system will depend on being able to predict which of the two *Septoria* spp. will be dominant in a given year. The factors determining this are, at present, unknown.

BACKGROUND

If a disease poses little threat to yield in a particular year, it should be possible to avoid spraying with a fungicide to control it. Thus the potential for reducing the number of fungicide sprays can be assessed over a period from the proportion of years in which the target disease causes damage costing less than control measures. The potential for increasing profitability is more difficult to assess, because it depends on costs and on improvements in spray timing. In England and Wales, the diseases of wheat caused by *Septoria tritici* and *S. nodorum* appear to have been of negligible severity in at least 5 of the last 15 years (King 1977, J.E. King pers. comm., Royle *et al*. 1986). Thus, a good management scheme should avoid sprays against Septoria in at least a third of years; probably more on a single given site. This calculation assumes that the overall prevalence of both diseases is not changing rapidly.

As an example of good current advice, the Agricultural Development and Advisory Service (ADAS) promotes the 'Managed Disease Control' (MDC) scheme (Anon. 1986) as an alternative to scheduled 2- or 3-spray programmes. In this scheme, spraying against Septoria diseases between Zadoks growth stages (GS) 39-55 is guided by the occurrence of a 'wet period', i.e. 4 or more days with 1 mm or more of rain, or 1 day with more than 5 mm of rain, in the last 14 days. Assuming GS 39-55 occupies the period 15-31 May, this condition would have been fulfilled in 34 of the last 36 years at Long Ashton in S.W. England, and in 22 of the last 25 years at Stanton Downham, Norfolk, in E. England. A saving in mid-season sprays from the use of the MDC system will therefore be made in no more than 5-10% of years. (The calculations assume the period of GS 39-55 is about 16 days but are insensitive to the precise dates between which it occurs). This small saving is because the MDC system is based on retrospective correlations. These are imperfect, so that caution is required in withholding sprays known to be profitable on average (Cook 1983).

A good forecast-guided Septoria management system should be able to achieve a saving in sprays directed against the diseases in at least a further 20-25% of years. Two factors make this a minimum figure. First, in a given year the average disease level does not allow for the farms where, even in bad years, disease may be absent. Second, if a scheme could forecast actual disease levels, exact cost-benefit calculations would become possible, leading to further savings.

Better disease forecasts, and hence both better control and spray savings, depend on better biological understanding of the diseases, and the integration of the various factors that determine the onset and progress of disease in a coherent framework. In the rest of this paper we shall outline the epidemiological framework now emerging from our research, and some encouraging preliminary experiments in forecasting using a scheme (Fig. 1) based on it. Details of results for which no source is given will be published elsewhere; our intention here is to give an overview of the work.

Septoria tritici

Experiments including completely enclosed areas of field crops show that primary inoculum arrives in UK winter wheat crops during autumn and early winter as airborne spores (presumably ascospores). These infect areas at least as large as 1 ha with little more variability than expected from the Poisson distribution. In 1985, the approximate observed density of primary lesions in a crop sown in mid-October was 50 m^{-2}. Visible lesions appear 5-12 weeks after infection, depending on temperature. Almost all sowings, therefore, suffer at least one round of secondary infections before stem extension (GS 30-31) starts. The long and frequent wetness periods during winter mean that most crops will have substantial numbers of active pycnidia on dead tissue in the spring if primary autumn infection occurred. In our experience, unless sown very late, most crops of most current wheat varieties sustain considerable infection in the autumn, but it is not yet clear how variable autumn infection levels are from year to year. Inoculum levels at the start of stem extension, however, integrate the effects of primary inoculum and winter secondary development. In a field, these spring inoculum levels seem to be fairly uniform spatially (Shaw & Royle 1987) and assessments of them are used in Stage I of our scheme (Fig. 1) to provide a direct indication of potential risk later in the year.

Leaves typically emerge on mainstem and tillers every 10 days or so as the stem extends during the spring. In cv. Longbow the stem grows upwards by about 20 cm per week during the emergence of the last three stem leaves. The relation of the latent period (time from infection to symptoms) of S. tritici on cv. Longbow to temperature is shown in Fig. 2. The latent period would be about 4 weeks at a typical average May temperature of 11°C (35-year mean at Long Ashton). Assume that the sowing date of the crop was mid October. Then, numbering leaves from the flag

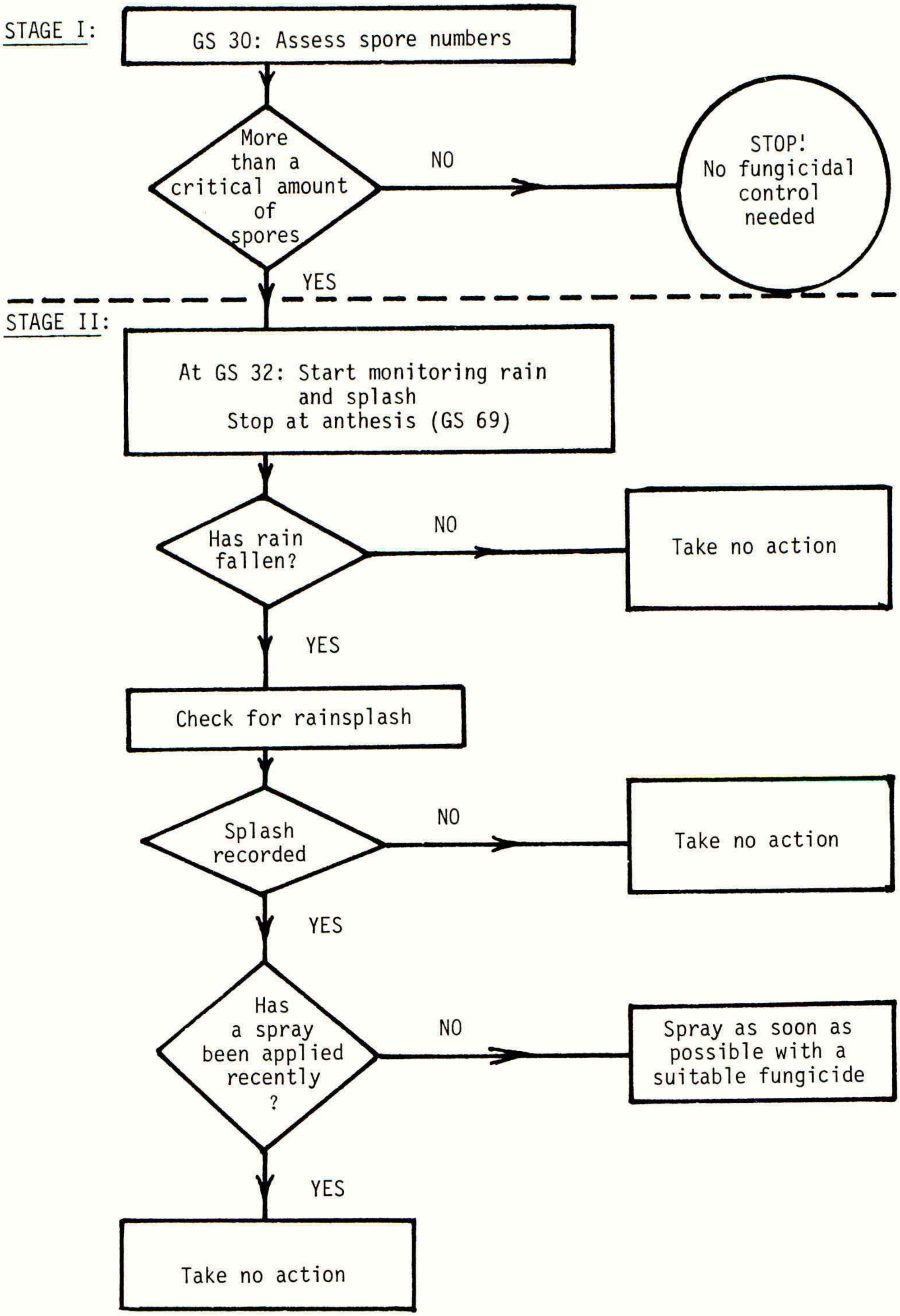

Fig. 1. Experimental forecasting scheme for *S. tritici*

downwards as 1, 2 ..., by the time infectious lesions are present in any numbers on leaf 5, leaf 2 is already emerging perhaps 40 cm above the ground, 30 cm above leaf 5. This is so even if leaf 5 is infected as soon as it emerges. Hence, infection of leaf 2 cannot occur unless spores from the pycnidia in the basal leaves are transported in sufficiently large numbers to heights of 30-50 cm. A similar argument applies to the flag leaf. Such transport can only occur by rain splash, since spores are not liberated in dry conditions (Eyal 1971). Thus, a potential factor limiting *S.tritici* epidemics is the occurrence of rain capable of causing substantial upward splash transport - splashy rain (Royle *et al*. 1986).

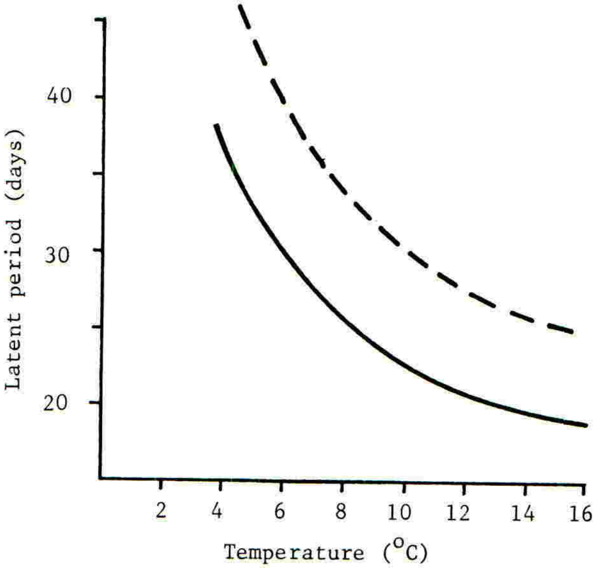

Fig. 2. The latent period of *S. tritici* in relation to temperature, determined from field data and controlled environment experiments. The solid line represents the first time at which any disease is seen following heavy (*c*. 10^6 spores/tiller) inoculations. A population of disease lesions appears over a considerable time interval, even though resulting from infections occurring simultaneously; the dashed line represents an estimate of the time at which 50% of lesions resulting from an infection event will have appeared. It is probably the more relevant period for the interpretation of field epidemics in which inoculum levels are relatively low.

Subsequent infection conditions are another possibly limiting factor. Even on susceptible cultivars, such as Longbow, a continuous leaf wetness period of 20 h has been reported to be required for infection (Holmes & Colhoun 1974). However, the precise effects of continuous or interrupted periods of wetness have not been studied. In studies so far at Long Ashton, post-infection wetness does not seem to alter *S. tritici* expression greatly. The period of leaf wetness resulting from a given rainy day clearly depends on many factors; if the canopy is saturated, wetness may persist considerably in excess of 20 h on parts of leaves, even in summer (Brain & Butler 1985). Royle *et al.* (1986) suggest that upward splash may be a more common limiting factor than leaf wetness.

The 'splashiness' of rain does not appear to be reliably related to rainfall intensity as measured with a 0.5 mm capacity tipping bucket rain gauge, although there is little splash-mediated transport of inoculum in low total amounts of rain (less than *c.* 2 mm). Despite this the 'splashiness' of rain varies considerably. For example, the most splashy storm during GS 34-65 in 1985 transported twenty-five times as much material above a given height as any other in that period at Long Ashton. Thus 'splashiness' is a potentially very useful measure for use in forecasting *S. tritici* and in Stage II of our experimental scheme (Fig. 1) we record it directly, with a simple device that detects the upward splash of an aqueous dye.

We have begun in 1986 to explore control of *S. tritici* using this scheme at several sites around the country; some trials are in collaboration with ADAS. The scheme is based on inoculum and splash measurements, and assumes that adequate leaf wetness for infection will always be provided by rain which causes enough spore transport to make an outbreak possible. At Long Ashton, assessments of inoculum levels at GS30 were made for crops sown at a range of different dates. All but the last sown crop (sown 22/11/85) had an inoculum level judged from past experience to be sufficient for a serious attack. Rain was monitored from the date of appearance of leaf 2 (estimated by stem height from past data) until anthesis. Fungicide sprays were applied following rain at least as splashy as that which caused damaging attacks at Long Ashton in 1985: such rains were much more frequent in 1986 than in 1985. A major unknown factor was the period after application during which the fungicide used would protect against new infections. For prochloraz, which was used at Long Ashton, we assumed a period of 2 weeks (Jordan *et al.* 1986). For the strategy to be successful, the fungicide must control disease even when applied a few days after infection. The period during which control is possible with prochloraz appears to be many days (Jordan *et al.* 1986). However, if *S.tritici* is growing within a leaf there could be effects which result in lower yields even before the appearance of visible lesions. Until it is known whether this is so we chose to spray as soon as possible after a presumed infection event.

Fig. 3 shows the disease progress observed on a single experimental plot sown in mid-October. It is clear that good disease control was achieved, but because of the very wet spring in 1986 the potential of the method to save sprays has not really been tested. Given the abnormally wet and cold spring, the inoculum threshold set seems to have been too high: it was based on years in which April was much less favourable to pathogen multiplication and more favourable to plant development.

Septoria nodorum

In many ways, the biology of this pathogen is harder to study than *S. tritici*. It is not clear how it usually enters crops, nor why it

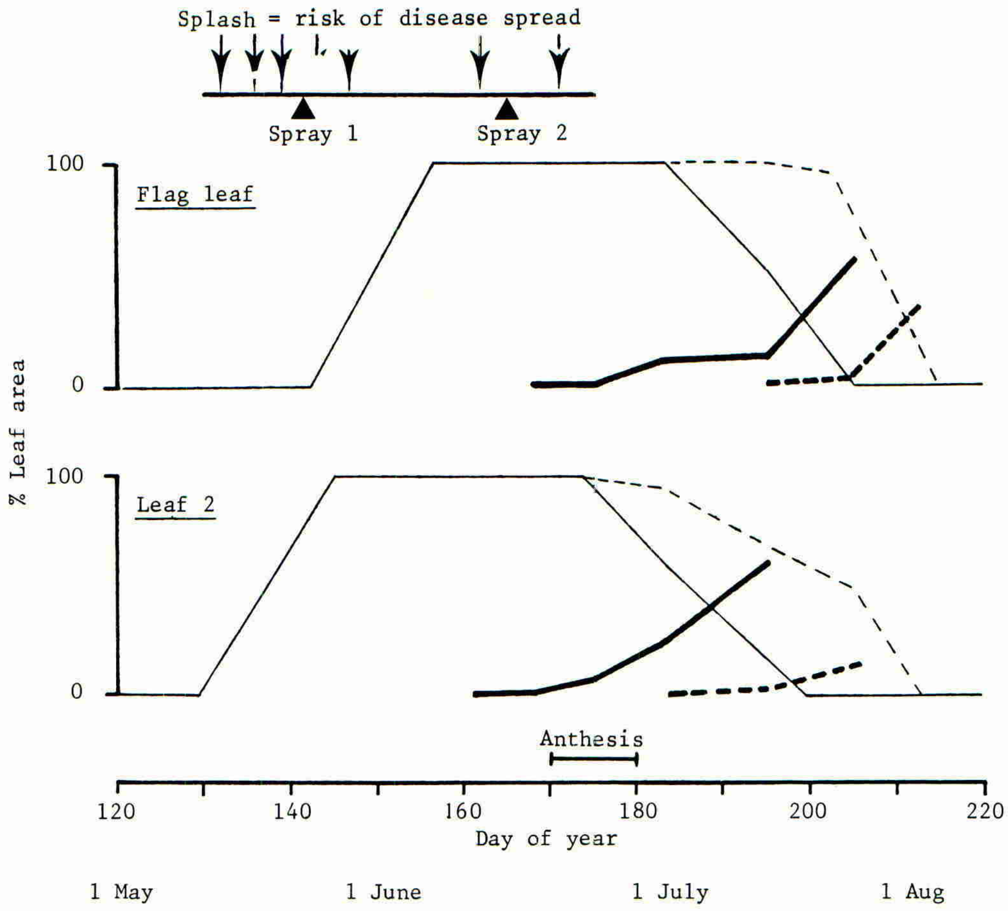

Fig. 3. S. tritici progress and control by a forecasting approach (Fig.1) during 1986. Leaves 1 (flag) and 2 of a crop of winter wheat cv. Longbow sown at Long Ashton on 10 October 1985 are shown. Solid lines: unsprayed, dashed lines: sprayed. Light lines: emergence and dieback of leaves. The non-senescent leaf area present is shown as a percentage of the maximum leaf area. Heavy lines: proportion of the entire leaf covered by S.tritici lesions, as a percentage of the maximum leaf area.

seems recently to have declined in importance. Seed infection remains a possible primary infection route; a very low level of infection could still multiply to produce substantial disease levels by the summer. O'Reilly & Downes (1986) have shown that debris remaining from a previous crop (trash) may produce high levels of infection which only become apparent in the spring, and Rapilly et al. (1973) have shown that spring infection by ascospores is possible. The recent demonstration of persistent and marked host specificity (Osbourn et al. 1986) makes the role of alternate hosts unclear, but they cannot yet be ruled out as a source. However, if entry into a crop is primarily via seed or trash then early spring (GS30-31) inoculum levels should still serve to set a risk threshold, as suggested by the results reported in Royle et al. (1986). Certainly, at Long Ashton in 1986, action on the basis of spring inoculum levels would have been correct; although the disease did eventually reach detectable levels, it never covered more than 0.5% of a leaf layer before the leaves died.

Although the latent period of *S. nodorum* can be much shorter than that of *S. tritici* at high temperatures and if wetness is also present, it is at least as long as that of *S. tritici* at average temperatures below 12°C. This means that at typical average May temperatures in the UK (11°C) inoculum transport is still likely to be a limiting factor, and the scheme proposed for *S. tritici* should be applicable. However, since late season multiplication could be rapid, an extra monitoring stage in the scheme around anthesis maybe necessary. Control would be applied if disease severity, though not yet damaging, could become so in suitable conditions.

DISCUSSION

During the last 6-7 years there appears to have been a substantial increase in the incidence and severity of *S. tritici* and a decline in the importance of *S. nodorum* in UK wheat crops. This has coincided with several other changes, e.g. earlier sowing, cultivar changes, increasing top dressing of nitrogen, development of resistance in *S. tritici* to MBC fungicides. Several of these factors may be contributing to the change: hypotheses are easy to propose but hard to test. Until we know what determines which of the two *Septoria* species is dominant in a given year any forecast-based management system runs a risk of failing. Meanwhile our results so far suggest that a soundly based short-term forecasting approach to the management of *S.tritici* could be very cost-effective so long as control of this pathogen remains a major problem.

ACKNOWLEDGEMENTS

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GUAZATINE - ITS USE AS A FOLIAR FUNGICIDE IN CEREALS AND OILSEED RAPE

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ABSTRACT

Guazatine is a non-systemic fungicide. It is used as a seed-dressing primarily against Fusarium spp, Septoria nodorum, and Tilletia caries in many countries. It is also used as a post-harvest dip in citrus against Geotrichum candidum and Penicillium spp. Guazatine has now been developed as a foliar spray on several crops. In field trials it has been found to be very effective as a spray against leaf and ear attacks of S. nodorum, ear infections of F. culmorum and F. nivale on wheat and against F. nivale as an overwintering disease in winter cereals. Guazatine is also shown to be effective against Sclerotinia sclerotiorum on oilseed rape.

INTRODUCTION

Guazatine is a non-systemic fungicide, primarily affecting lipid biosynthesis. It is active against a wide spectrum of seed-borne fungal diseases, e.g. Fusarium spp, Tilletia caries, Septoria nodorum, Drechslera spp. Guazatine was developed by KenoGard and introduced in 1973 as a replacement to the organomercury seed-dressings.

Guazatine is of low oral and dermal toxicity to rats (LD_{50} = 300 and >1000 mg/kg respectively) and extensive toxicological studies have shown it to be neither mutagenic nor carcinogenic.

Guazatine is now registered and marketed in most European countries for the disinfection of cereal seeds either alone or in combination with fenfuram, imazalil or with both these compounds.

In 1979 guazatine was introduced as a post-harvest dip for citrus, and it has an outstanding ability to control sour rot (Geotrichum candidum). It is also very effective against green mould (Penicillium digitatum) and blue mould (Penicillium italicum) on citrus.

Recently guazatine was developed as a foliar spray for use against Septoria spp and Fusarium spp on cereals and against Sclerotinia sclerotiorum on oilseed rape.

MATERIALS AND METHODS

The trials were carried out as randomized block trials with four replicates. Guazatine was formulated as a water soluble concentrate containing either 300 or 600 grams of active ingredient per litre. The spray volume was kept at 400 litres per hectare in cereals and 400-600 litres in oilseed rape. The growth stages of the crops at treatment is stated in the tables presented. In cereals the decimal growth stage key (Zadoks _et al._ 1974) is used. Development stages of rape were according to Schütte _et al._ (1982). The assessments in the cereal trials were made 3-5 weeks after treatment except in the rye trials where the assessments were done in early spring, 5-6 months after treatment. No artificial inoculation was made in the trials presented in tables 1-7.

RESULTS

Cereals

Guazatine has been evaluated in a large number of field trials against foliar and ear diseases on wheat. It may be used alone as a preventive spray at a dose rate of 900 - 1200 g active ingredient per hectare against _S. nodorum_ and _S. tritici_ on the leaves and against _F. culmorum_, _F. nivale_ and _S. nodorum_ on the ears.

Some of the results where guazatine has been used against _S. nodorum_ are presented in tables 1, 2 and 3.

The use of guazatine to control _Fusarium_ in the ears is given in table 4. In these trials with natural infection the most important _Fusarium_ species were _F. culmorum_ and _F. nivale_. Significant yield increases have also been achieved in other trials where artificial inoculation of _F. culmorum_ has been carried out.

TABLE 1

Field trials in winter wheat against _Septoria nodorum_.

Treatment at GS 55. Average of 7 trials. West Germany 1986.

Treatment	Dosage g a.i./ha	_S. nodorum_[1)] Flag leaf -1	Flag leaf -2	Yield dt/ha	Relative
Untreated	-	39	60	68.2	100
Guazatine	900	21*	53*	71.8*	105
Guazatine	1200	18*	51*	72.3*	106
Anilazine	1920	20*	47*	71.6*	105
Duncan multiple range test		*	*	*	

* = The treatment differs statistically from the untreated with 95% confidence.
1) Flag leaf - 1, Flag leaf - 2 = first and second leaf underneath the flag leaf.

TABLE 2

Field trials in winter wheat against Septoria nodorum.

Treatment at GS 55-61. Average of 6 trials. West Germany 1984, 1985.

Treatment	Dosage g a.i./ha	S. nodorum Leaf infection (3 trials) %	S. nodorum Ear infection (4 trials) %	Yield dt/ha	Yield Relative
Untreated	-	29	17	70.0	100
Guazatine	900	14	12*	74.7	107
Captafol	1680	18	12*	73.3	105
Duncan multiple range test		n.s.	*	n.s.	
Coefficient of variation		24.6	11.9	4.6	

* = The treatment differs statistically from the untreated with 95% confidence.

TABLE 3

Field trials in winter wheat against Septoria nodorum.

Treatment at GS 39-57. Average of 4 trials. Sweden 1985.

Treatment	Dosage g a.i./ha	S. nodorum Leaf infection %	Yield dt/ha	Relative
Untreated	-	16.7	58.2	100
Guazatine	900	11.5	62.3	107
Guazatine + Fenpropimorph	900 + 750	9.4*	64.7*	111
Chlorothalonil	1000	10.3*	62.8*	108
Duncan multiple range test		*	*	
Coefficient of variation		31.1	3.2	

* = The treatment differs statistically from the untreated with 95% confidence.

TABLE 4

Field trial against Fusarium spp on ears of winter wheat.

Treatment at GS 55. Variety Arkas. West Germany 1984.

Treatment	Dosage g.a.i./ha	Fusarium spp Ear infection %	S. nodorum Ear infection %	Yield dt/ha	Yield Relative
Untreated	-	19.7	14	40.5	100
Guazatine	900	11.3	10	45.9**	113
Guazatine	1500	13.3	10	46.2**	114
Captafol	1680	12.3	9	44.9**	111

** The treatment differs statistically from the untreated with 99% confidence.

TABLE 5

Field trials in spring wheat against Erysiphe graminis.

Treatment at GS 30-31. Average of 4 trials. Sweden 1985.

Treatments	Dosage g a.i./ha	E. graminis Leaf infection %	Yield dt/ha	Relative
Untreated	-	1.16	45.5	100
Guazatine	900	0.42*	48.9	108
Guazatine + Fenpropimorph	900 + 750	0.00*	53.5*	118
Fenpropimorph	750	0.04 *	51.9*	114
Duncan multiple range test		*	*	
Coefficient of variation		88.0	4.0	

* = The treatment differs statistically from the untreated with 95% confidence.

TABLE 6

Field trials in winter rye against Fusarium nivale.

Treatment November 1984. Average of 4 official trials. Sweden 1985.

Treatment	Dosage g.a.i./ha	Stand1) spring (0-100)	F. nivale No. of spots /100 sq.m.	Yield dt/ha	Yield Relative
Untreated	-	67.5	2314	27.4	100
Guazatine	900	90.5*	829*	32.7*	119
Guazatine	1200	94.5*	644*	32.9*	120
Benomyl	150	89.7	717*	32.0	117
Duncan multiple range test		*	*	*	
Coefficient of variation		11.9	37.0	5.8	

* = The treatment differs statistically from the untreated with 95% confidence.
1) Stand: Estimated relative no of plants/plot. 0 = No plants, 100 = Maximum number of plants.

TABLE 7

Field trials in spring oilseed rape against Sclerotinia sclerotiorum.

Treatment at full flowering. Official trials in Sweden 1985.

		Variety Niklas			Variety Hanna		
Treatments	Dose g a.i. /ha	Sclerotinia Infected plants, %	Yield Raw fat/ha kg	rel.	Sclerotinia Infected plants, %	Yield Raw fat/ha kg	rel
Untreated	-	28	837	100	14	794	100
Guazatine	300	0*	1004*	120	3	811	102
Guazatine	600	2*	953*	114	5	847	107
Guazatine	900	0.5*	966*	116	6	876	110
Vinclozolin	750	0*	952*	114	2	887	112
Duncan multiple range test		*	*		n.s.	n.s.	
Coefficient of variation		25	2.0		55	4.5	

* = The treatment differs statistically from the untreated with 95% confidence.

TABLE 8

Field trials in winter oilseed rape against Sclerotinia sclerotiorum.

Treatment at GS 63. Variety Jet Neuf. West Germany 1985.

Treatments	Dosage g a.i./ha	Sclerotinia Infected plants %	Yield dt/ha	Yield Relative
Untreated	-	5.2	46.1	100
Guazatine	900	0.9	48.1	105
Guazatine	1200	0.9	47.2	102
Vinclozolin	750	0.8	47.9	104
Mult. t-test: P = 0.05 = 2.79 dt/ha			n.s.	

Treatment at GS 63/65. Variety Jet Neuf. West Germany 1985.

Treatments	Dosage g a.i./ha	Sclerotinia Infected plants %	Yield dt/ha	Yield Relative
Untreated	-	8.0	36.9	100
Guazatine	900	2.5	41.5*	113
Guazatine	1200	2.0	42.9*	116
Vinclozolin	750	0.5	37.5	103
Mult. t-test: P = 0.05 = 2.81 dt/ha			*	

* = The treatment differs statistically from the untreated with 95% confidence.

Guazatine has some effect against both Erysiphe graminis and Puccinia recondita in cereals. In table 5 trials against E. graminis are presented. Although the levels of infection were quite low in the four trials the yield increase is significant. In these trials only very low infection of Septoria spp on the lower leaves was present.

Official trials carried out by the Swedish University of Agricultural Sciences against overwintering diseases in winter rye, particularly F. nivale, show significant yield increases after treatment with 900 and 1200 g guazatine per hectare late in the autumn (Table 6). The yield increases are due to the larger number of plants per square metre and a better plant vigour in treated plots compared to untreated.

Oilseed rape

The effect of guazatine on the severe disease S. sclerotiorum on oilseed rape was evaluated during 1985 and, as can be seen from tables 7 and 8, guazatine gives very good control and high yield increases even at quite low application rates.

Guazatine has a low toxicity to honey-bees. The dermal LD_{50} is higher than 200 µg/bee and the oral LD_{50} is 59 µg/bee.

DISCUSSION

As a foliar spray on wheat, guazatine is especially useful as a late treatment against attacks of Septoria spp, and Fusarium spp on the flag leaf and ear. Other fungicides such as diclobutrazol, fenpropimorph, flutriafol, propiconazole, triadimenol may be "tank-mixed" with guazatine in order to increase the spectrum of disease control.

Guazatine has also been shown to be an effective fungicide against F. nivale as an overwintering disease in winter cereals. The disease is severe in northern climates such as in Sweden and may cause large yield losses. Treatment there is normally performed using benzimidazoles in late autumn. Benzimidazoles caused resistance in F. nivalis. Guazatine belongs to the low-risk compounds in this respect and is therefore considered a useful benzimidazole replacement.

Also in oilseed rape the mode of action of guazatine is of importance since many of the fungicides used against S. sclerotiorum belong to the same chemical group - the dicarboximides.

Further uses of guazatine as a foliar spray are under investigation. Promising results have been obtained against important foliar diseases in peanuts, soybeans, rice, bananas and coffee.

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SESSION 9

PROTECTING CROPS AND THE ENVIRONMENT

CHAIRMAN	DR I. J. GRAHAM-BRYCE
SESSION ORGANISER	DR B. D. SMITH
INVITED PAPERS	9-1 to 9-5

ENVIRONMENTAL EFFECTS OF AGRICULTURAL PRACTICES

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The organizers of this session have done their best to ensure each contribution is linked and relevant by sending us, along with the invitation to take part, a short list of questions for us to address. They have also tried to achieve a diversity of points of view by inviting representatives of different organizations. I infer that I am expected to put forward a NERC or ITE view.

I find this difficult to do because we have a jealously guarded stance of non-alignment. The remit of NERC institutes is limited to finding out the facts of a situation and we deliberately avoid making value judgements on the desirability of particular courses of action. NERC does not wish to appear either for or against farming or in favour or against wildlife conservation.

However until 1973 the official Government body responsible for conservation was part of NERC and a major part of the contract funding for projects at Monks Wood still comes from the Nature Conservancy Council. While I cannot promise that my answers to the questions posed will all coincide with those of my colleagues, nor should my answers be construed as an official NERC view, I do think that my reactions are fairly typical. But I must also say some of the organizers' questions are framed in a way which makes it impossible for me to resist the temptation to give a personal response.

I will begin by not being controversial.

The most basic questions, is the application of chemicals to protect crops a major source of pollution in the environment or is crop protection incompatible with wildlife conservation, are questions which I would answer with a qualified no. I would qualify my no in the semantic sense of preferring to think of pesticides as an important or significant source of pollution. I doubt whether major is the right word given a context of other sources of different pollutants. These include some of agricultural origin such as nitrate, either from fertilizer or slurry but we must also remember sulphur dioxide and radiation. Acid rain or Chernobyl provide the background against which to judge which of major, important or significant is the right word.

I would also qualify my no if particular criteria were specified. There is a sense in which any form of crop protection, even farming itself, is inimicable to wildlife. Any increase in agricultural yield of dry matter is the outcome of a diversion of an energy flow from wildlife to stock or crop. This could come about by what a farmer regards as the reclamation of wasteland by draining it and a conservationist regards as destruction of wildlife habitat. Perhaps fortunately for our specific concern with herbicides and insecticides used in crops, the intensity of conservation interest in cleavers or aphids is rather lower than that in Marsh Orchids or lapwings. Nevertheless there is a view that farming is merely a means of directing energy to man and away from wildlife and anything such as pesticide use which increases the efficiency of the process must, as a consequence, be seen as damaging to wildlife. For myself I would suggest that this view might lead to a policy of reducing population expansion but as everyone now existing wants to eat, is unlikely to prevent a proper use of pesticides.

Also the answer no might have a geographical qualification. On the whole I believe that pesticides are properly used in the UK. The Pesticide Safety Precaution Scheme has now been running for nearly 30 years. There were problems in the earliest days of getting environmental or conservation criteria accepted. However in the classic case of the organochlorine insecticides the number of uses has been progressively curtailed since 1964. The remaining minor uses of DDT and endrin were withdrawn in 1984. There remain some minor uses of aldrin and there is some evidence from residue analyses that suggests that DDT is still used (improperly?) on a wide enough scale to have some environmental effects.

More recently the scheme has been approving synthetic pyrethroids but as concern for environmental effects was expressed in 1980 their use was reviewed in 1982. As a result there are now restrictions. The scheme can now produce a fairly rapid response to environmental hazards. While we should not be complacent we can be reasonably satisfied with our record. I cannot be so happy with some other parts of the world. The population increase, and increased expectations of that population, in some countries does seem to me to lead to attempts to increase agricultural productivity at any cost. Pollution by pesticides is becoming a serious problem elsewhere in the world.

So to the first question the answer could be yes or no. In the context of Britain and this conference I can only say: no, the use of pesticides is not the major source of pollution but yes they can be significant in a number of situations.

Judged from the wildlife conservation viewpoint it is usually held that pesticides are important. To me that is a little like placing all the blame for the camel's broken back on that single last straw. If the camel's back can be broken by that single straw our beast must be dangerously overburdened already. Instead of focussing attention only on the last straw we should examine the rest of the load. Are all the tents, rugs and cooking pots necessary? Is a single camel's back significant in the context of our caravanserai? This is indeed what your organizers are implying by the remaining seven questions. And having given a qualified no or an equivocal yes/no answer to the first question I am afraid the answer to all these seven remaining questions is a very definite negative if not always actually no.

No, we do not properly design our experiments to trace out the many causal factors. No, we do not take sufficient account of scale, in terms of space and time. No, we cannot rely on key species. No, our progress is not satisfactory nor is our current approach. Yes, we are insufficiently linked and co-ordinated and yes, too much emphasis is given to direct effects.

That is a blanket condemnation of the present situation and I should make clear that I feel that, not only are some of these negative points more important than others, the very fact that these questions are being posed now gives hope that the situation will change rapidly in the near future.

It will only change if we are clear on the reasons for the present unsatisfactory state of affairs. Some are apparently trivial. It is much easier to design and carry out a carefully controlled experiment on the direct effects of a single chemical on a single organism and cheaper, too. It is guaranteed to produce publishable results. Individual research scientists have particular interest and expertize. Hence we have a lot of work on the effects of x on y. We do not know all the other factors which affect y and whether these other things interact with x to produce changes in the quantity or quality of y.

More important than these personal and individual reasons are reasons pertaining to groups. Discrete groups, whether they be funding or research organizations, customer or contractor organizations, make their own objectives. Some remits are clear and precise; aims which are more readily realized. Others are less precisely defined, progress toward them less easily measured but are they necessarily less important? Organizations differ in size, in numbers of staff and thus in cost and power. But is cost and power necessarily commensurate with the benefit accruing from their more or less successful pursuit of their aims? Organizations try to co-exist. They carve out territories for themselves, leaving areas free for others. Is there a no-mans-land between them? Is trespass a punishable offence? Without comment I ask you to consider the Ministry of Agriculture, Fisheries and Food and the Nature Conservancy Council as organizations. Consider, too, the Natural Environment Research Council, if you will. I am not saying MAFF and NCC are at fault. It is the structure and nature of organizations which so often hinders progress. Nor is it chaos and anarchy that I seek. My aim is merely that organizations should recognize their own shortcomings and be more flexible in their outlook.

Yet more important than individuals or organizations, I feel, is an underlying, all pervasive, valuation of the various sciences in English society. Real science is hard science. The physical sciences rank higher than the biological, which in turn rank higher than the social sciences. Within each set one can rank the subsets. Within ecology the study of populations of a single species has more rigour, is more scientific, than, say, phytosociology or community ecology and how many accept landscape ecology as a science? These are only different levels of interaction. It may be easier to find and provide answers to questions at the lowest level but is not the highest level of greater importance? I am even tempted to suggest that knowledge of the effects of x on y in a limited set of circumstances is trivial. Of course it is a necessary step in understanding the effects of z on y in the same circumstances and the effects of x in different circumstances. The real problem is that though we can continue to build in such careful, painstaking, rigorous way, unless there is, perhaps a crude soft science, overview at a landscape ecology scale we may find we have built the wrong sort of edifice.

There are hopeful signs of change. The Advisory Board of Research Councils has set aside money for collaborative research on agriculture and the environment and AFRC and NERC are producing plans for work in the future. Meanwhile there are already in existence co-ordinated projects in this field which form the subjects of the next two papers.

I still fear progress will be slow for we are all prisoners of our past experience. One of my earlier professional mentors, brought up in the rapid urban sprawl of the interwar years, failed to appreciate the impact of agriculture upon widlife in the Sixties. I was at Bedford College (L.J. Audus), then at Wye (R.L. Wain) and finally at Monks Wood (N.M. Moore) so my views may also show the bias of my experience. Perhaps I am wrong in some details. However I am sure that it is and will continue to be NERC policy to continue work in this field, by itself and by collaboration with others.

THE BOXWORTH PROJECT - A PROGRESS REPORT

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ABSTRACT

ADAS started a project in 1981 to examine the ecological and economic effects of different pesticide regimes in intensive winter wheat production. After a baseline period of two years, three years have now been completed of the five year treatment phase at Boxworth Experimental Husbandry Farm. A prophyllactic programme of pesticides is routinely applied to the full insurance area. Pesticides are applied to the supervised and integrated areas only if regular crop monitoring reveals that economic thresholds are exceeded by particular pests, weeds or diseases. A wide range of ecological studies are monitoring non-target fauna and flora to identify treatment related effects.

INTRODUCTION

Agricultural pesticide use has risen steadily in the United Kingdom since the 1940's contributing greatly to the increase in cereal yields obtained during this period. Varietal improvement and the more efficient use of fertilisers and machinery are the other major contributory factors. Whereas in 1948 the total home and export pesticide market was equivalent to £70M (at 1948 prices), by 1985 this had risen to £895M. Agricultural and horticultural pesticide use together accounted for 90% of the £367M home market in 1985 (BAA 1986).

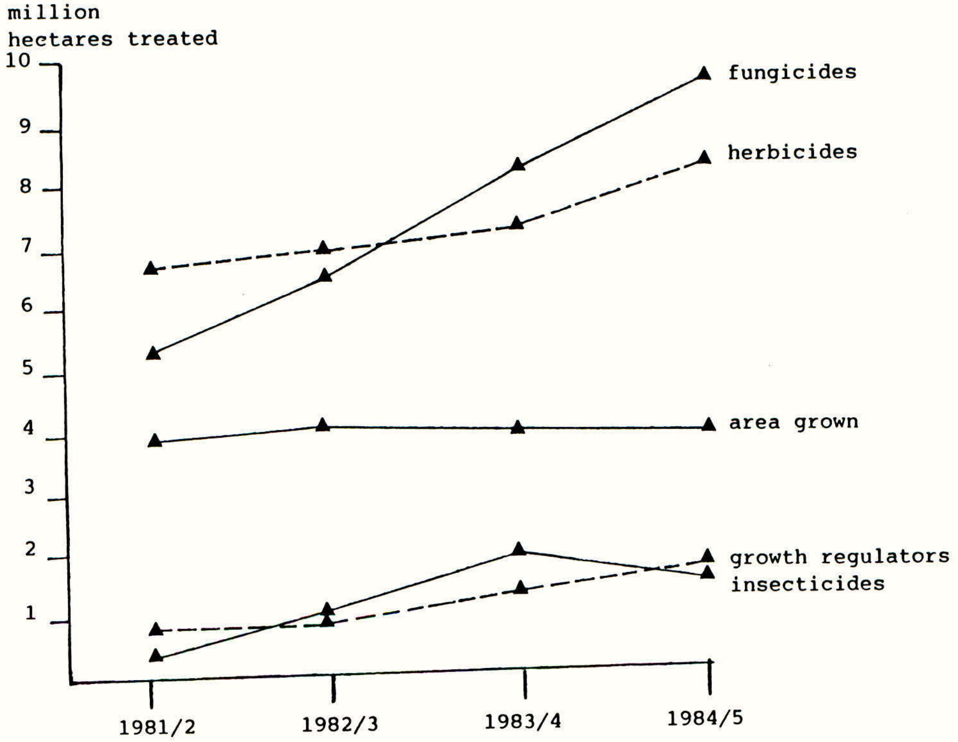
More detailed information on the use of agricultural pesticides has been collected by the MAFF Pesticide Usage Survey Group since it was formed in 1965. It was estimated in 1977 that approximately 9090 tonnes of pesticide active ingredients were applied annually to 9.5 million treated hectares of cereals (Steed et al. 1977). In the latest published survey conducted in 1982, the estimated use had risen to 16708 tonnes of active ingredients on some 17.7 million treated hectares of cereals (Sly 1984). Comparison of the results of these two surveys highlights the dramatic increase in the application of foliar fungicides in particular. The continuation of this trend is apparent from the published figures for the annual pesticide market since then (Figure 1).

The increased areas of barley and winter wheat grown in recent years and the substantial increases in pesticide use reflect the economics of grain production. Cereal crops excluding maize occupied 58% of the 7.0 million hectares of arable land in the U.K. in 1986 (MAFF 1986). Winter wheat represented 48% of this cereal area. Maintained cereal prices have enabled the farmer to achieve satisfactory profits which have provided the incentive to increase yields. Farmers have been increasingly prepared to exploit pesticides strategically to protect their crops in order to insure the financial return. However, the clearly demonstrated financial benefits of using pesticides on cereals on this scale must be considered in relation to their possible environmental effects (Stanley and Hardy 1984). While acknowledging the need for pesticides in modern agriculture, the Seventh report of the Royal Commission on Environmental Pollution (Command 7644) recommended in 1979 that pesticide use should be reduced to the minimum necessary to maintain yields and productivity.

The long-term effects of pesticides on the non-target flora and fauna associated with agricultural field crops are not clearly understood particularly indirect effects normally arising through changes in habitat or food supply (Bunyan and Stanley 1983). The only long-term information available for cereal crops is derived from the insect monitoring studies of the Game Conservancy conducted in Sussex over the last 15 years. Although these studies were designed to support investigations of the survival of the grey partridge Perdix perdix, they have involved the annual sampling of insect populations in 100 cereal fields. Numerical trends were established for 104 insect species, 52 of which appeared to decline in abundance and only 4 of which increased during the study period (Potts 1984a and b). It has, however, been difficult to separate the effects of pesticide usage from the overall effects of the farming systems in the study area since usage and practices are interdependent.

Against this background, ADAS identified in the late seventies the need for long-term studies of the environmental effects of various pest, weed and disease management systems for cereals. A project was therefore formulated with the original aim of developing suitable methodology, building on experience within ADAS and that gained by the insect monitoring work of the Game Conservancy, to examine the ecological and economic implications of pesticide use in a single crop where complete control over farming practice would permit the identification of pesticide related effects over several years.

Figure 1 Pesticide use on cereals in Great Britain (Source BAA 1983, 1984, 1985 and 1986).



THE BOXWORTH PROJECT

At the end of 1981, ADAS embarked on a major multidisciplinary project programmed to run for a period of seven years. Entitled 'Pest and disease control systems : their ecological and economic effects in intensive cereal production', the study has become known as the 'Boxworth Project' through being sited at the Boxworth Experimental Husbandry Farm (EHF) in Cambridgeshire. The principal aims are:-

1) to determine the long-term ecological effects of three different pesticide treatment regimes on animal and plant species associated with the cereal ecosystem.

2) to determine the effects of three different treatment regimes on crop yield and to provide an economic appraisal.

3) to identify the practical management and operational problems that arise from maintaining closely supervised pesticide programmes.

GENERAL DESCRIPTION

The three pesticide regimes being studied are a full insurance treatment, where a scheduled programme of insecticides, fungicides and herbicides is routinely applied to the crop at the relevant growth stage, equivalent to the input adopted by farmers seeking maximum yield; a supervised treatment, where essentially the same pesticides are applied to the crop only if the appropriate pest, disease or weed has attained an economic threshold in the crop; and an integrated treatment, where pesticides are again applied according to thresholds in the crop but where husbandry changes may further reduce chemical input. The necessary spray decisions are based on regular pest and disease monitoring by ADAS regional staff from Cambridge and weed monitoring by staff of the Weed Research Division, Long Ashton (WRD). Since the aim of the Project is to isolate and identify pesticide treatment related effects, as far as possible husbandry operations are identical on the full insurance and supervised treatment areas. This has been achieved by the matching of fields between areas.

The Project is using 133 hectares of the EHF at Boxworth and during the first two crop years, all three treatment areas received the same pesticide regime currently employed on the farm. Fauna and flora associated with the crops were monitored to provide baseline information on populations initially present on the designated treatment areas. In addition this period was used to test the husbandry operations required by the Project. Treatment regimes were introduced in autumn 1983 to continue for five crop years. As far as is practicable, the treatment areas are being maintained in winter wheat for the duration of the Project, although for farming reasons oilseed rape is grown as a break crop on a five year rotation (matched between treatment areas in any year). One field in each of the three areas is being maintained in continuous wheat for intensive study. This Project is being conducted under practical farming conditions and, since the practices and husbandry techniques adopted are generally representative of commercial cereal growing, the design does not include an area receiving no pesticide applications.

FULL INSURANCE PROGRAMME

The insurance treatment area consists of four fields totalling 67 hectares receiving a routine programme of pesticides. Cereal treatments are included to control slugs prior to drilling, wheat bulb fly and frit fly at drilling, frit fly and aphids in the autumn, cereal and grass flies in winter and aphids in the summer. Fungicides are routinely applied to control eyespot, Septoria, mildew, rusts and Botrytis. Herbicides include the pre-sowing, early post-emergence and spring applications of wide spectrum herbicides to control broad-leaved weeds and grasses, a wild oats herbicide and pre-harvest wide spectrum treatments.

Pesticides are applied to oilseed rape crops to control slugs, cabbage stem flea beetle, cabbage seed weevil and pod midge. Fungicides are used to control light leaf spot, Sclerotinia and Alternaria.

SUPERVISED PROGRAMME

Principally the same pesticides are used on the three fields of the supervised area which occupies 45 hectares. Where available, environmentally more desirable chemicals are used e.g. pirimicarb is used as a more selective aphicide in place of demeton-S-methyl. Applications depend on closely monitored threshold levels of pests, diseases or weeds in the crop and each field is considered independently.

INTEGRATED PROGRAMME

The three fields of the integrated area (21 hectares) receive essentially the same chemicals as the supervised area according to thresholds on individual fields. However husbandry operations are modified to further reduce the need for pesticide applications. These include deep cultivation, later sowing dates, higher seed rate etc. In addition, varietal choice is made for increased disease resistance rather than yield characteristics. The aim of this programme is to achieve positive reduction of pesticide usage consistent with maintaining a viable crop.

PEST, DISEASE AND WEED MONITORING

In order to provide the necessary information required for spray decisions in the supervised and integrated areas, the levels of pests, diseases and weeds are being closely monitored. This includes the monitoring of disease status within the crops, from emergence to the milky-ripe stage, by ADAS Regional Plant Pathology. ADAS Regional Entomology staff are monitoring the status of slugs, various stem borers, grass and cereal flies and aphids by regular inspection of field crops through the growing season. Established ADAS advisory thresholds are used to formulate spray decisions. Staff from the WRD are monitoring field weed populations. Each field is surveyed in the summer using gridded co-ordinates to count the established population of major grass weeds and to measure the potential seed crop. Repeat surveys are made in the autumn and spring and also detailed estimates of weed populations made from transects from the study fields into adjacent non-crop habitats. Weed thresholds have been established by WRD (Wilson 1986) and are being tested and refined during the Project.

ECONOMIC APPRAISAL

In order to provide data for an economic appraisal of each treatment regime, the costs of seeds, fertilisers and pesticides are being recorded for each area and every agricultural operation is being costed for both labour and machinery. The advisory time spent by ADAS regional staff and WRD staff to monitor crops to determine pest, disease and weed status will be included in both the supervised and integrated programme costs. In an attempt to overcome the effects of inter-field variation across the treatment areas, a replicated small plot trial has been sited on one of the fields in the full insurance area. This provides additional data on the effects of yield of the insurance and supervised pesticide programmes for comparison with the individual field data. Included in this plot trial is a third treatment with minimal pesticide applications of herbicide alone, sufficient only to obtain a crop off the plots.

ENVIRONMENTAL MONITORING

A wide range of environmental studies are being conducted by research staff from ADAS, WRD and universities in order to monitor as many taxonomic groups as possible of the fauna and flora associated with the winter wheat crop and its immediate surroundings. In combination, these separate studies will provide the capability to monitor long-term population changes on the three treatment areas for the duration of the Project.

Invertebrate populations are being monitored by university staff at Cambridge and Southampton Universities. Studies include a detailed investigation of the relationship between major cereal pests, particularly aphids, and their parasites and predators. A second study involves monitoring the abundance of a wide range of invertebrate fauna and aims to investigate the life histories and population dynamics of important polyphagous predators. Field data are being supplemented by pesticide toxicity measurements on insects in the laboratory.

University personnel are also studying the distribution, population dynamics, movements and feeding ecology of small mammals, particularly the wood mouse Apodemus sylvaticus and shrews. These studies will be closely linked to the entomology projects. ADAS staff are studying the breeding success and feeding ecology of resident insectivorous birds to assess the effects of exposure to different pesticides applied to the cereal crops. This study is closely tied to the entomology studies and includes both pesticide residue measurements of invertebrates in the crop and biochemical measurements from the birds. Certain other taxonomic groups, not being covered by other studies, are being monitored by ADAS staff.

In addition to monitoring the abundance and distribution of weed species in the crop, WRD staff are also monitoring flora in the field margins to study the effects of adjacent crop treatments. This includes the assessment of seed banks in the soil through the subsequent germination of collected samples. During the course of the treatment phase of the Project individual applications of selected pesticides, of particular interest to various research studies, are being studied to determine the environmental fate of applied residues. These include drift studies of hedgerow contamination and entail both residue measurements and biological sampling.

PRELIMINARY RESULTS

Since there are a further two crop years before the completion of the five year treatment phase of the Project, it is considered premature to draw firm conclusions from the agronomic results obtained so far in view of the rather different crop years to date. However various trends are beginning to appear from the ecological monitoring of the treatment areas. There is growing evidence that the autumn and winter insecticides have a marked direct effect on various insects and other groups where all or part of their populations overwinter at or near the soil surface out in the fields. Several Coleoptera eg. Bembidion obtusum and Linyphiid spiders, which can be important predators of some pests, have shown reduced spring populations in the full insurance area. This contrasts with some predatory beetles eg Agonum dorsale that overwinter in the hedge bottoms and whose populations appear unaffected. No such differences are apparent in the supervised and integrated areas. The ecological and practical consequences of these differences are not yet known but are being investigated by manipulative techniques using exclusion barriers within the crop. Collembola populations are lower on all fields of the full insurance area than in the other two treatment areas and this is reflected in their lower frequency of occurrence in the diet of A. dorsale in the insurance area.

Studies of small mammals on and adjacent to the cereal crops suggest mortality of woodmice Apodemus sylvaticus after the autumn application of methiocarb slug pellets though there is no direct evidence. Comparison of trap captures before and after field treatments show that mice present in September are replaced within a month by younger immigrant mice thought to have come from nearby habitats. This coincides with the autumn peak usually seen in mice populations (Watts 1969) but the long-term biological significance of this population turnover is not yet clear. Early indications from the census studies of common farmland birds breeding in the treatment areas are that resident birds do not show direct effects from the spraying of pesticides on the crops. However the application of aphicides may reduce the local food supply of insectivorous species eg the Tree Sparrow Passer montanus which feeds on insects in the crop. The implications of this are being studied by monitoring the food and foraging behaviour of adults and their breeding success and looking biochemically for evidence in both adult and young birds of exposure to aphicides.

Floral studies by WRD of the three intensive study fields indicate reductions in grass weed populations on the insurance field where numbers of dicotyledonous species recorded in the fields are also lowest. There was initial evidence of a trend for increased species diversity in the field margin where fewest herbicides were applied but further monitoring is required to clarify this (Marshall 1985).

DISCUSSION

In the early stages of project design, the decision was taken on the basis of the mobility of faunal species, that it would not be feasible to work on small plots. A working farmland system was required including whole fields and boundaries which would provide as large areas as possible of given pesticide treatments in order to reduce any edge effects to a minimum. However in the light of resource limitation such an approach precluded a high degree of replication. With this departure from classical experimental design, it was considered important that variability other than that directly attributable to the treatments should be kept as low as possible to permit the identification of treatment effects. A system of twinning was therefore introduced to match fields between the full insurance and supervised areas for all non-treatment field operations. For example, at sowing time first one field is drilled then its twin immediately afterwards. The second pair is then dealt with followed by the next twinned fields. In the event of unfavourable weather delaying progress, it is probable that at least some twinned fields in each area will have been sown relatively close together in time. Opportunity exists to correct the yield data from individual fields statistically using historical data from the previous 15 years in order to reduce the inter-field variation. The inclusion of a replicated small plot trial provides a further comparison of treatment effects on yield. However, its results must be interpreted with due caution since, for example, the pest and disease pressures of the full insurance area surrounding the supervised treatment plots are lower than if the plot trial had been sited on a field in the supervised area. Pesticide applications to the supervised treatment plots of this replicated trial are therefore based on threshold monitoring in the twinned field in the supervised area.

It is of course accepted that the Boxworth Project will not provide definitive answers about the economic and ecological significance of the effects of pesticide use strategies on winter wheat on a national scale. However, as a test-bed of ideas, it is hoped to identify those particular groups of flora and fauna which should be studied in further detail, perhaps as indicator species, on other sites and under different conditions. This will permit the replication necessary to clearly identify treatment-related effects which are beginning to become apparent at Boxworth. The results of this Project will be used as a source of advice to both advisers and farmers to assist them to achieve a sensible balance between the essential use of pesticides on the one hand and the exploitation of the natural control of pests, diseases and weeds on the other.

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THE CEREALS AND GAMEBIRDS RESEARCH PROJECT: AN INDEPENDENT VIEWPOINT.

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ABSTRACT

Two methods of alleviating any undesirable side effects of the uses of pesticides on farmland on wild gamebirds and other forms of farmland wildlife are proposed from the viewpoint of an independent research unit; the farmer-funded "Cereals and Gamebirds Research Project". This being accomplished firstly, by providing farmers with advice on the spectrum of the insecticidal activity against beneficial non-target arthropods of the pesticides used on farmland and secondly, by experimenting with areas of the crop selectively sprayed at only certain times of the year, expressly for the benefit of farmland wildlife. Advantages and disadvantages of the approaches undertaken by the Project in terms of scale and species studied are discussed.

INTRODUCTION

Bunyan & Stanley (1983) concluded that there was little evidence to suggest that the survival of individual species was threatened by the direct effects of pesticides used on British farmland. The Game Conservancy consider that this conclusion is misleading because data collected on the population status of one species of lowland gamebird, the Grey Partridge (*Perdix perdix*) have shown an 80% reduction in the national average breeding pair density of this species over the last thirty years (Potts 1986). Increasing levels of annual chick mortality over this period caused primarily by the decreasing abundance of insects found in cereal fields that are vitally important in the diet of young chicks is now considered to be the major factor responsible for this decline. Pesticide use is implicated in this decline because intensification of farming with its associated increased levels of pesticide use has been shown to be responsible for some of these observed increases in chick mortality, by the removal of many groups of non-target insects, especially those known to be preferred food items of partridge chicks (Green 1984). The majority of pesticides currently used on farmland are not directly toxic to gamebird chicks if used properly. The effects on partridge populations occur through a removal of insect food material either directly by the action of insecticidal compounds with broad-spectra of activity on non-target species (Vickerman & Sunderland 1977, Vickerman & Sotherton 1983, Sotherton 1982a, Sotherton 1985), or indirectly, in the case of phytophagous species, following the removal of host plants by herbicide applications (Southwood & Cross 1969, Vickerman 1974, Sotherton 1982a).

The Game Conservancy is an independent research organisation funded primarily by farmers and landowners. Thus, we are acutely aware of the need to promote efficient agriculture with the appropriate attendant requirements for crop protection. But this must be achieved in such ways as to minimise the adverse effects on wild game and farmland wildlife. Farmers need agrochemicals to achieve the highest standards of crop hygiene and yield, (both quantity and quality). But can we afford to achieve these aims, if it is at the expense of farmland wildlife? Our response to this question was to set up "The Cereals and Gamebirds Research Project" and fund the research from the farming community itself.

AIMS

The project's aims are to devise methods of alleviating the adverse effects of pesticides on farmland wildlife in ways compatible with efficient modern farming and with minimum cost to the farmer.

METHODS AND APPROACHES

Three methods have been suggested to achieve these aims, two of which are the research priorities of this Project. However, the third approach to pesticide use is worthy of mention here. That is, a system of crop protection based on decisions to carry out a treatment following the perception of pest organisms above economic threshold levels. In other words, spray only when necessary! Examples of this approach to pest management can be found in these proceedings (Wratten *et al* 1986) and elsewhere (Wilson 1986).

The Project's approaches are therefore two-fold; firstly we advocate the use of pesticides with a minimum spectrum of activity against non-target arthropods, not only amongst the insecticides but also the fungicides, and for those reasons already stated, amongst the herbicides. Our second approach has been to experiment with small areas of cereal fields selectively unsprayed with certain chemicals at certain crucial times of the year to promote the resources that are necessary for game and other wildlife.

INDICATOR SPECIES

Throughout our researches, we have chosen to study indicator or key species rather than carry out studies on the total crop ecosystem. The choice of the grey partridge as an indicator species is an obvious one. Not only is it a species of the arable landscape and therefore more likely to show changes in its populations following changing farming practices, but also being a quarry species its decline has been detected and monitored far earlier than would have been the case with, for example a carabid beetle.

Other indicator species would, we believe, also provide information to help quantify pesticide impact, the choice being based on existing autecological studies. For example, a weed feeding chrysomelid beetle (Sotherton 1982b), other preferred food items of gamebird chicks (Green 1984, Hill 1985), and farmland species of Lepidoptera (Dover 1986). Other choices could be made from studies to assess the importance of natural enemies of cereal pests, either where natural enemies have been ranked in order of their importance as predators (Sunderland & Vickerman 1980, Wratten *et al* 1984), where groups of natural enemies have been studied (Vorley & Wratten 1985; Sunderland *et al* 1986), or again where appropriate autecological studies have been carried out (Griffiths *et al* 1985, Coombes 1986).

ACTIVITY OF PESTICIDES AGAINST NON-TARGET FAUNA

Assessing the spectrum of activity of a pesticide has involved laboratory and field screening. In the Project, we have screened in a laboratory twenty-seven single active ingredient foliar fungicides approved for use in cereal fields in Britain. So far, based only on contact toxicity of compounds used at recommended field dose rates and dilutions, only one compound has shown significant insecticidal properties. Laboratory work, however merely identifies candidate compounds for further screening in large-scale, replicated field trials. In this case, the use of the fungicide pyrazophos under field conditions showed the extent of this insecticidal action (Table 1). Reductions of preferred food insect densities by 60% were predicted by computer simulation (Potts 1986) to have subsequently reduced chick survival rates from 31% to 12% in 1984 and from 20% to 16% in 1985 (Sotherton & Rands *in press*).

TABLE 1

The effects of three foliar fungicides on non-target, beneficial arthropods in United Kingdom cereal fields.

	% reduction due to pesticide compared to untreated areas				
	propiconazole*	triadimefon*	pyrazophos *	pyrazophos **	pyrazophos ***
Total chick food insects	9.6	3.3	44.6	69.4	31.0
Total predatory arthropods	0.0	0.0	24.9	25.1	47.6
Total aphid-specific predators	0.0	16.9	83.8	80.4	34.6
Parasitoids	0.0	0.0	55.2	36.0	34.0

* = 1984, winter wheat, sprayed at GS 50, sweep samples
** = 1985, winter barley, sprayed at GS 37, suction samples
*** = 1984, spring barley, sprayed at GS 60, suction samples

Similar work in 1986 on the spectrum of activity of four insecticides currently approved for control of summer aphids has now begun and will provide farmers with the information needed to choose suitable pesticides based on the existing two criteria i.e. their price and efficacy and now a third criterion; that of relative safety to non-target species.

SCREENING PROCEDURES: ADVANTAGES AND DISADVANTAGES

Our large-scale, replicated field trial approach following initial laboratory screening has many advantages but a criticism of this approach sometimes put forward by those who do not accept that crop protection methods can cause environment damage is that the effects of pesticides cannot be separated from those of other agricultural practices. In experiments of this nature where plots within fields receive identical treatments except for one particular pesticide application, the only parameter being measured is the response of the fauna of flora or that pesticide. However, this approach can have associated problems of data interpretation that are on first inspection not easy to resolve. For example, an extreme case was found in one of our experiments in 1984 where a two treatment in two fields design produced data showing a 93% reduction in chick food insects on plots of spring barley treated with pyrazophos compared to untreated controls. Statistical analyses based on the one degree of freedom inherent in this design meant that those levels of reduction were statistically non-significant.

Another problem arises with the observed persistence of the effect of a pesticide and the plot size chosen in field-scale experiments. In 1985, significant reductions in non-target insects were found up to seven weeks after treatment on plots as large as 24ha. Small plot size will lead to more rapid recolonisation from adjacent unsprayed areas (Powell *et al* 1985). Short-term persistence of the effects of a pesticide do not therefore imply safety, but merely reflect the scale of most field experiments. There is therefore a need to resolve the problems of plot size and rate of recolonisation to aid the interpretation of field experiments assessing the effects of pesticides on mobile and sedentary species. Again the choice of indicator species based on their relative mobility would not be difficult. Nor would it be difficult to devise experiments to assess the optimum plot sizes for realistic data interpretation. Is it therefore necessary to spray the entire farm or even most of Hampshire to convince our critics?

Our laboratory screening has so far been based on tests measuring initial contact mortality. We have now begun to examine some of the sub-lethal effects on non-target species. Experiments have begun whereby the survivors in our fungicide screenings are allowed to develop so we can detect perhaps more subtle effects on, for example, longevity, subsequent adult fecundity, egg viability and predatory potential. We have been mainly concerned with broad-spectrum or persistent compounds. What we are now asking ourselves is what are the effects of repeated doses of less toxic compounds?

SELECTIVE USE AND TIMING OF PESTICIDES AT THE CROP MARGIN: "CONSERVATION HEADLANDS"

Our second approach to alleviate the effects of pesticides on farmland wildlife has been to leave small areas of cereal fields selectively unsprayed with certain chemicals at certain crucial times of the year: a technique that has become known as "unsprayed" or "conservation headlands". The technique has involved manipulating herbicide use on the outermost 6m around the crop edge in such a way as to remove the pernicious weeds such as wild oats, grass weeds and cleavers but retain the broad-leaved species that are the host plants of many of the non-target species of phytaphagous insects. Insecticidal compounds are also not used in this area.

In 1983, experiments were carried out on 520ha of a 1200ha farm near Basingstoke. On each of the three gamekeepers' beats, two blocks of cereal fields were marked out, one block was fully sprayed following normal farming practice whilst the outermost 6m of the cereal fields on the second block on each beat had no pesticides applied from January until harvest. In 1984 the treatments on the blocks were reversed so that headlands fully sprayed in 1983 were "unsprayed" in 1984 (Rands 1985). The absence of herbicides predictably encouraged the weed flora in these crop margins but also significantly increased the numbers of preferred chick food insects (Sotherton *et al* 1985). The impact on wild gamebird production of the use of those techniques over the last three years has shown significant short-term increases in the autumn stock (Rands 1985, 1986) but also an increase in the spring pairs per km^2 from about four pairs in the early 1980's to around eleven pairs in 1986 (Rands, unpubl. data).

This aspect of our work also highlights the need not only to quantify the spectrum of activity of a compound, and to pursue work on sub-lethal effects, but also to consider indirect effects, for example the consequences of the removal of host plants by herbicide use.

Our work has now expanded to quantify the benefit of pesticide manipulation for gamebirds to other forms of farmland wildlife. Currently, projects are underway to study the interactions of butterflies, small mammals and wild flowers with the resources found within unsprayed headlands relative to other areas of farmland. For example, butterfly census transects carried out on equivalent areas of fully sprayed and selectively sprayed cereal field headlands has over the past two years produced observed increases in the numbers of many species of farmland butterfly in these "conservation headlands" (Rands & Sotherton 1986, Dover 1986) (Table 2).

TABLE 2.

The numbers of different butterflies seen in sprayed and conservation headlands, north-east Hampshire, 1984 and 1985.

	1984		1985	
	"Conservation"	Sprayed	"Conservation"	Sprayed
Brimstone	52	10	17	5
Common Blue	18	1	0	0
Green-veined White	140	21	196	176
Gatekeeper	93	59	134	32
Holly Blue	29	13	3	2
Large Skipper	17	1	10	4
Large White	56	38	13	20
Meadow Brown	123	46	109	32
Orange Tip	11	0	1	1
Peacock	39	19	29	2
Ringlet	52	23	17	6
Small Heath	11	0	0	0
Small Skipper	41	2	6	1
Small Tortoiseshell	95	42	131	77
Small White	19	14	1	3
Speckled Wood	10	2	3	2
Wall	9	4	0	0
Transect length (km)	3.6	3.2	2.1	2.3
Total	815	295	670	373

THE SITUATION IN EUROPE

The concept of "unsprayed" or "conservation headlands" is now being tested in Europe. In Denmark, research workers are currently involved in multi-disciplinary studies to investigate "pesticide exclusion zones". These are funded by the Government and modelled directly on our work (Hald 1986). The scale of their experimentation is smaller than ours and therefore the scope of their work is limited to quantification of agronomic consequences, pesticide residue work and botanical and entomological studies. Enquiries about our work has also been made by the Dutch Ministry of the Environment. In West Germany, several States have funded work on unsprayed crop edges for the conservation of rare arable weeds (Schumacher 1980) and they compensate farmers accordingly. Similar work is in progress in Austria and Switzerland.

COLLABORATION WITH OTHER STUDIES

From the other presentations in this session, it can be seen that our work compliments that of the work already being undertaken in this field by Government Agencies. Indeed, much of our recent funding for specific projects have come from the Ministry of Agiculture, Fisheries and Food, the Natural Environment Research Council, Science and Engineering Research Council and the Nature Conservancy Council as well as many charities and charitable trusts. We are also actively co-operating with Agriculture and Food Research Council institutes and A.D.A.S. officers, making maximum use of specialist advice in, for example entomology, agronomy and statistics. The objectives of the Cereals and Gamebirds Research Project are well defined and specific, and we believe achievable. There is perhaps scope for more or better coordination of the various projects within the U.K. to answer the many fundamental questions which remain. Recently, the U.K. Government has reduced the research budget to Agriculture and has shifted the emphasis from food production to other areas, but insignificant funds are available for the research necessary to answer the environmentalists' criticisms of our agricultural system praciced on a land area that represents 80% of the United Kingdom's lowlands.

THE FUTURE?

Finally, it may be useful to consider the future. Much has been heard of Sites of Special Scientific Interests (S.S.S.I.'s) and Environmentally Sensitive Areas (E.S.A.'s) but the percentage of arable land involved is quite insignificant, most E.S.A.'s being in Less Favoured Areas (L.F.A.'s) in the North and West, and are therefore less favoured for wildlife (O'Connor & Shrubb 1986). Perhaps the most important questions are related to what will happen in Europe to curb surpluses and ensure a more sympathetic farming system. Are "conservation headlands" practical or not? - it depends on whether you describe your glass as half full or half empty!

For many farmers, weed control is necessary not simply to ensure crop yield but also to maintain a clean "crop floor". Against this background, it is not easy to develop an unsprayed headland system which encourages some weeds. It must be remembered that much of the research to date did not even query the need for complete control until the work of G.W. Cussans and B.J. Wilson (Weed Research Division/Long Ashton Research Station) on "crop equivalents". Yet, their interests in reducing inputs because of cost mirrors our requirements almost exactly.

Farmers are proud, and dislike their farms to look untidy. If one is to farm sympathetically to nature, we must not be so tidy, so how do we achieve the balance? It takes courage on the farmer's part to change from tidiness to a weedier farm risking comments from those who may not know why the weeds are there.

The future of the Cereals and Gamebirds Research Project is clear. Over the remaining period for which the project is funded, we will continue to advise farmers on the spectrum of activity of the pesticides they use on their land and to devise a working management system for reduced pesticide use at the crop margin.

We hope that a desire to enhance wildlife or partridge populations may in future become a stronger motivation than pride in clean crop margins. The important point is that the technique is practical and any agricultural problems can be overcome with research, care and forethought.

Overall, the Project has tried to fill a gap in agricultural research which, over the last 20 years, has emphasised production, but at some cost to farmland wildlife. Our approaches have not been particularly innovative. Indeed, our methodologies put forward to alleviate the pressure on farmland wildlife are those already used in integrated control programmes. However, we hope you will agree that the Project has broken new ground in many areas not least in farmer funding, in private management, in speed of reaction to changes in farming technology such as the introduction of new pesticides, and in using a collaborative multi-disciplinary approach.

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INTEGRATED CROPPING OF WINTER WHEAT AS AN EXAMPLE OF INTEGRATED FARMING

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ABSTRACT

Since 1979 on the national experimental farm for development and comparison of alternative farming systems (DFS) at Nagele, the Netherlands, an integrated farming system is being developed. As an example the integrated cropping of wheat is discussed and placed in the context of the whole farm. The preliminary results show that the conventional wheat cropping has the highest physical yields and gross margins. Yields in the integrated system could not be sufficiently compensated for by cost reduction based on a considerable lower input of fertilizers and pesticides. However, the yield level can further be improved, mainly by a better timing of the N-fertilization.

INTRODUCTION

The Dutch experimental farm for development and comparison of alternative farming systems was started in 1979 under the name Development of Farming Systems (DFS). It is situated near the village of Nagele in the Northeastpolder, 3-4 meters below sea level on heavy sandy marine clay (lutum fraction of 24%). The size of the farm is 72 ha.

Three farming systems are studied. Biodynamic, Integrated and Conventional. They are run independently of each other on a commercial basis by only one manager and four co-workers. The Biodynamic farm (22 ha) began as a mixed farm with 20 dairy cows and a 10-year rotation. Its main objective is to be self-supporting in fertilizers and fodder. No pesticides are allowed. The conventional and the integrated farms are 17 ha each, with the same four year rotation of arable crops. The plot-size is 2 ha. The conventional farm serves as a reference. Its main aim is a maximum financial return. The integrated farm should produce a corresponding financial output, but is also aimed at minimum input of fertilizers, pesticides and machinery to avoid pollution of the environment and save non-renewable resources.

The main objective of research in the first 10 years will be the development of the two alternative systems. Comparative research between the systems will become more important when they are nearing a more or less optimum state. For more details concerning design, research and results of the project see Vereijken (1986).

The concept of integrated farming

The concept of integrated farming is extensively described in a recent IOBC-bulletin (Vereijken et.al., 1986). It is stated that 'an integrated farming system relies as much as possible on cultural and biological inputs, with chemicals as integrated supplements. The main aims are to minimize inputs of non-renewable resources and to provide a better balance between adequate production of yields and farm income on one hand and ecological, environmental and sociological aims on the other. All these considerations must be compatible with cost effectiviness'. Integrated crop protection should be considered as part of an integrated crop production system. Considering the problem of overproduction and production-limiting measures, cost reduction and improvement of efficiency should be emphasized more than raising yields.

INTEGRATED CROPPING OF WINTER WHEAT

The main elements of the integrated cropping of wheat will be highlighted in comparison with the conventional approach.

Rotation

The crop rotation is a major element in an integrated approach. It is a highly effective preventive measure against diseases, pests and weeds. Moreover it is of great significance for the maintenance or improvement of the structure and fertility of the soil. Unfortunately the use of a healthy rotation is limited by the demands of the economy.

Therefore and for reasons of comparative research the integrated farm on DFS has the same 4-year rotation of high yielding crops as the conventional farm (Table 1). Potatoes are the most profitable, followed by sugarbeet and the vegetables, carrots and onions. Peas and wheat are financially less attractive but especially the latter is needed as a break crop. Potatoes need a good soil structure and react very well to fresh organic matter in the soil. From this point of view wheat is an excellent preceeding crop. Grown after sugar beet it restores the structure of the soil. Secondly it offers good opportunities for the undersowing of a green manure crop. This provides together with the straw of the wheat a lot of fresh organic matter.

TABLE 1

Crop rotations.*

	Conventional + Integrated
1.	½ ware potato, ½ seed potato
2.	½ pea, ¼ onion, ¼ winter carrot
3.	sugar beet
4.	winter wheat

*) Rotations from 1985 onwards. Before this vegetables were not grown. On the conventional and integrated farms winter barley was grown instead of pea and winter carrot.

Choice of cultivar

From Table 2 it appears that in the integrated system more attention is given to disease resistance and weed suppression than to yield potential, contrary to the conventional approach. Generally, tall cultivars with a greater distance between leaves and between flag leaf and ear are more "resistant" to the vertical spread of diseases, in particular Septoria nodorum blotch (*Leptosphaeria nodorum*). Leaf-abundance and early soil covering are important for effective weed suppression. Yield capacity is less important, but nevertheless it should be not less than 95% of that of top cultivars. The current cultivar fulfills these demands. Baking quality is getting more important but its exact significance is not yet clear.

TABLE 2
Criteria for the choice of cultivar (1 = most important, 5 = least important).

Criteria	Conventional	Integrated
winterhardiness, recovery after frost	1	1
yield capacity	2	4
resistance against		
- lodging	3a	2b
- presprouting	3b	2c
- major pathogens	3c	2a
- preharvest kernel loss	3d	2d
suitability as cover crop*	4	3
early ripening	5	5
baking quality	?	?

* weed suppressing capacity

Fertilization

High input of especially N-fertilizers may lead to a heavy and dense crop which is more susceptible to lodging and attack by pests and diseases. Moreover, it may encourage abundant weed growth. Therefore, we decided to restrict the first N-application in the integrated system by some 40 kg compared to the conventional system (Table 3). The P- and K-fertilization for the whole rotation is applied on the potatoes.

TABLE 3
Fertilization.

	Conventional	Integrated
Mineral N in kg/ha		
first application	140 - Nmin	100 - Nmin
second application*	60 -(30)	
third application	40 dependent on crop and weather condition	
P/K - application	0	
green manure	sugar beet leaves and tops	

* Second application can be reduced with 30 kg N/ha because sugar beet leaves and tops are incorporated.

Undersowing of green manure crops

From Table 4 it appears that in the integrated system a mixture of grass and clover is preferred for undersowing instead of only grass. The green manure crop should be sown as soon as possible, so it can establish before the light interception by the wheat impairs further growth. Then it only has to maintain itself during the crop phase to start off in the stubble with 2-3 weeks lead compared to sowing after harvest. Red clover is prefered because it combines a good production and weed suppression in the stubble with a tolerance for certain herbicides which may have to be used.

TABLE 4

Criteria for a green manure crop as undersow.

Conventional	Integrated
Criteria	
chance for succes and production	the same
no limitations for chemical weed control in crop and stubble	good weed suppression
	preferably legumes
Choice	
Perennial or Italian ryegras	mixture of Perennial or Italian ryegrass with red clover

Disease and pest control

As shown in Table 5 the conventional system mainly relies on chemicals for the control of pests and diseases. The integrated crop protection starts with the choice of a highly resistant cultivar in both the physiological and phenological sense. Postponement of the sowing until around the first of November reduces the risk of autumn infections by pests and diseases, for example aphids, slugs and foot rot diseases. According to our experience attack by Fusarium spp can be reduced by abandoning seed treatment. A possible lower emergence can be compensated for during tillering, ear development and grain filling. The somewhat lower N-fertilization makes the crop less susceptible to attack by many pests and diseases.

TABLE 5

Pest and disease control.

	Conventional	Integrated
seed treatment	yes	no
sowing date	october	± 1st november
choice of cultivar	yield capacity more important than resistance	the reverse
growth regulator	if necessary	no
N-fertilization	economically optimal	restricted first application
pesticides	supervised control, EPIPRE	adapted EPIPRE

For the additional chemical control of aphids and diseases the so-called EPIPRE-system is used (Zadoks, 1981). It is based on field observations, epidemiological simulation models, yield expectations and economic damage thresholds. We have adapted EPIPRE somewhat for the integrated system by relating the growth and multiplication rate of obligate diseases and aphids to the N-fertilization. A second adaption was the introduction of an extra 'levy' on the use of biocides, thus raising the damage thresholds. In the adapted version the yield expectations, are approximately 500 kg/ha lower.

Weed control

Also in the integrated weed control many elements are combined to restrict the use of herbicides as much as possible (Table 6). Delaying ploughing and sowing until around the first of November has generally no negative impact on yield and is such an effective prevention of weeds in our region that autumn applications of herbicides are not necessary. The lower N-level together with the strong weed-suppression of the chosen cultivar usually makes spring applications also superfluous.

TABLE 6

Weed control.

	Conventional	Integrated
sowing date	october	± 1 november
choice of cultivar		maximum weed suppression
N-fertilization	optimal	restricted first application
mechanical control	harrowing at undersowing	
herbicides in crop or stubble	broad spectrum combinations full-field applications	no, unless heavy weed pressure, preferably spot-treatments

Perennial weeds are controlled during the whole rotation by spot-treatments of chemicals, especially in the stubble of wheat and peas. In the choice of herbicides to be used their spectrum of activity and their toxicological properties are considered.

Stubble management

Contrary to the conventional system, straw in the integrated system is usually chopped and left on the field to serve as a carbon source for the soil micro organisms after ploughing. Thus they can incorporate mineral nitrogen and prevent it from leaching. However, when straw prices exceed DFL 70 per ton, the straw is sold (Table 7).

TABLE 7

Management of the stubble and green manure crop.

	Conventional	Integrated
straw	selling	chopping unless prices higher than DFL 70/t
stubble	short	long, unless straw is sold
organic manure after harvest	liquid chicken manure	no
herbicides	full field	preferably spot-treatment
cultivation of stubbles and green manure	ploughing in autumn under good soil/weather conditions	rotary cultivation before ploughing

On the conventional wheat stubble liquid chicken manure is applied, to give the potatoes, the following crop, fresh organic matter, P and K. Most of the N is lost by volatilization of ammonia and leaching of nitrate. Only a part of the N is taken up by the green manure crop. To avoid such undesirable effects in the integrated system, organic manure is only applied in spring shortly before seed-bed preparations. To supply the potatoes with some extra nitrogen, red clover is sown under the wheat.

In the conventional system the grass green manure is ploughed directly under, together with the wheat stubbles and straw. In the integrated system however, the mixture of straw, stubble and grass-clover is first rotary cultivated to enhance the aerobic and fast decomposition, and to avoid disturbance of the air- and waterstatus, and root development of the next crop.

PRELIMINARY RESULTS

Table 8 shows that over the years 1982-1984 on average only 2.2 chemical treatments per field were applied in the integrated system against 5.1 in the conventional system. Expressed in active ingredients the pesticide input was reduced from 6.11 to 0.75 kg/ha.

TABLE 8
Chemical control over the years 1982-1984.

	average number of treatments per field		active ingredients (kg/ha)	
	Conventional	Integrated	Conventional	Integrated
herbicides	1.3	0.2	3.24	0.08
growth regulator	0.5	0.0	0.42	0.00
fungicides	2.3	1.0	2.23	0.50
insecticides	1.0	1.0	0.22	0.17
total	5.1	2.2	6.11	0.75

TABLE 9
Yields over the years 1982-1984.

	Conventional	Integrated
physical yield 1)	8.3	7.4
total returns 2)	4.55	4.05
allocated costs 3)	1.20	1.02
gross margin 4)	3.35	3.03
world market prices		
total returns 2)	2.65	2.37
allocated costs 3)	1.20	1.02
gross margin 4)	1.45	1.35

1) t/ha
2) price/t x t/ha in 1000 guilders
3) costs of pesticides, fertilizers, hired labour, sowing seed, insurance, interest
4) total returns minus allocated costs

From Table 9 it appears that over the same period the wheat in the integrated system yielded in average 0.9 ton/ha less, eventually leading to a DFL 330/ha lower gross margin. Table 9 also shows that at world market prices for the grain (DFL 0.32/kg) the difference between the two systems was reduced till DFL 110/ha. So, even then the lower physical yields were insufficiently compensated for by cost reduction, based on the lower input of pesticides and fertilizers.

Nevertheless, it should be mentioned that in the same period over the whole rotation the integrated farm had slightly better economical results, thanks to large reduction in costs (Vereijken, 1986).

DISCUSSION

Although in recent years, the yields of winter wheat in the Netherlands have increased considerably, the inputs, especially of pesticides, have remained on a rather low level. The average number of chemical treatments per field is only some 6-7 (including herbicides, seed treatment and growth regulators).

In a situation like this with very efficient use of inputs there is little opportunity left for substantial decrease of allocated costs. However we tried in our experimental integrated approach to abandon most of the chemical control treatments and to reduce the N-fertilization by some 40 kg/ha.

However, economically this only meant an average input reduction of 180 guilders/ha equalling 320 kg wheat at EC-prices, or 560 kg at world market prices. This was not enough to compensate for the average yield loss of about 900 kg/ha over the years 1982-1984. So, it has to be concluded that economically integrated wheat cropping cannot yet compete with a conventional approach, unless the average yield loss can be brought back from 900 to approximately 350 kg/ha.

How can the yield level in the integrated system be improved? In our opinion mainly by better timing of the second N-application. A result of the reduction of the first application by some 40 kg/ha with the normally timed second application around GS 31, is that the development of side-tillers is reduced. To avoid this, the second application should be given earlier.

Progress on this major point may also enhance the yield stability. This can further be improved by helping the farmer with his decisions making by a computerized guidance system, which we are developing.

In summary: the final goal is a cropping system with stabile, but probably lower physical yields than a conventional system. The pesticide input is strongly reduced to the benefit of nature and environment. If the loss of yield can be kept within the limits set by cost reduction, the resulting gross margin will be more or less the same as conventional. The lower the yield level or the grain prices, the greater is the potential for the integrated approach.

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CROP PROTECTION : IMPACT ASSESSMENT IN THE FARMLAND ENVIRONMENT

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ABSTRACT

Habitat manipulation, in particular by physical disturbance but also fertilization, pesticide application and crop choice, has had an enormous effect on the flora and subsequently the fauna. On the fauna alone, pesticides have both direct and indirect effects. Techniques for investigating direct effects on wildlife are improving but more work is needed to identify key sets of non-target species, especially insects, and what constitutes a significant effect on their populations. The significance of indirect effects are less well known as they are often associated with management systems rather than individual chemicals. A greater understanding of the exposure patterns and population ecology of farmland species is needed before we can fully appreciate the implications of pesticide impacts.

INTRODUCTION

In general, the abundance and diversity of animal communities is mediated by the abundance and diversity of the plant community with which they are associated. The clearing and subsequent management of land by man has had the most profound affect on plant and therefore animal communities. In the arable ecosystem, the tools of management are physical disturbance, the addition of manures, pesticides and crop plants. With respect to pesticide application, Bunyan & Stanley (1983) considered that though pesticides have had both "direct" and "indirect" effects on the wildlife, there was little evidence that the survival of any individual species is threatened. Firstly, this paper considers some individual effects of these management tools and secondly, how we can assess the impact of crop protection chemicals in the farmland environment. The environment consists of the physical, chemical and biological surroundings of an organism. For the purposes of this paper, I will confine my arguments to terrestial biological communities with particular attention to field studies. Choice of crop will not be addressed here.

HABITAT MANIPULATION AND THE FARMLAND ENVIRONMENT

As the animal community is largely determined by the nature of the plant community, it is first necessary to examine the effects of farming practice on plants. Harper (1977) shows intensively cultivated areas have a quantitatively larger seed bank than cultivated (2x) and natural (6x) grasslands and woodlands (50x). The diversity of this arable field flora is quite high as the community is characteristically comprised largely of *r*-selected species (MacArthur & Wilson 1967) colonists of low competitive ability which can only invade open microsites. This allows the co-existence of a variety of closely related species (Harper 1977). They may thrive in the field but find it difficult to invade the closed hedgerow community. Though competitively aggressive, most hedgerow plants are disturbance-intolerant and are not therefore found in fields. Only 25% of the plant species found in fields are also found in the densely-packed hedgerow community (Marshall & Smith 1986). The few species of plants that manage to colonize both habitats (for example, Cleavers Galium aparine, Barren Brome (Bromus sterilis), Wild Oats (Avena spp.) and Couch Grass (Agropyron repens), combine efficient dispersal of competitive propagules with disturbance tolerance.

The addition of manures has a considerable impact on the flora of farmland. A large body of data examined by Tilman (1982) supported the theory that the relationship between resource richness and species richness was "n-shaped". Initially species richness increases quickly with increased fertilization but eventually it reaches a limit and slowly declines at higher levels of fertilization.

Physical disturbance has both direct and indirect effects on animals. Within the farmland environment, the effects of ploughing alone has been shown to decrease the abundance of arthropods by a factor of 10 (Raw 1967). The benefits of mixing the organic material with mineral soil over the top 15-23cm are outweighed by the physical disturbance and effects on the microclimate (Wallwork 1976). In comparison with direct drilling, ploughing has been shown to be detrimental to earthworm populations (Edwards & Lofty 1977) due to disturbance.

Under a majority of arable conditions, the addition of inorganic manure has few direct effects on soil arthropods, Wallwork (1976) considers that effects are only detectable in class III and IV soils. Likewise, there are few detectable effects on earthworms, though increases in herbage biomass may result in indirect population increases (Watkin 1954). Edwards & Lofty (1969) found a greater increase in the abundance of soil animals after the application of organic manures than inorganic or no manures.

With respect to birds, the degree of disturbance in the farmland habitat type has an overwhelming impact on the abundance and diversity of the avifauna. The abundance of 42% of the species of common British birds is directly related to the density of field margin (O'Connor & Shrubb 1986). In a similar manner to the plant diversity/resource richness relationship, the species richness of the farmland avifauna is related to the density of hedgerow per unit area of farmland in "n-shaped" curve with maximum diversity at 20m of hedgerow per 40 ha (also noted by O'Connor in preparation). The overall abundance of birds does however increase linearly with density of hedgerow (O'Connor & Shrubb 1986).

Habitat disturbance also has a central role in the abundance of the less common predatory birds. In Ohio, USA, Colvin et al (1984) have shown that the decline of the Barn Owl (Tyto alba) population over the period 1931-1980 is strongly correlated with the change from pastural to intensive rowcrop (especially soya bean) farming. They take the cause of the decline to be the loss of permanent grassland in which the Barn Owl's favoured food, (microtine rodents - voles) flourished. Similarly in the UK, the only breeding bird of prey which is not increasing in abundance is the Merlin Falco columbaris (Newton 1984). In a study of Welsh Merlins from 1970-1984, Bibby (1986) has shown that this is largely due to the reseeding, fertilization and afforestation of heather moorland adjoining farmland and bracken slopes, decreasing the richness and abundance of the Merlin's small bird-prey in the early spring.

From this it can be seen that habitat manipulation, even in the absence of pesticides, has had profound effects on the communities of farmland plants and animals.

Pesticide use

Direct effects

A considerable body of literature associates organochlorine insecticides (especially DDT and the cyclodienes) and their metabolites, with effects on a wide range of species, in particular birds of prey (see Newton 1979). These compounds combine stability and bio-magnification potential with acute and chronic toxicological effects. In the UK, several birds of prey, in particular bird-eating species, began to decrease in number during the 1950s and 1960s following the introduction of these compounds. Similar phenomena were observed in the USA and Europe. Voluntary controls in the UK, progressively introduced from 1962, were largely successful in limiting use, though the use of DDT in some small, unauthorised outlets continued (Tait 1983). All British birds of prey are now increasing in numbers (Newton 1984) except the Merlin, for reasons discussed above.

Persistent organochlorine compounds have been implicated in the declines of Otters *Lutra lutra* (Chanin & Jefferies 1978) and bats (Jefferies 1972) in the UK though habitat disturbance may also be involved. Most other incidents concerning mammals have been sporadic and without population significance. With less persistent compounds, effects on mammals and birds have been noted but not on such a wide scale. Deaths of wildlife resulting from the use of these compounds in the UK are mostly concerned with a number of individual incidents of acute exposure, many of these through deliberate misuse of toxic compounds to control predators or specific occurrences such as flocks of birds landing in flooded fields previously treated with granular soil pesticides or seed dressings (Hardy & Stanley 1985).

At high rates of application, certain compounds, such as chlordane, heptachlor and the benzimidazole fungicides are known to kill earthworms. However, the soil provides considerable protection for these animals as many pesticides are strongly adsorbed to organic matter and clay particles or are metabolized, decreasing the potential exposure. Some organochlorine compounds are known to accumulate in earthworms (Edwards & Lofty 1977); this is important because of the earthworms central role as a food source for many vertebrate and invertebrate predators. The bio-concentration factors are, however, usually lower than those found in some aquatic ecosystems.

In general, the direct effects of a majority of modern pesticides on mammals, birds, Honey Bees, earthworms and soil microorganisms are well known and at recommended field rates few problems are anticipated or reported. However, the direct effects on a range of arthropods other than Honey Bees are less well known, and much current research is centred in this area.

Indirect effects

Obviously, the use of herbicide allows better control of weed species than in the past, resulting in a decrease in the abundance of non-crop plants in arable fields and a subsequent decrease in the abundance of the invertebrates associated with these plants. This is of importance to the birds that actually feed on insects in the crop, for example the Partridge *Perdix perdix* (Southwood & Cross 1967). The majority of farmland birds, however, do not feed in arable fields to a great extent and are therefore largely unaffected by such treatments (Fuller 1984). The benefits for game and wildlife of leaving unsprayed headlands in cereal fields are described by Sotherton *et al* (1985). Reductions in the abundance of arable invertebrates from the use of broad-spectrum insecticides (Potts 1977) and insecticidal fungicides (Sotherton 1985) have been noted as potentially deleterious to Partridge populations.

In general, much less is known about indirect than direct effects and more information is needed concerning what effects can be considered important. The true economic significance of many arable field arthropods (other than as gamebird chick food) is still poorly understood.

ASSESSING PESTICIDE IMPACTS

Impact assessment is a process by which the outcomes of a management practice are predicted and if necessary, valued in a risk/benefit analysis. Currently, such work is more concerned with direct than with indirect effects. Impacts can be forecasted through the use of computer simulations. However, because of the number of parameters necessary, such models have little predictive power concerning the outcome for complex communities but if properly constructed they may help in identifying the processes that are behind a number of different possible outcomes. It is essential that impact experiments of pesticides are designed in such a way that both direct and indirect effects can be separated from those of the management system in general.

For individual or small groups of species, risk can be defined as a function of hazard (intrinsic toxicity) and exposure (Johnson 1982). With respect to pesticides, much is now known about what constitutes a biological hazard, perhaps less is known about exposure, as this is affected by complex behaviour patterns. For example, many animals vary their diet according to their needs and the changing abundance of food. To assess the environmental impact of a crop protection agent it is logical to follow a tiered or stepwise approach as currently employed by many of the world's regulatory authorities, as described by Bunyan & Stanley (1979).

Step one - expected environmental significance

Many aspects of chemical behaviour in the environment depend on the partitions of chemical between air, soil, water and organisms; therefore an estimate of the likely environmental fate can be gained from examining some of its basic physico-chemical parameters. Non-polar, lipophilic molecules have bio-accumulation potential but will tend to be strongly adsorbed in soil, whereas polar, non-charged compounds are less likely to accumulate in biological organisms but are more mobile. Both the parent compound and the major metabolites must be characterised. Estimations of octanol/water partition coefficients (P_{ow}), dissociation characteristics (pKa), water solubility, vapour pressure and adsorption/desorption characteristics (Kd) will indicate how mobile a compound is likely to be in the environment. Examination of hydrolysis, photolysis, soil metabolism and P_{ow} data will give information on persistence and bio-accumulation potential from water. Several of these parameters are interrelated or can be predicted from the chemical's structure, as can potential metabolic pathways (Briggs 1981).

The potential significance of residues of the chemical under test, or its metabolites, to wildlife can be assessed in the laboratory. Chronic and acute eco-toxicological tests are frequently conducted on 40-50 standard species representing mammals, birds, fish, crustacea, annelids, insects, plants, microorganisms and the processes they mediate. The detail into which these tests go (sometimes spanning more than one generation) depends on the likely use and wildlife exposure pattern, fate and concentration of the chemical in the environment and bio-accumulation potential, in relation to its toxicological profile. These tests may also cover both primary and secondary exposure.

From these hazard factors and the proposed use pattern, a set of direct risks can then be defined for a species, or number of species, where the exposure pattern is known. Where there is a good safety margin, further assessments will be unlikely to reveal any new direct effects. Where the safety margin is less clear, predictions of the likely effects should be made through reference to the existing ecotoxicology and "baseline" data on the species possibly exposed. The significance of these effects should then be assessed, at present there is no agreement on what constitutes a significant effect on any populations other than those of microorganisms. The likely effects of persistent chemicals can be predicted from pharmacodynamics and exposure data. The additive effects of repeated application of non-persistent chemicals on the fauna can only be predicted from a detailed understanding of dynamics and the "resilience" of various populations.

Though the flora and fauna of the British Isles is arguably the best known in the world, much of the baseline data that is required for impact assessment is lacking. Above and beyond the natural history of a species, knowledge of how it varies its diet, activity pattern and home range in relation to food abundance is necessary. The minimum data set that is required should include analyses of survivorship and fecundidty drawn from different sites in different years such that the effect of density dependent and independent factors on these population attributes can be assessed. It is vital that these statistics are known because species respond differently to perturbation depending on their life-history strategy. Long-lived species with low intrinsic rates of increase are much more vulnerable to disturbance than short lived ones with relatively high intrinsic rates of increase.

It is important that the intrinsic toxicity to a range of species is known. Further field-plot or open field studies should then be considered if:

a) There is reason to believe that the direct effects observed in the laboratory studies would not occur in the field due to low exposure in practice.

b) There are expected to be significant indirect effects that require further investigation.

Step two - further studies

In and around an average British arable field, there may well be a minimum of 500 species of surface-dwelling arthropods, another 100 in the soil, 30 species of birds, 12 species of mammals and 12 species of earthworms, as well as many nematodes, enchytraieds, protozoa, plants, microorganisms, the farmer and his dog. Attempts at measuring everything that happens in the field following chemical application are rarely conclusive and often result in an unsatisfactory *post hoc* analysis. By chance, we might expect statistically significant effects on 30 or more of the species mentioned. However, large studies designed to examine particular aspects of the risk associated with a particular use pattern of a chemical can be successful if well planned, for example Bunyan *et al* (1981).

Species for toxicity testing should be selected to cover a wide range of taxonomic groups, whereas estimates of exposure can be facilitated by considering the ecosystem under study as functional groups or guilds of species that share common resources of food and habitat. The effects of chemicals on representative, or "indicator", species of these taxonomic groups and guilds can be estimated. Detailed work on such species is important because if assessments are made of changes in numbers only, then inference can only be made about abundance and diversity, without an understanding of the underlying population processes. These statistics are valuable however, but care should be taken in the selection of diversity indices. The most reliable alpha-diversity statistic (May 1975) is *d*, the Dominance Index (Berger & Parker 1970) which expresses the proportion of the total sample that is due to commonest species.

Detailed population studies of indicator species should include estimates of impacts on birth, death, immigration and emigration rates. It is important also in making estimates of percentage parasitism and predation rates that account is taken of the density dependent nature of these processes. A population of aphids at a low density after spraying may experience low levels of predation and parasitism not because the natural enemies have been killed but because they are exploiting more profitable higher aphid density patches in unsprayed areas.

The scale of field studies depends on the species studied and the questions asked. Studies of microorganisms or animals such as edaphic Collembola can be successfully conducted in plots measured in square metres. To study surface dwelling insects in most British arable fields, it is necessary to work with square plots of at least 5ha (preferably larger) if it is necessary to look at effects in the absence of re-invasion. An alternative to such large areas is to use barriers to manipulate the movement of insects. Here, exclusion of predatory insects can be done on a relatively small scale, the size of plots dictated only by the activity of the species. The size of inclusion barriers must be such that the insects included in the plots can behave in a normal manner. In many other European countries fields are often less than 5ha and long and thin in shape. Here the aims of the experiment must be clearly examined as the effects observed in single fields will often be nullified by re-invasion. If in practice few fields are to be treated, such an experiment is valid. If the use is expected on a wider scale, more fields should be treated or barriers used.

Studies of the effects of chemicals on bird populations are difficult to conduct because of the size of plots needed, the small numbers (in relation to insects) and the number of factors unrelated to treatment that can confound the tests. To assess the direct effects of treatments to which birds are potentially exposed, a methodology of changes in territory number and size has been proposed and tested by Edwards et al (1979).

To fully understand the effects of pesticides on particular species, it may be necessary to investigate the significance of some effects observed in the field in the laboratory under more controlled conditions.

Step three - monitoring

It is extremely difficult to derive experiments to study the chronic direct and indirect effects of any single chemical over a number of years. In most cases sufficient data should have been generated at earlier stages to make such an exercise unnecessary. Failing this, experiments to quantify and interpret a particular aspect of the problem should be agreed. In addition to this it is most important that an objective body provides a scheme by which incidents involving wildlife can be investigated and recorded. Indirect effects can only be investigated by conducting detailed studies over a number of years at a number of large sites. Such work is more suited to management systems than to the effects of particular chemicals, but is essential both to science and public confidence.

CURRENT APPROACHES

During the 1980's several experiments have been set up by governmental organisations in the UK and West Germany, private groups and industry to investigate the long term effects of high pesticide inputs, particular management practices and the effects of particular chemicals. In most of these projects, the importance of scale has been recognised, and observations have been made over a number of years, however not all have been able to look at contrasting sites. The advantage of contrasting sites are that treatment effects can be separated from field-specific variables. The costs and practical difficulties of such experiments are unfortunately prohibitive to most organizations.

Many studies are concerned with attempting to measure everything. Diversity and overall abundance estimates are important, however it is essential to know most about species that have been previously identified as being important to the community either for practical (e.g., they are the most abundant aphid predators or food for partridge chicks) or aesthetic reasons (e.g., a species is declining in numbers and is intolerant of disturbance). The work of Sunderland & Vickerman (1980) and Wratten et al (1984) have been of particular importance as first steps to identifying the relative importance of types of arthropod natural enemy.

Increasingly, the scientific community is concerned with the indirect effects of pesticides rather than the direct ones. This may be partly because fewer pesticides presenting direct threats to wildlife are reaching the potentially dangerous outlets. The indirect effects of compounds are extremely difficult to predict as they depend entirely on the exact use pattern that they eventually acquire; moreover, whether these indirect effects are of significance is often a subjective assessment.

FUTURE OPTIONS

Overall, the research that has been done over the last few years has made a considerable contribution to our understanding of the farmland environment. It is important that future work in this area is carefully planned to answer a series of clearly defined questions, rather than attempting to measure everything.

It is important that sets of key species, valuable for practical or aesthetic reasons, in different farmland environments are identified. Agreement must be reached on what constitutes a significant effect on populations of these species and baseline data can then be collected on their ecology and exposure patterns. It would also be most valuable to estimate the extent of between-field variability in the abundance of faunas, to be assessed as much as possible independently of particular management systems and treatments. It is important that more attention is also paid to functional aspects of communities, e.g., the level of insect predation, as this cannot necessarily be predicted from abundance and diversity statistics and is of central importance to modern integrated control schemes.

Finally, who should pay? Obviously the costs involved in future research will be too high for any one section of the community to bear alone. If a basic data set can be created that is useful to all, then all sectors should contribute. People seeking the further use and expansion of this data set to fulfil their own objectives should obviously seek funding for this work along conventional lines.

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