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THE BIOLOGY AND CONTROL OF CEREAL APHIDS

by

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THE BIOLOGY AND CONTROL OF CEREAL APHIDS

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ABSTRACT

Background. This review has been prepared by authors from the main organisations which have been involved in research into cereal aphids in Great Britain. Recent research findings are summarised and recommendations made for improvements in current aphid control practice and for research in areas where further opportunities are identified. The review is restricted to problems of direct aphid damage to cereals in the summer and does not consider the aphids' role as vectors of barley yellow dwarf virus.

Surveys of aphid incidence have confirmed that aphid problems are mainly confined to 'outbreak years' with few, if any, fields requiring treatment in the intervening years. Aphids can increase in number very quickly in suitable conditions and in these outbreak years sprays are often applied too late to prevent yield loss, which mainly occurs between flowering and the milky-ripe stage. ADAS advice has been to

check crops during early flowering and spray if 5 or more aphids per ear are found; further checks are advised later if conditions are suitable for aphid increase. Counting aphids has proved too unpopular with farmers and, following a detailed analysis of aphid survey results, a threshold of two-thirds of ears infested was substituted in 1988. The University of Southampton has made a simulation model available through PRESTEL which allows more refined decision making based on simple aphid assessments and other factors.

Either of these systems would improve decision making greatly if more widely adopted; at present neither is used in most cases and sprays are still applied too late to be effective. This has led many independent consultants and farmers to the view that it is preferable to apply a cheap aphicide in tank-mix with a fungicide routinely during ear emergence as a precaution. In non-outbreak years, whilst cheap, this practice is unlikely to be profitable and due to the broad spectrum of activity of the insecticides used, many beneficial insects are killed leading in some cases to additional pest outbreaks. The present situation is, therefore, considered unsatisfactory in both cases, usage of aphicides being too late in outbreak years, and too great in between.

Biology. The life cycles of the two principal pest species differ, the grain aphid (Sitobion avenae) spending the winter actively feeding on cereals and grasses whilst the rose-grain aphid (Metopolophium dirhodum) overwinters as eggs on roses. The forecasting and monitoring of the two species, therefore, requires different approaches and farmers should make a clear distinction between the problems posed by them.

Deficiencies in the knowledge of the underlying mechanisms of varietal resistance to aphids are identified and recommendations made for further research. Such resistance has been identified in wheat, but clarification of the mechanism is required to enable exploitation by plant breeders. The genetics of aphids are also poorly understood and fundamental studies are required to determine clonal stability and the potential within populations to overcome varietal resistance and develop resistance to insecticides.

Natural enemies. The role of natural enemies in restricting aphid outbreaks has received much attention. In addition to specific aphid predators, parasites and diseases, the greater effect of general predators, such as ground beetles and spiders, in preventing outbreaks has been recognised. However, no simple method of quantifying predation in the field has been developed and an evaluation of the importance of natural enemies has not been possible. Wide variations in levels of predation occur from field to field and the underlying causes for this have been investigated. This has provided the opportunity for influencing the degree of predation and experiments are in progress on the enhancement of natural enemy levels in fields by the creation on non-crop habitats. This work is considered timely and worthy of continuation.

Recent research has demonstrated the feasibility of using low rates of aphicides to limit aphid numbers without harming natural enemies and thus enhancing the relative rate of predation. Further testing of this approach is considered high priority and a proposal for further work is made.

Monitoring and forecasting. At present aphid flights are monitored by the Rothamsted Insect Survey (RIS) network of suction traps and populations in fields are regularly monitored by staff of the IACR and ADAS. Warnings are issued in the RIS Aphid Commentary and in ADAS Crop Intelligence reports. Possible improvements in the aphid monitoring and forecasting systems currently in use are identified. These include simplification of field assessment methods, development of a greater understanding of the reasons for, and sources of, aphid outbreaks and the assimilation of the data sets required for this purpose. Much of this work is in hand as part of existing research but will need sustained funding to achieve the desired objectives.

Damage assessment. Aphid feeding has been shown to reduce the flow of assimilates to the developing grain, and the principal cause of yield loss is from reduction in grain size. The bread-making quality of the grain is also reduced. However, since significant reduction of yield occurs at lower aphid densities than would affect quality, decisions on spray application can be based on potential yield reduction alone.

Conclusions. Simulation modelling of aphid population build-up and the damage caused has shown that the critical factor in aphid control is timeliness, both in decision making and in spray application. This requires regular field monitoring to detect changes in aphid numbers, an exercise which can be expensive in time or cost of field walking. To overcome this difficulty, a system of "directed field scouting" is proposed whereby the available forecasting methods are used to tell farmers when and where to asses aphid numbers providing rapid decision making guides in the process. Payment for this system would involve a direct charge for access while a greater uptake of the information should ensure its continued provision and development.

The review team proposes that this system forms the best base for the future adding the use of resistant, or partially resistant, varieties and the substitution of low-dose selective aphicides for broad-spectrum insecticides to enhance natural controls. Natural enemy levels could be further enhanced by the provision of suitable habitats. None of these measures involves a significant increase in cost to the farmer; overall the total cost of controlling aphid damage should be substantially reduced. The current cost of poor control practice to the industry fluctuates widely according to aphid numbers. However, taking all factors into account, the cost, including yield losses where control is not achieved, is estimated to vary between £2 million and £24 million at present day values with a median of about £5 million.

The following recommendations are made for further research:

The value of reduced-rate, selective pesticides requires testing with a view to replacing out-dated, broad-spectrum insecticides. The following components should be investigated:

1. The effectiveness of control.
2. The implications on development of insecticide resistance.
3. The economics and effects on yield and quality.
4. The effects on natural enemies and any enhancement of their role.

The initial evaluation should be on winter wheat, and an extension to spring wheat and other cereals could be considered later.

This review, completed in November 1988, and with 67 pages in the full article, was funded by the HOME-GROWN CEREALS AUTHORITY, Hamlyn House, Highgate Hill, London N19 5PR, from whom copies may be obtained at £7.50 each (postage and packing included).

GLOSSARY OF TERMS

Antibiosis	Restriction of the rate of aphid population increase.
Antixenosis	Deterrence of aphid settling and colonization.
Broad-spectrum insecticide	Insecticide killing a wide range of species in addition to that targeted.
Carabidae	Ground beetles.
Clone	Genetically identical progeny.
Parasitoid	A parasite which kills its host in the later stages of feeding. Aphidius spp. are mainly involved with cereal aphids causing brown mummified aphids from which the small, black, adult wasps emerge.
Parthenogenesis	The females produce offspring without fertilization; each is theoretically genetically identical to the parent; hence the formation of aphid clones.
Polyphagous predator	A general feeder; in addition to small invertebrates some may consume plant and fungal material.
Viviparity	Birth of live offspring.

INTRODUCTION

This review has been commissioned by the Home-Grown Cereals Authority to summarise research on the damage caused by grain (Sitobion avenae) and rose-grain (Metopolophium dirhodum) aphids to cereals in the summer. The role of aphids as vectors of barley yellow dwarf virus is excluded. Much work has been done in recent years by researchers at Rothamsted Experimental Station, the Universities of East Anglia and Southampton, and by ADAS. Authors from each of these organisations have contributed to this review. Cereal aphids are a problem throughout the temperate wheat growing region and, where relevant, overseas research findings have been included. A more detailed technical review has recently been published by one of the authors (Dixon, 1987); readers requiring a more comprehensive list of references should refer to it. This review attempts to identify the best available control strategy for cereal aphids and where further research is required to fulfil short- and long-term needs. The recommendations made are the personal opinions of the authors and do not necessarily represent official MAFF policy.

Grain aphids overwinter on grasses and early-sown cereals, flying on to infest cereal crops in summer. All cereal crops can be infested but most interest has been focused on winter wheat. Spring wheat and oats probably suffer greater damage, but occupy too small an area to have justified research work in the UK.

The rose-grain aphid overwinters on roses and migrates to cereals in the early summer. Again, all cereal species are attacked but winter wheat has been damaged more frequently; consequently, research has been concentrated on this crop. Rose-grain aphids feed mainly on the flag leaf and populations build up later than for grain aphid.

Cereal aphids pose a particular problem to the farmer; individually they are small and easily overlooked in the early stages of an infestation but are capable of very rapid reproduction in suitable conditions, leading to significant damage. Two methods of dealing with this problem have developed: firstly, a rational system based on crop scouting with the use of threshold levels or computer models to decide

on treatment; secondly, a prophylactic approach of treating all fields as a routine, usually using a cheap organophosphorus insecticide tank-mixed with a fungicide during ear emergence.

There is no doubt as to which method is the best approach in economic terms; a tank-mixed application of dimethoate can be applied for around £2 per hectare - the approximate cost of an aphid count. The arguments against such an approach centre on the side-effects from these broad-spectrum insecticides. Many other non-target insects can be killed including the aphids' natural enemies, which can lead to a later outbreak of aphids if favourable conditions occur (Powell et al., 1985).

ADAS colleagues observed one such outbreak in south Lincolnshire in 1986 (J. M. Holliday, pers. comm.) where rose-grain aphid reached damaging levels only in fields that received an earlier dimethoate spray. A trial was conducted in a field which had been sprayed with dimethoate on 2 July. By 21 July the field had become re-infested with rose-grain aphids, averaging 13 per tiller. Aphid numbers on plots re-sprayed with dimethoate on 21 July declined to 2 per tiller on 6 August when numbers had risen to 28 per tiller on unsprayed plots. Yields were increased by 0.3 tonnes per hectare on the re-sprayed plots.

Numbers of parasited aphids were counted in ADAS trials in 1987. In several trials, where significant reductions in parasite numbers followed early sprays, populations of rose-grain aphids increased later. The role of natural enemies has been studied in considerable depth in recent years and is summarised in the sections on aphid biology and natural enemies.

Various systems of forecasting aphid outbreaks are available; weather data coupled with current knowledge of aphid biology for long-term forecasting, a national network of suction traps continuously monitoring aphid migrations for medium-term forecasts and computer projections of aphid counts on crops for more localised short-term forecasts. This review considers how these can be combined into a system to reduce field scouting efforts, hence minimising costs without increasing the risk of crop loss.

Research and development work has concentrated on various aspects of the problem opening possibilities for improving control strategy further. These are highlighted in the review and consideration is given to how these can be integrated and a new strategy developed.

GENERAL STATUS AND POTENTIAL CROP LOSS

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Aphid infestations in cereals can generally be characterised as occurring in occasional outbreak years, with widespread damage, separated by several years of very low levels with little, if any, loss. Either grain or rose-grain aphids may cause damage in any one year but not usually both. Rose-grain aphid outbreaks seem to occur in years when grain aphid numbers are very low following severe winters, but when a warm, settled spell of weather occurs during grain-filling (Dewar et al., 1984). Such conditions occurred in 1979 in eastern England and in 1982 in eastern Scotland. The effect in these years appeared similar to the more localised outbreaks following dimethoate sprays in 1986, and was due to low numbers of natural enemies being present on crops when migrant rose-grain aphids arrived in seasons favouring rapid increase. Many crops were sprayed for rose-grain aphid in 1979 and yield responses of up to 25 percent were reported. K. S. George (unpublished report) collated results from 9 trials with a mean response to sprays of 0.79 tonnes per hectare; an increase of 12% over untreated yields.

The incidence of grain aphid has been recorded in ADAS surveys since 1976 (Figs 1 and 2) and these show the trend for occasional outbreak years. The dry summer of 1976 was the worst for grain aphid damage for some years and represented the upper end of the possible range with three quarters of the wheat in England and Wales requiring treatment to prevent significant yield losses. George and Gair (1979) reported on five trials conducted in 1976 with an average 33 percent yield increase in response to a single spray of insecticide. These results may have indicated the actual loss in that year as, although many farmers sprayed against aphids, the sprays were generally applied too late to prevent yield loss (Watt et al., 1984). In ADAS trials, the yield response obtained from controlling aphids declined as spraying was delayed beyond GS (Growth Stage) 61 (Fig. 3). The subject is discussed in greater depth in the section on damage assessment.

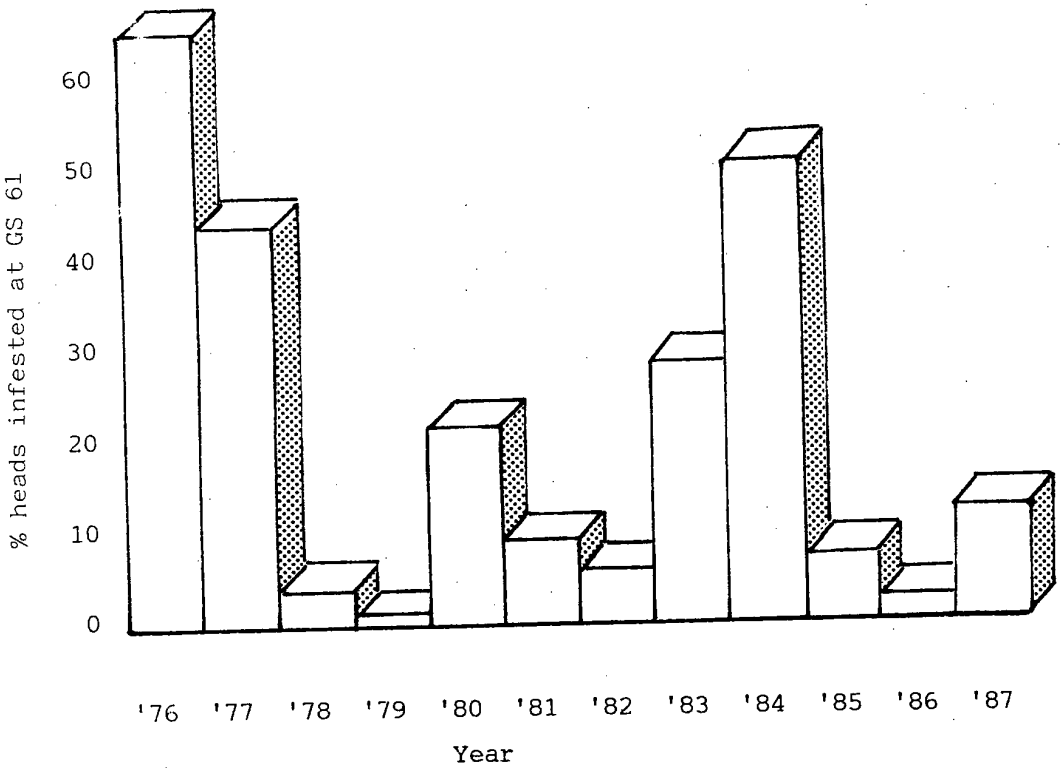

FIGURE 1 Results of ADAS Pest Monitoring Surveys on winter wheat 1976-87 expressed as percentage of heads infested with grain aphid in each year at GS 61.

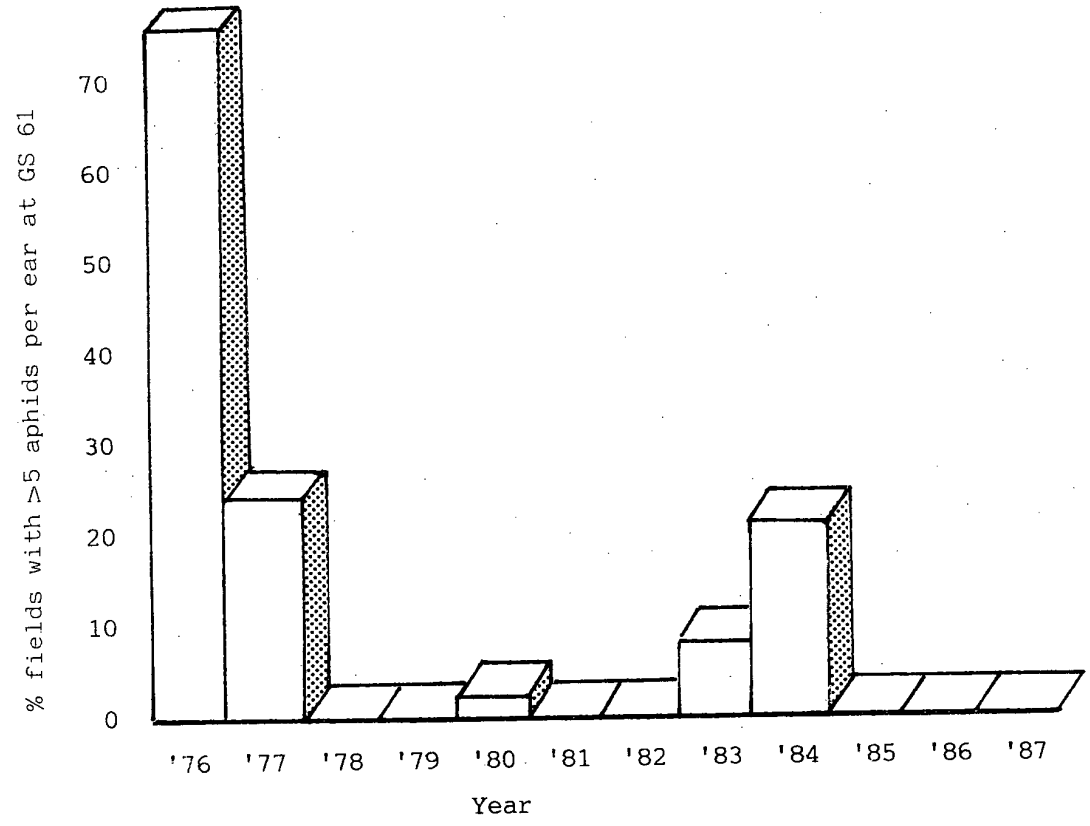

FIGURE 2 Results of ADAS Pest Monitoring Surveys on winter wheat 1976-87 expressed as percentage of fields with more than 5 grain aphids per ear at GS61.

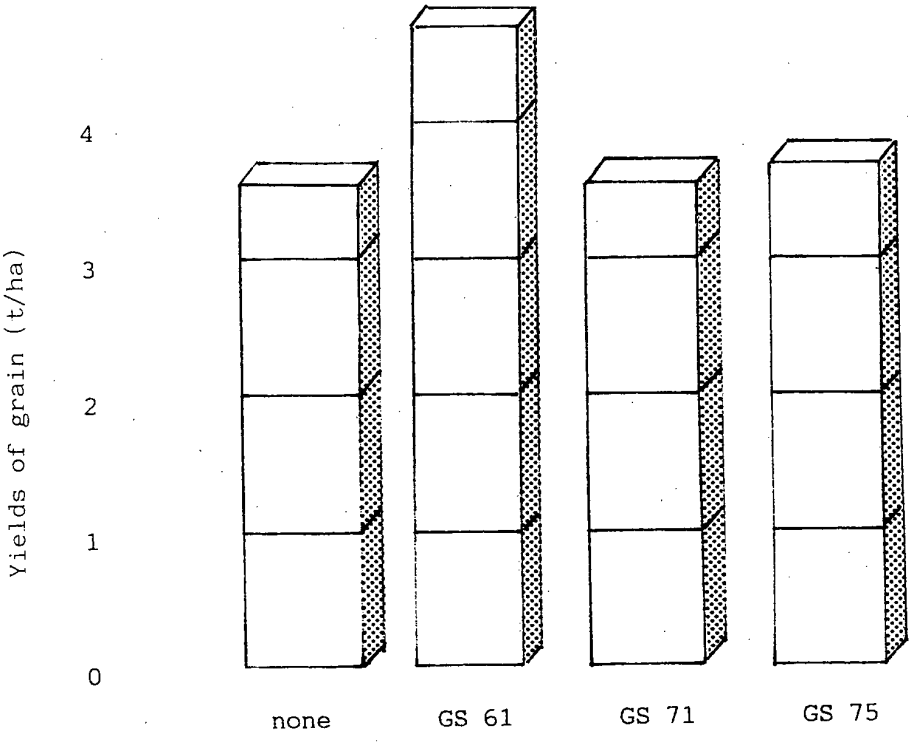

FIGURE 3 Mean yields from 5 trials of unsprayed plots and plots sprayed at growth stages 61, 71 or 75 (George and Gair, 1979).

Spray usage has been recorded in various surveys. MAFF carried out Pesticide Usage (PU) Surveys on stratified samples on farms in 1974, 1977 and 1982 (Sly, 1986) (Table 1).

TABLE 1 Pesticide usage survey estimates of summer aphicide use on area of winter wheat in England and Wales (Hectares).

Chemical Group	1974	(%)	1977	(%)	1982	(%)
Demeton-S-methyl	26,690	(85)	108,793	(22)	193,325	(68)
Dimethoate			119,679	(24)	43,556	(15)
Other systemic organophosphates			30,639	(6)		
Pirimicarb	4,627	(15)	230,534	(47)	35,973	(13)
Others					11,758	(4)
TOTAL TREATED	31,317		489,645		284,106	
Total wheat area	1,138,693		1,024,808		1,602,064	
Percent treated	3		48		18	

Southampton University surveyed Game Conservancy members in 1975, 1976 and 1977 (Watt et al., 1984) and again in 1984 (S. D. Wratten, pers. comm.) (Table 2).

TABLE 2 **Southampton University surveys of aphicide usage by Game Conservancy members.**

Chemical	Percentage of area treated			
	1975	1976	1977	1984
Demeton-S-methyl	48	31	82	16
Dimethoate	19	8	0	50
Pirimicarb	33	61	18	28
Others	0	0	0	6
Percentage of wheat crops treated	38	71	42	76

Aerial application of pesticides has been recorded each year since 1980 and published in Pesticide Usage Survey Reports up to 1986 (Chapman and Longland, 1987) (Figs 4 and 5).

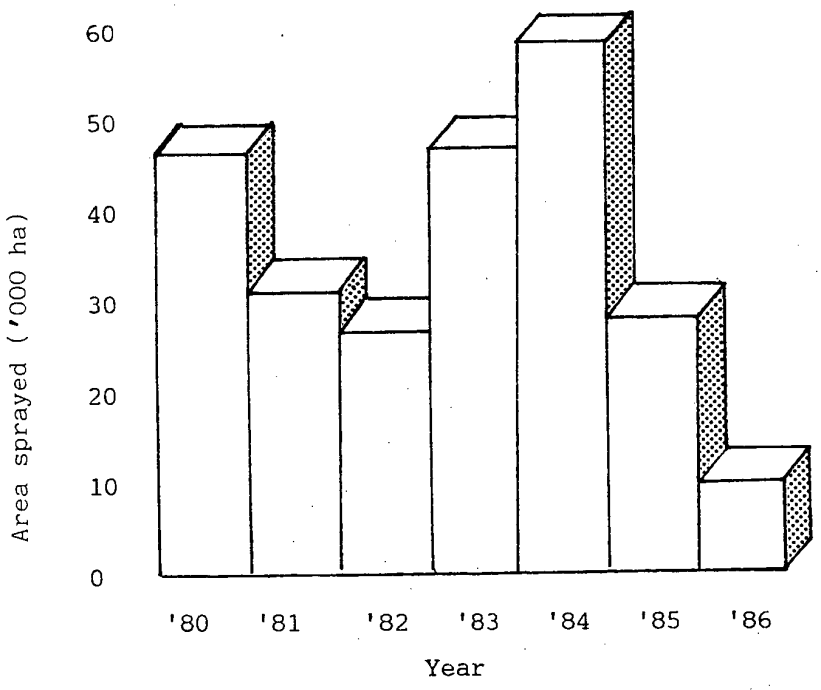

FIGURE 4 Area of winter wheat sprayed by air with aphicide in the summer as recorded in Pesticide Usage Surveys 1980-1986.

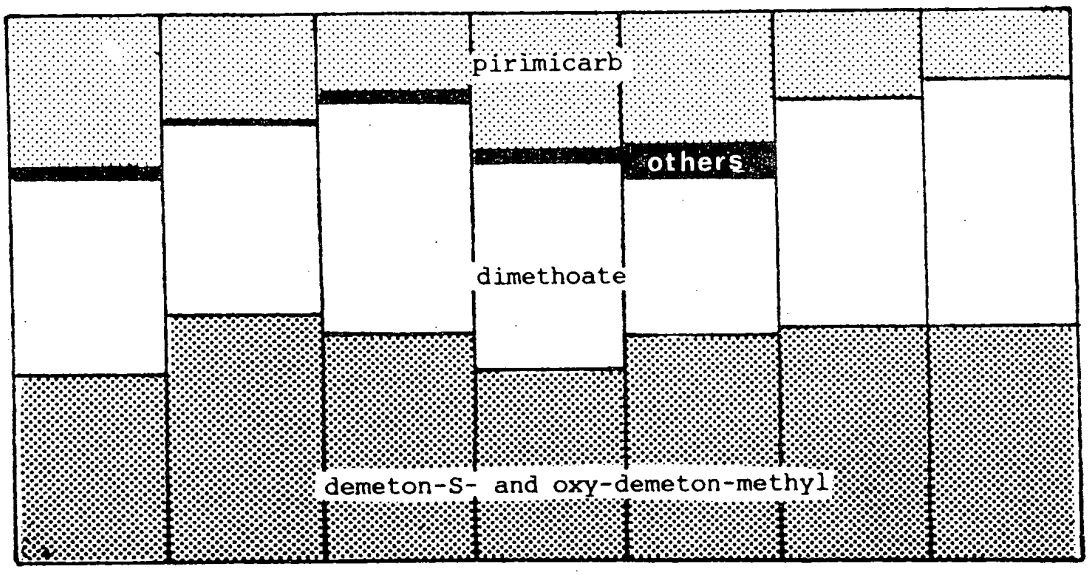

FIGURE 5 Proportion of winter wheat sprayed with main aphicide groups in summer as recorded in Pesticide Usage Surveys 1980-86.

Various trends can be detected in these surveys. Approximately 15-20 percent of wheat fields are sprayed prophylactically each year, dimethoate or demeton-S-methyl sprays being preferred for this use. The PU Survey of 1982 (Table 1) reflects typical usage in a non-aphid year. In outbreak years, such as 1977 and 1984, usage increased with a greater proportion of fields being sprayed with pirimicarb. However, the trend shown by Watt et al. (1984) for these reactive sprays to be applied too late was also shown by the University of Southampton's survey in 1984, the year of highest grain aphid incidence since 1977. The increase in the proportional use of dimethoate appears due to the expanding role of private consultants, who tend to recommend the cheapest material.

Recent ADAS trials re-evaluated the earlier damage assessment work with modern varieties and husbandry. In non-outbreak years late increases in grain aphid numbers can occur and George and Gair (1979) reported yield reductions of 3.9 percent in such situations (Table 3).

TABLE 3 Mean percent increase in grain yield resulting from one spray at early flowering (GS 61) for each category of aphid infestation (George and Gair, 1979).

	Category and description	Mean % increase
1.	5-10 aphids/ear at GS 61 and increasing	11.5
2.	10.1-30 aphids/ear at GS 61 and increasing	13.9
3.	5 or more aphids/ear at GS 61 and decreasing	1.5
4.	5 or more aphids/ear later than GS 61	3.9
5.	Never more than 5 aphids/ear	0.7

In the first year (1987) of the most recent ADAS trial series significant yield increases were obtained at three of the 11 sites. At these sites, aphid numbers were low at flowering, but increased to higher levels later on the sites where yield increases were obtained. These yield increases averaged 3.7 percent, a similar increase to the fourth category of George and Gair (1979) above. The mean yield increase for all 11 sites was only a 1.0 percent yield return for a preventive programme.

These results have confirmed that even in a year of very low aphid incidence preventive spaying could be economically justified. The arguments against the practice are based on the environmental impact of the broad-spectrum insecticides used and other pest problems which they can create, such as resurgence in aphid numbers which failed to make a significant impact in the wet season of 1987.

Aerial spraying is usually done in response to the presence of aphids in the crop and there was a very close relationship between the area sprayed and aphid numbers in ADAS Pest Monitoring Surveys at early flowering in 1980-86; 99.4 percent of the variation in spray usage being accounted for by fluctuations in the aphid counts (Fig. 6).

An apparent reduction in aphicide spraying at greater aphid infestations is evident, not due to reduced intentions but by the limit imposed by

availability of aircraft during the critical period reducing responses over about 30,000 hectares and imposing a limit of around 60,000 hectares. The closeness of this relationship suggests that aerial spray usage is predicable by early flowering.

In outbreak years, shortage of aphicide may also restrict the area that can be sprayed responsively over a short time scale. The problem is compounded by the increase in aphid problems on all crops during hot dry weather. Unless such outbreak years can be reliably forecast and aphicide stocks adjusted there can be no reliance on rational spraying strategies. A preventive control approach is, therefore, likely to remain in areas prone to aphid attack, and there is a need to find cheap alternative insecticides to dimethoate, which have fewer environmental drawbacks.

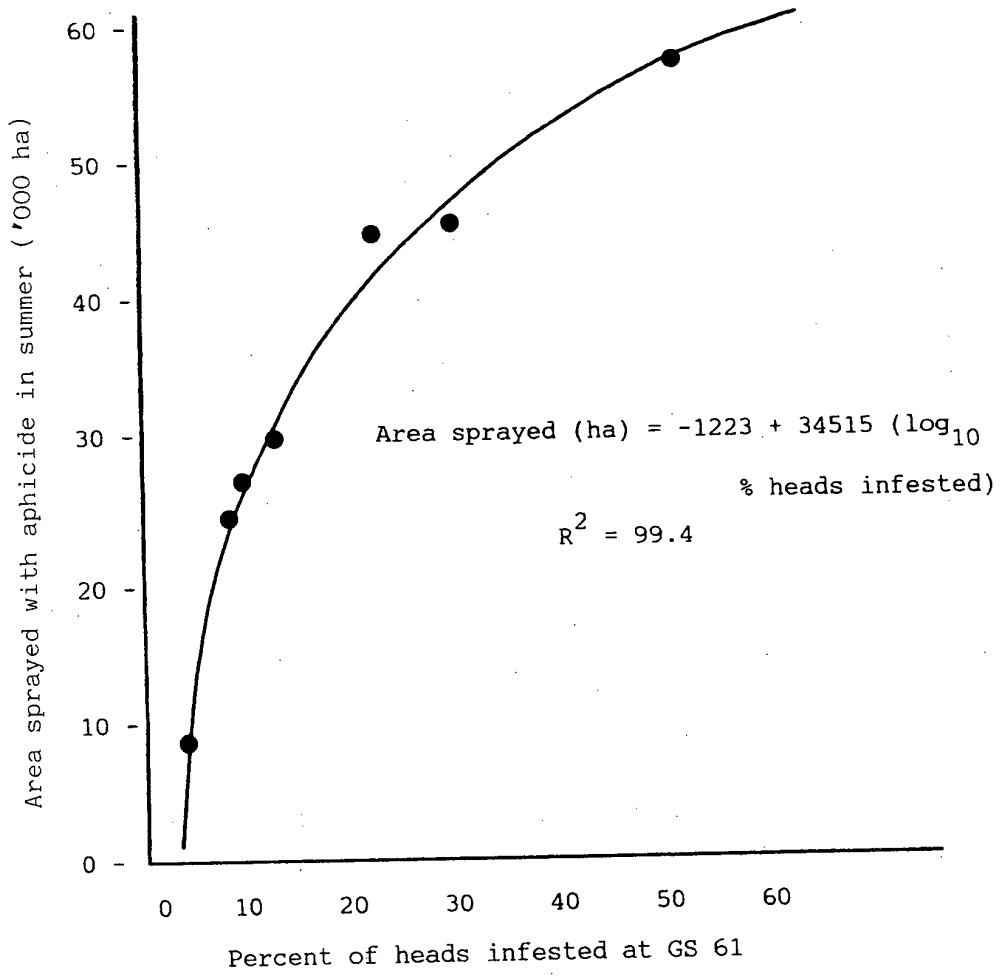

FIGURE 6 Relationship between area sprayed by air and ADAS Pest Monitoring Survey grain aphid results on wheat 1980-86.

BIOLOGY OF THE ROSE-GRAIN APHID [*Metopolophium dirhodum* (Walker)] AND THE GRAIN APHID [*Sitobion avenae*(Fabricius)]

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In common with other aphids, those infesting cereals reproduce parthenogenetically for most of the year, i.e. the females produce offspring without fertilization. Each aphid completes its embryonic development within the body of its mother; the embryos near to term also have embryos developing within them. This telescoping of generations, which results in each parthenogenetic individual being an expectant grandmother, and viviparity (birth of active offspring), have enabled aphids to achieve prodigious rates of increase. In addition, the adults can be either winged or unwinged, and such polymorphism (difference in form) allows the highly fecund and specialized parasitic non-winged forms to coexist with more mobile and less fecund winged forms (migrants) that disperse the species. Although weak fliers, aphids nevertheless are adept at riding the winds and seeking out suitable host plants. These features have been major factors in determining the pest status of aphids.

A. LIFE CYCLES

The life cycles and host preferences of the two most important cereal aphid in Britain differ. The rose-grain aphid (Fig. 7) is an host alternating species that overwinters mainly as eggs on rose (*Rosa* spp.), its primary host. The eggs hatch very early in spring, from late January to the end of February, and give rise to up to three parthenogenetic generations on rose, of which the last generation is winged and comprises the spring migrants (Fig. 7b). These migrants colonize several species of grass (secondary hosts), showing a marked preference for cereals. The spring migrants give rise to a number of generations of unwinged individuals on grasses where, because the aphids are inconspicuously coloured and feed on the leaves, they are often overlooked. Under certain circumstances they can become very abundant before producing the winged summer migrants and dispersing to

colonize other grasses. The switch to producing summer migrants (Fig. 7d) is maternally controlled and is in response to crowding and the nutritional quality of the host plant. On wheat the summer migrants are induced from the milky-ripe stage onwards (GS 73) in the absence of crowding, but at an earlier growth stage if aphids are crowded (Howard, 1988).

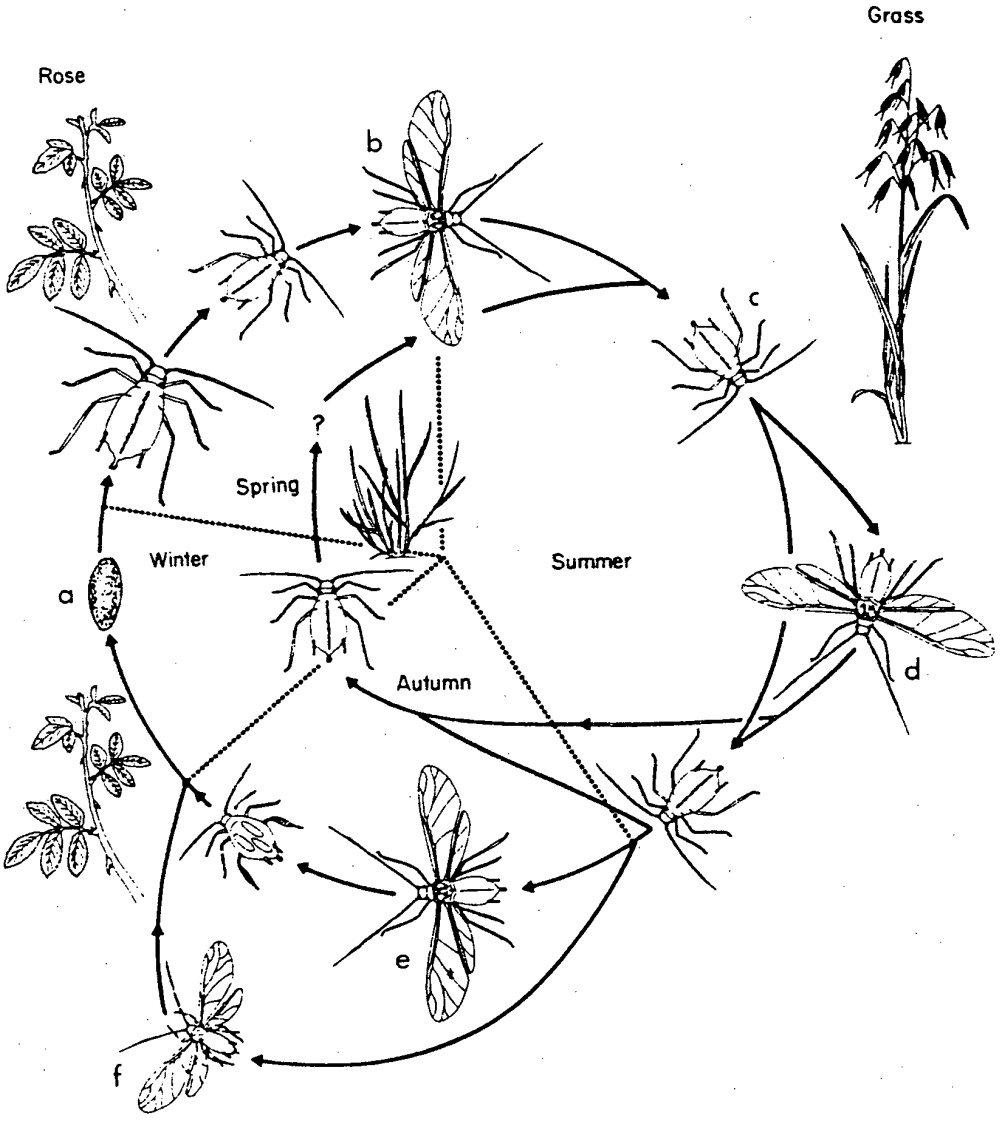

FIGURE 7 Life cycle of the rose-grain aphid, Metopolophium dirhodum. (a, egg; b, spring migrant; c, unwinged individual; d, summer migrant; and e and f, autumn migrants).

In autumn, in response to short day lengths and low temperatures, the aphids switch to producing autumn migrants (Fig. 7, e and f), which consist of males and parthenogenetic females. These individuals return to the primary host where the winged parthenogenetic females give rise to sexual unwinged females which, after mating with the males, lay the overwintering eggs.

The grain aphid (Fig. 8) differs from the rose-grain aphid in that it lives all year round on grasses, moving from species to species during the course of each season.

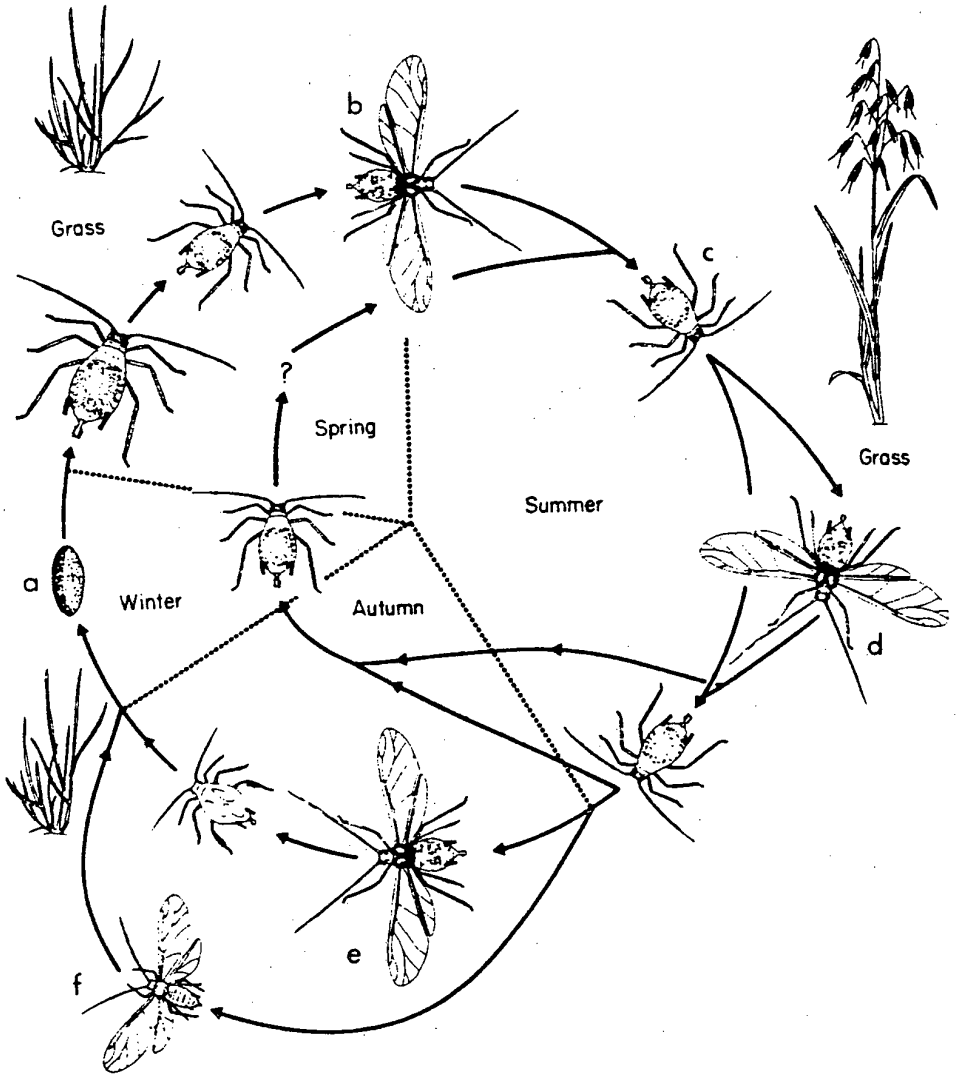

FIGURE 8 Life cycle of the grain aphid, Sitobion avenae. (a, egg; b, spring migrant; c, unwinged individual; d, summer migrant; e and f, autumn migrants).

It overwinters mainly as eggs in the north and as parthenogenetic females in the south of Britain (Newton and Dixon, 1988). Like the rose-grain aphid this aphid also shows a marked preference for cereals, especially in summer. The grain aphid often colonizes winter cereals in autumn and may overwinter on them.

The eggs begin to hatch in March and the third generation from the eggs gives rise mainly to spring migrants (Fig. 8b), especially if crowded. These migrants colonize other grasses, and along with the aphids that overwinter parthenogenetically, initiate the summer increase in abundance. As the species has a number of colour forms, yellow through greens and reds to brown, and prefers to feed on the flowering head and developing seed of grasses, it is much more conspicuous than the rose-grain aphid. The grain aphid can achieve very high rates of increase feeding on the ears of cereals and regularly becomes very abundant. For example, this species has exceeded 10 aphids per tiller in five out of the last 11 years in Norfolk.

In the absence of natural enemies, the production of summer migrants (Fig. 8d) first slows down and then terminates population build-up. The development of summer migrants is induced by crowding and poor host quality, to which an aphid can respond both in its pre- and post-natal development. The production of summer migrants enables the species to exploit a sequence of grasses that flower and seed throughout the season.

As in the rose-grain aphid, the short day lengths and low temperatures of autumn induce the appearance of the autumnal migrants and sexual forms in those populations that overwinter as eggs (Fig. 8, e and f). These forms prefer to colonize, and then overwinter on, grasses of the genus Poa, in particular P. annua and P. trivialis (Newton, 1986).

B. COLONIZATION AND POPULATION INCREASE ON CEREALS

Cereals, especially those sown in spring, are available for exploitation by aphids for only a very short period. The build-up and collapse in aphid numbers on winter wheat in Norfolk in 1976 lasted only five weeks (Fig. 9). Thus there is often very little time in which to monitor and respond to aphid population increase on cereals before aphids reach damaging levels.

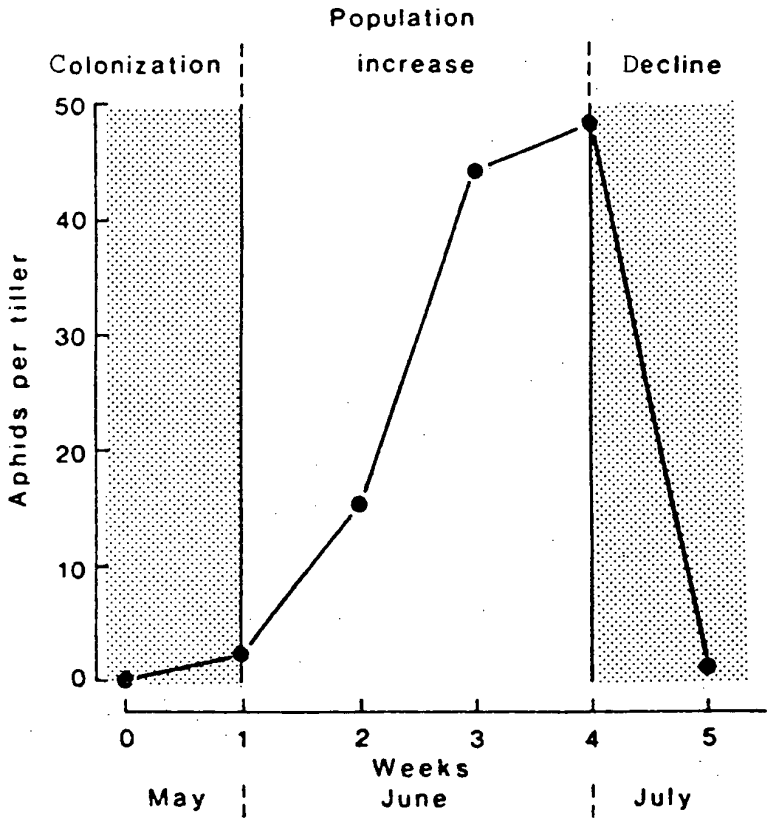

FIGURE 9 The numbers of the grain aphid per tiller in wheat crops during the summer of 1976.

Peak abundance is dependent on the numbers of aphids colonizing cereals and the period and rate of population increase. The numbers of aphids that colonize cereals are dependent on the number flying in autumn and spring, and the visual attractiveness and resistance of the plants. The time available for population increase is dependent on the crop growth stage when colonization starts, which is partially dependent on weather conditions during the winter. For example, winter cereals mature later in years following severe winters which gives more time for aphid population increase. This is especially important in determining the likelihood of outbreaks of the rose-grain aphid (Howard, 1988). The rate of population increase is dependent on host quality, weather and the activity of natural enemies (Fig. 10).

C. COLONIZATION

The numbers of cereal aphids flying in autumn and spring in the southern counties of Britain are largely dependent on the severity of the weather, especially winter weather. Although low temperatures and low light intensities inhibit the flight of cereal aphids they appear to be well adapted to the conditions prevailing at the time of year at which they develop. Thus the timing of the migration into cereals is only likely to be delayed rather than prevented by adverse weather. Although weak fliers, cereal aphids can fly for up to 14 hours, and can fly at high altitudes and may be carried by the winds for considerable distances. At present there is a tendency to assume that cereal aphids come from local sources. However, the source(s) could be distant, perhaps even from continental Europe. This aspect of cereal aphid biology needs further study if long-term forecasting is to be improved.

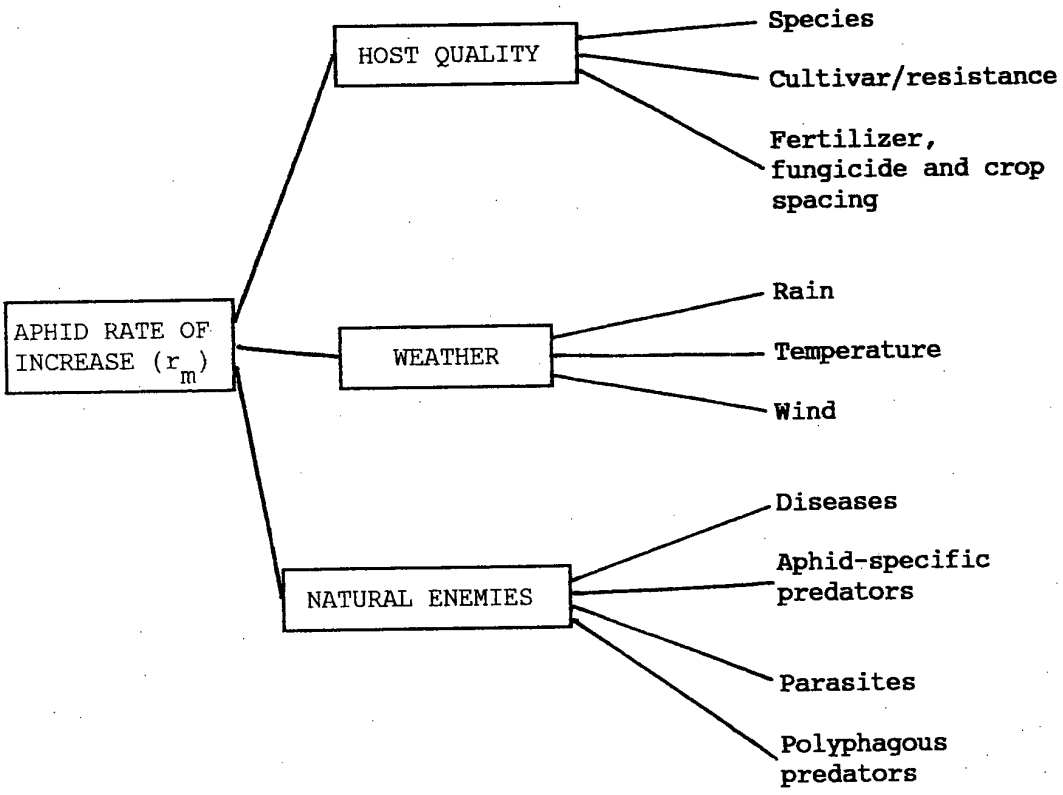

FIGURE 10 Factors that affect the rate of increase of aphids.

An aphid's response to colour alters during flight. At take-off aphids fly towards light coming from the open sky, but become increasingly attracted to yellow/green the longer they fly. This

An aphid's response to colour alters during flight. At take-off aphids fly towards light coming from the open sky, but become increasingly attracted to yellow/green the longer they fly. This response leads them to fly towards vegetation, but they do not discriminate between host and non-host plants before landing. They accumulate on host plants by tending to remain on them longer than on non-host plants. The role of plant spacing in determining the level of colonization is most likely independent of plant density in commercially-grown cereal crops.

D. POPULATION INCREASE

1. Host quality : The migrants that colonize the crops give birth to wingless offspring that have both a shorter developmental time and a higher reproductive rate than the migrants, so the wingless form is well adapted to exploiting an ephemeral food source - the cereal crop.

The rates of increase of aphids of both species are profoundly affected by the stage of growth of their host plants. The grain aphid has its highest reproductive rate when feeding on ears of cereals at the milky-ripe stage and is almost three times as fecund as when feeding on leaves. The grain aphids feeding on the ears cause proportionately more of the plant's nitrogen to be translocated to the ears, where it is taken up by the aphids; thus to a certain extent, aphids can manipulate the metabolism of cereal plants to their advantage.

Planting density also affects aphid population increase, with the rose-grain aphid doing better in dense, and the grain aphid in sparse, stands. The recent increase in the quantity of nitrogenous fertilizer applied to cereals is thought to have favoured the development of aphid outbreaks. That nitrogen affects the aphids' rates of increase is well supported by laboratory and field studies, all of which indicate that more aphids develop on plants that receive the highest levels of nitrogenous fertilizer, and the grain aphid is more markedly affected than the rose-grain aphid. However, nitrogenous fertilizers affect both the rate of growth of the aphids and the cereals plants. Although the numbers of aphids per plant increase, the numbers per unit weight of plant decrease with the amount of nitrogen applied. The damage done

to plants by aphids appears to depend on their abundance and they are possibly more damaging to high- than to low-yielding plants.

The potential value of plant resistance for reducing the incidence of damaging aphid infestations has been known for some time. Although much research has been done recently on the nature and level of resistance shown by various species and cultivars of cereals, there has been little attempt to use this resistance in cereal breeding programmes to produce cultivars that are more aphid resistant. To varying degrees, cereals can deter aphids from settling and colonizing them (antixenosis), can restrict the rate of increase of aphids (antibiosis) and can tolerate the nutrient drain imposed by aphids (tolerance).

The effects of antixenosis and antibiosis are often difficult to separate as an aphid has to settle and feed before any antibiotic effect becomes apparent. In the absence of obvious defensive barriers such as hairs and waxes, there is a clear positive relationship between antixenosis and antibiosis (Fig. 11), and the plant cultivars resistant to one species of aphid are likely to be resistant to another (Fig. 12). Antixenosis has been attributed to variations in the quantity and nature of the epicuticular waxes, which alter the visual appearance of a plant or make it difficult for an aphid to cling to its surface. Similarly, hairy stems and leaves and the presence of awns on the ears can deter winged aphids from settling or can dislodge them as the stems brush past each other. As these features are easily identified from the appearance of the adult plant and do not appear to have any agronomic penalty, they could easily be bred into cereals.

In the absence of these surface defences aphids probe and feed. There is an association between the rate of increase of an aphid population and the concentration of certain chemicals in the superficial tissues of cereals. A six-fold increase in the concentration of hydroxamic acid is associated with a halving of the rate of increase of aphids feeding on wheat. The presence of this and similar chemicals at different concentrations is thought to account for differences in the level of resistance shown by different cultivars, different growth

stages and different parts of the cereal plants. There is a suggestion that the chemical structure of the cell walls of cereal plants might determine the ease with which aphids can penetrate the plants' tissues and locate the translocating elements, and thus may explain the variation in the resistance of cereals to aphids.

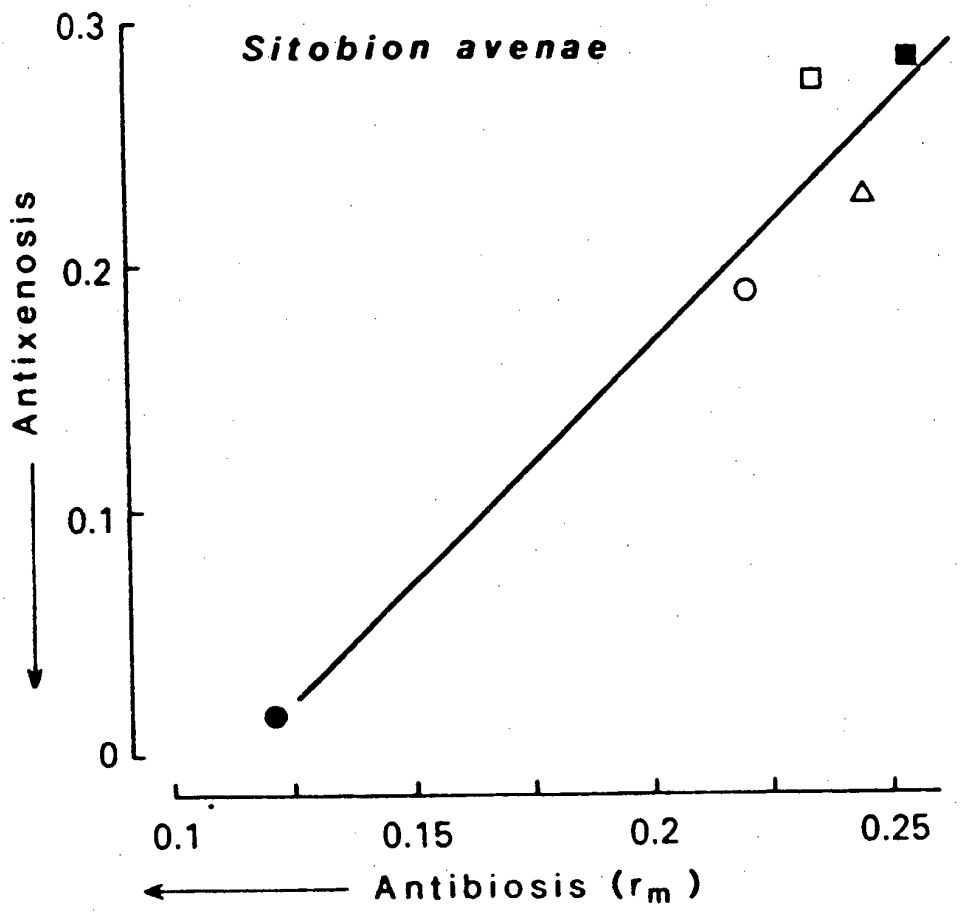

FIGURE 11 The relationship between the levels of antixenosis and antibiosis to the grain aphid shown by three ancient wheats (Einkorn ● Emmer ○ and Spelt ■) and two more modern varieties (Sicco □ and Timmo △) of wheat (After Sotherton and Van Emden, 1982). Antixenosis is represented by the proportions of alates settling on each variety in a multiple choice experiment.

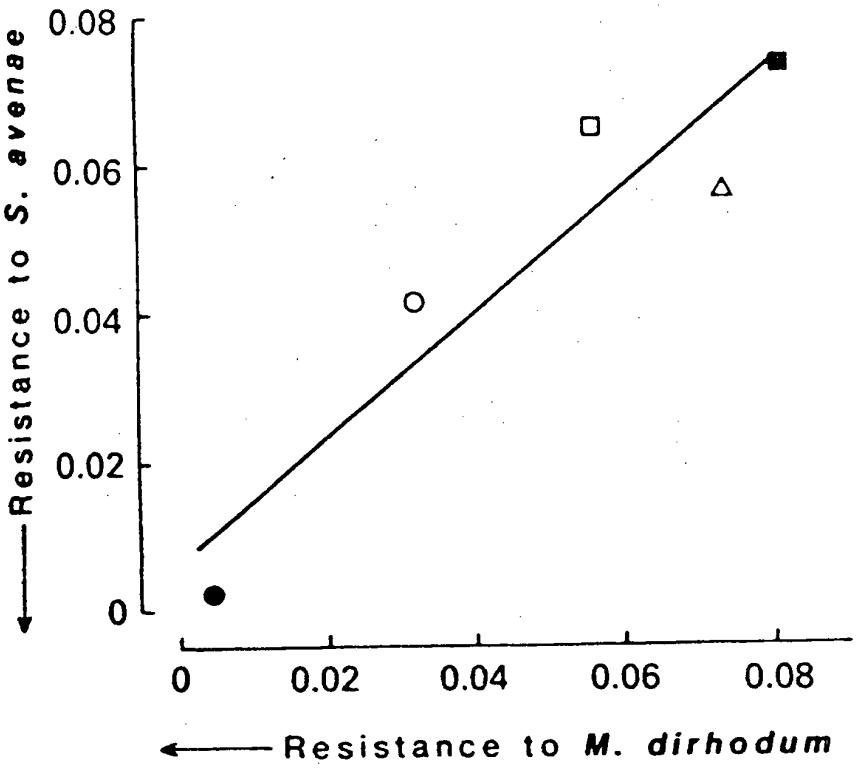

FIGURE 12 The relationship between the level of resistance (antibiosis times antixenosis) to the grain aphid and that to the rose-grain aphid shown by three ancient wheats and two more modern varieties (symbols as for Fig. 11) (After Sotherton and Van Emden, 1982).

It is likely that the incidence of aphid outbreaks on winter wheat that matures as early as winter barley would be greatly reduced. Indeed the effective resistance (i.e. avoidance) in the field of some wheat cultivars has been attributed to their precocity.

With a few notable exceptions the tolerance by cereals of aphid infestation has not been considered. This could be a serious omission because low levels of aphid infestation on resistant cultivars could be just as damaging to yield as higher levels of infestation on the more susceptible cultivars. Thus it is important that resistance and the effect of aphids on yield are considered together.

There is now an urgent need to obtain a clearer understanding of the mechanisms underlying the resistance of cereals to aphids and their mode of inheritance. Such understanding would help plant breeders to incorporate greater levels of aphid resistance into cereals. The potential advantage is considerable; for example, early maturing cultivars support fewer aphids than later maturing cultivars, and awned cultivars support 40% fewer aphids than comparable unawned cultivars. Combined with the levels of antibiosis in current cultivars, these factors could reduce aphid infestations of wheat by 85%. However, it is important to avoid using resistance mechanisms which counter the effect of natural enemies which also reduce the rate of increase of aphids.

The same sort of variability of resistance shown by cereals to aphids is also likely to be shown by aphids in their ability to overcome the resistance of cereals. Thus in screening for resistance a wide range of forms of each of the cereal aphids (genotypes) should be used; although costly, it would reduce the risk of marketing a 'resistant' cultivar for which a resistance-breaking aphid genotype may already be present. In this context it is surprising that there have been few genetical studies of cereal aphids.

2. Weather : Although undoubtedly important in determining the rate of population increase of aphids the very complexity of weather factors has made its effects difficult to quantify. Temperature affects the rate of development and reproduction of aphids, but there are differences between species. However, as temperature affects the rate rate of development of the crop as well as that of the aphids (as does the application of nitrogenous fertilizers) it is the relative effect that is important. Low temperatures slow down crop development more than aphid population growth; thus aphids have more time for reproduction while the crop is checked and, as a consequence, are likely to achieve higher peak numbers in cooler than in warmer years. Wind has been implicated in dislodging aphids from plants, especially prior to ear-emergence. Poor colonization by winged aphids and reduction of the number of aphids on crops are both associated with heavy rainfall.

3. Natural enemies : Aphids on cereals are attacked by a wide spectrum of both aphid-specific and polyphagous predators, as well as insect and fungal parasites. By killing aphids, natural enemies suppress the aphids' rates of population increase and thus reduce the likelihood of the aphids achieving damaging population levels. The problem has been, and still is, that of quantifying and predicting the role of natural enemies in reducing cereal aphid abundance.

In certain years, aphid populations decrease when the cereal plants are still nutritionally favourable for aphid increase, and this is associated with (an abundance of) ladybird beetles and hoverflies. This has occurred at aphid densities below 4 per tiller and as early as booting or heading, well before any damage is done to the crop. Thus anything that increases the abundance of these insect predators is likely to reduce the incidence of damaging cereal aphid outbreaks.

The importance of fungal diseases of aphids varies from year to year. However, early in a season diseased aphids often appear when conditions get humid; such conditions are, therefore, thought to be important in reducing aphid abundance. In France, rainfall in May, which is thought to affect the incidence of aphid fungal disease, is an important predictor for forecasting cereal aphid abundance. Similarly, the insect parasites of aphids can also be active early in the year and suppress the population increase of cereal aphids, especially when springs are mild.

Many species of beetles, harvestmen, mites and spiders forage on the surface of the soil beneath cereal crops and are known to feed on aphids. They tend to be nocturnal and can be very numerous. Of the 391 species of polyphagous predators recorded from cereal fields in the UK possibly as many as 50% eat aphids. The consumption of aphids by these polyphagous predators early in the season could have a significant effect in reducing peak aphid abundance.

Although the factors that affect the colonization, and population build-up of cereal aphids on cereals are well known, it has proved very difficult to quantify their effects on aphid abundance. This is

particularly true of the factors that affect the rate of increase (Fig. 10). The complexity of the system, in terms of numbers of species and interactions is formidable. Thus for forecasting there is a need to identify easily measured and reliable predictors of aphid rates of increase. However, for this we need sequences of population counts of aphids that have been collected over many years. The possibility of using natural enemies in the integrated control of cereal aphids has attracted attention but has not yet been realised. The prospect of using plant resistance to reduce cereal aphid abundance, however, is both exciting and largely unexploited.

NATURAL ENEMIES OF CEREAL APHIDS

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A. INTRODUCTION

Early studies of cereal aphid natural enemies (e.g. in the late 1960's) concentrated mainly on aphid-specific predators (Carter et al., 1980). While these have been shown to play a role in reducing aphid numbers within a season, work from the mid 1970's onwards has implicated other, more generalist feeders (polyphagous predators) in aphid control; these are involved in "background" predation, having a role to play in preventing outbreaks rather than in limiting them. This possibility arises from the fact that polyphagous predators (mainly ground beetles, rove beetles and spiders) feed on a range of prey types and can perhaps concentrate on aphids (rather than their other prey, e.g. flies, springtails or earthworms) when aphid populations start to increase in late spring/early summer (Sunderland et al., 1987).

A third group of beneficial insects is that to which the parasitic wasps (parasitoids) belong. These can be very abundant, are mobile between fields and can, like the generalist predators mentioned above, be active in the winter and early in the season (Powell, 1983; Vorley and Wratten, 1987).

This section will briefly review types of evidence that these groups of natural enemies can reduce aphid numbers. More importantly it will go on to analyse the ways their effects can be enhanced. The latter is an urgent need in the light of farmers' examining their variable costs more closely with the declining value of grain in real terms, and it is especially relevant within the framework of extensification as set-aside areas can be manipulated to enhance natural enemy levels.

B. EVIDENCE THAT NATURAL ENEMIES REDUCE THE NUMBERS OF CEREAL APHIDS

Correlations of aphids/predator numbers : This approach is limited because causality cannot usually be demonstrated but it has usefully pinpointed the potential role of some groups. Large-scale field

surveys often give data of this type, where existing differences in aphid and predator numbers within and between fields are used in attempts to make correlations.

Experimental manipulation of predator numbers : This experimental technique has been used increasingly throughout Europe, but is often more flawed experimentally than is at first obvious. The principle is to erect barriers or cages in a crop and to remove predators from within them or to supplement their numbers. Aphid population development is then studied and related to either reduced or enhanced predator numbers. These studies are often large-scale and sometimes unreplicated and suffer from the problem that the predators responsible for any aphid population reduction are not always identifiable because many species are sampled together within the barriers. However, work in the late 1970's in England and some more recent work in Sweden has pointed to the role of Carabidae and Staphylinidae as potentially important predators. Work at Southampton University in 1986 and 1987 using polyethylene barriers vertically sunk into the soil has in some circumstances demonstrated that a 50 percent reduction in predator numbers can lead to the aphid population rising to above the ADAS 'threshold' of 5 aphids per ear at flowering.

C. IDENTIFYING WHICH SPECIES ARE RESPONSIBLE FOR APHID POPULATION REDUCTION

There may be 400 or more predatory and parasitic insect species and spiders in a wheat field in the south of England so the barrier experiments mentioned above, although pointing to useful predation potential, do not identify which species are important. Methods such as trapping of the predators and dissecting them for evidence of prey remains in their gut, or more recently, analyses based on immunological techniques, have begun not only to identify which are the most important species of the polyphagous groups but also have tried to quantify their role. The latest view from work in the south of England is that spiders and staphylinid beetles, amongst the polyphagous groups, are probably the most important, followed by Carabidae, the ground beetles. Some species, including carabids and earwigs, for example, may eat large numbers of aphids but are often limited for some

other ecological reason such as their slow penetration of the field in the spring. Others may have a rather weak response to aggregations of their prey in the field, so limiting their effectiveness for a different reason, while others may have a low voracity, or a low "preference" for aphids. One of the features many of the polyphagous groups have in common is their phenology in that many of them leave the cereal field at or just before harvest. This behaviour is thought to relate to the history of the groups, many of which were originally marshland species. The agronomic advantage is that they leave the field before cultivation (possibly burning) and drilling and spend the autumn, winter and spring in the field boundary (see below).

D. SUSCEPTIBILITY TO INSECTICIDES

Some broad-spectrum insecticides such as the organophosphate dimethoate and to a lesser extent, demeton-S-methyl and even some fungicides, all produce significant mortality among predatory insects in cereal fields. These effects are important for several reasons; firstly, there is evidence that considerable overspraying takes place anyway (see damage assessment sections), secondly that 'softer', but more expensive alternatives exist, and thirdly because the predators themselves may be responsible for reducing or preventing aphid outbreaks.

E. OVERWINTERING STUDIES

Many predatory species spend the winter in the field boundary. This habitat seems to be less important for the more mobile ladybirds and hoverflies, but for the polyphagous Carabidae and Staphylinidae it is the main overwintering habitat for some species at least. Recent work has shown that the raised bank at the base of the hedge, especially if well drained, covered with matted grass and facing south, can harbour up to 1,000 predatory insects per square metre, while other areas a few metres along the same hedge can be very impoverished because of their differing botanical and micro-climate characteristics. This knowledge concerning overwintering has been exploited recently and will be mentioned below.

F. APHID-SPECIFIC GROUPS AND PARASITOIDS

There is no doubt that larvae of hoverflies and of ladybirds can occur in very large numbers during even a moderate aphid outbreak. They have been shown to stop populations becoming extremely high, but the data are still rather equivocal concerning whether or not these groups can prevent outbreaks in the first place. This is because the adults are specific to aphids in their egg-laying and, therefore, aphid density thresholds exist below which they will not lay eggs at all (Sunderland and Vickerman, 1980). This egg-laying threshold is in contrast to the polyphagous groups mentioned earlier, which may aggregate numerically without egg-laying or may lay eggs in response to the densities of non-pest insects in the crop. However, hoverflies in particular do seem to have very low aphid thresholds for oviposition; recent work has suggested that these thresholds may be lower than 1 aphid per stem. The voracity and high level of foraging of the larvae combine with this low threshold to make them a useful group. They show very few associations with field boundaries, however, because of their mobility and there do not seem to be many opportunities for manipulating the non-crop environment of these insects other than perhaps in the provision of more pollen and nectar sources.

G. POTENTIAL FOR THE MANIPULATION OF PREDATORY AND PARASITIC INSECTS IN THE GENERAL ECOSYSTEM

A rational pesticide use coupled with more selective compounds, possibly applied at reduced doses is proposed. In most cereal enterprises in the UK, dimethoate is the cheapest insecticide available but its broad-spectrum nature makes it incompatible with many of the predators discussed above. Pirimicarb, although more expensive, is much more specific. Pyrethroids, have been shown to be less toxic to beneficials than dimethoate in recent field trials in wheat but in the UK at least their use is restricted to the autumn. This was because at the time of their introduction there was insufficient data on the potential side effects of summer use. One way of reducing the effects of pesticides on beneficials and, therefore, enhancing the latter's potential has been investigated collaboratively in Germany and in the UK recently (Poehling, 1987) and involves reducing the quantity of insecticide applied per hectare. Quantities of active ingredient have been reduced

to a half, or even one quarter on an experimental basis and results have usually been as follows; firstly, not all aphids are killed by the pesticide (a residual population remains, often on the flagleaf). Some statisti-cally-detectable yield loss is sometimes associated with these remaining populations, but they do have the benefit of providing aphid food for predators after spraying, the predators otherwise either being killed by the toxic pesticide, or starving to death. The predators are then able to "mop-up" the residual aphid population, preventing it from becoming too high, while the yield reduction, although measurable statistically, is balanced by the reduced cost of pesticide.

Some scientists believe that reduced doses of insecticides are ecologically dangerous because they may promote a more rapid increase in aphid resistance. However, all the well-studied cases of insect resistance in arable crops and in glasshouses (e.g. Ffrench-Constant et al., 1988) are associated with high uses of full doses, rather than the opposite; furthermore, the theoretical reasons for expecting resistance to appear following reduced-dose applications are questionable.

An earlier section in this review pointed out the importance of resistant cultivars as part of an integrated control programme for aphids. Theoretical and practical studies have often shown how varietal resistance, when combined with normal predatory activity levels, can be synergistic when one or the other would not be good enough alone. One ideal Integrated Pest Management (IPM) package would be a resistant cultivar and reduced-dose insecticide acting together. Even this, however, would still depend on the predator and parasite resource available in the crop and there is evidence that over the past decade the background numbers of these animals have declined, partly because of changes in the non-crop environment and partly because of increasing fungicide usage.

Biological information mentioned earlier concerning the non-crop habitats used by these predators and parasitoids could, however be exploited dynamically in the 1980's. Work at the University of Southampton, funded by MAFF, for example, has created raised banks across cereal fields, simulating the hedge bank which is already known

to be important for predator over-wintering. These banks are 2 metres wide and about 40cm high and have been drilled with a range of grass species in a replicated plot trial. Predator colonization in the autumn, their survival in the winter and movement out from the ridges in spring is being monitored and already in the first winter densities of predators ten or more times those in open fields have been produced, even under conditions of patchy grass establishment. The advantage of these ecological "islands" is that they are agronomically very easy to create and with a herbicide or rotovated strip next to them can be relatively protected from the agrochemicals used on the nearby cereals. They have the potential for harbouring 0.5 million predators/bank when established (Thomas and Wratten, 1988).

Some other types of ecological "island" have been studied recently by researchers at the Game Conservancy in their well-known unsprayed strip experiments (conservation headlands); in these, the crop itself does not receive broad-leaved weed herbicides or spring insecticides for a strip 6 metres wide out from the field boundary. The effects on many non-pest insects have been profound with big consequences on the survival of game bird chicks. Recently, butterfly ecology has been studied in association with these strips and it has been found that butterflies use them intensively for basking, feeding and possibly egg-laying. The role of the strips for aphid predators has only just begun to be investigated with NERC funding to the Game Conservancy and Southampton University. One aspect where the use made by natural enemies of non-crop environments is well studied is that of parasitoid wasps; although some of these spend the winter in the cereal fields, migration in the spring is largely from grassland sources. Recent work has shown that one grass field can produce enough parasitoids to colonize several wheat fields and these invaders have been shown by fieldwork and modelling to have the potential to reduce aphid numbers to one seventh of their control numbers (Vorley and Wratten, 1987). As with specific natural enemies of aphids, the rate and timing of these parasitoids' arrival may limit their effectiveness, although once arrived they can be very useful bio-control agents.

The set-aside scheme announced by the MAFF in June 1988 may increase the amount of grassland in "fallow" fields; a more tractable change is that of producing grass trips around cultivated fields. ADAS is investigating this idea on a range of Experimental Husbandry Farms, with the University of Southampton providing the entomological advice. However, the strips in these experiments are only 2 metres wide, are drilled only with Lolium perenne and are not elevated. The problem here may be that they are too cold and too wet to harbour many predators during the winter. They could be useful ecologically if they were wider (up to 6 metres, as proposed by MAFF in their extensification scheme), or had an elevated region within the strip. Boundaries next to these strips which have been poor for predators and parasitoids for years could then be effectively improved because of the biological benefits of having a predator and parasitoid overwintering reservoir near them. In this case the value of the field edge becomes maximised.

MONITORING AND FORECASTING

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A. INTRODUCTION

Monitoring is a type of sampling which can be done routinely and simply at critical times in the life cycle of a pest. Migrant pests, which include aphids, can be monitored on host plants prior to the migration to crops, during this migration, and on crops before they cause damage. Monitoring, however, only gives an estimate of the density of pests present at the time of sampling, while forecasting gives an indication of likely future population levels. Forecasting schemes should ideally be linked to monitoring the pest populations but can also be related to prevailing weather conditions. Some fungal disease forecasting schemes, such as for potato blight, are based on the assumption that sufficient inoculum is present and an outbreak will occur if the correct sequence of weather conditions develop. Forecasts based soley on weather conditions are rare for insects; one example is the timing of the start and end of hop aphid migrations. Such forecasts are potentially useful, however, as automatic weather stations can be programmed to alert farmers when outbreaks are likely or when crops should be monitored. Not only will weather conditions influence aphid population development on crops but also the timing, size and distances of migrations.

Complex computer models have been developed for grain aphid (Carter et al., 1982) and rose-grain aphid but these are unlikely to be used directly in forecasting schemes. This is primarily because they require daily minimum and maximum temperatures, aphid colonization rates and information about natural enemies, and these values are impossible to predict. Instead, they are useful for developing an understanding about how the crop, cereal aphids, and natural enemies interact and they expose gaps in knowledge, thus enabling research to be concentrated in the most important areas. At present, these models are being used in the UK to study: (i) the damage relationship of rose-

grain aphid on wheat, (ii) the effectiveness of predators (such as spiders, and rove and ground beetles which do not feed specifically on aphids) in controlling aphid populations, and (iii) the spread of barley yellow dwarf virus (BYDV) by the bird-cherry aphid, Ropalosiphum padi.

The most developed monitoring and forecasting system for aphids is for the black bean aphid, Aphis fabae, which overwinters on spindle, Euonymus europaeus, and migrates to spring beans and other crops in May and June. The risk of damaging populations in the summer can be forecast with increasing certainty from assessment of the size of the migration the previous autumn, the winter egg count, the numbers of aphids on spindle in the spring, the size of the spring migration (both migrations measured with Rothamsted Insect Survey (RIS) 12.2-m suction traps) and populations on beans (Way et al., 1981). The suction trap samples are useful as they provide systematic, continuous information and give regional indications of likely problems while population monitoring on host plants gives more detailed, localised information.

B. MONITORING

Overwintering host plants : As the rose-grain aphid has an autumn migration of similar size to black bean aphid and probably also overwinters mainly as eggs on its primary host (members of the rose family), monitoring during the winter and spring may prove useful for this species too. However, as it is only a pest occasionally it would require a long-term project to collect sufficient field data to test whether such monitoring would be useful. Several projects have studied overwintering of rose-grain aphid but these have been short-term and localised. In addition, the eggs are relatively difficult to find and, as several aphid species overwinter as eggs on roses, some confusion is possible.

Aphid populations, especially of the grain aphid, overwintering on cereals, can be monitored either by plant inspections or by using a portable suction sampler. Such sampling is time-consuming especially at low aphid densities. However, as overwintering success is

determined largely by temperature it may prove possible to estimate the size of the reservoir population in the spring indirectly from the coldness of the winter. In general, mild winters result in increased survival of aphids, although near to the south coast, where weather conditions are generally less severe than in eastern England, warm winters may benefit natural enemies more than aphids, leading to fewer aphids in the spring.

It is important that the locations of the sources of migrant populations are known, i.e. whether local or distant, as this will determine the relevance of any sampling which is carried out over the winter to the development of a forecasting scheme. It is usually assumed for cereal aphids that sources are local but this has yet to be proven.

C. MIGRATION

The size of the aphid populations in the spring which have survived the winter largely determines the extent of the migrations to crops in May and June. In south-east England, more grain aphids migrate following mild winters while the reverse is true for rose-grain aphids (Dewar and Carter, 1984). These migrations are monitored routinely by means of a network of suction traps, which sample the air at 12.2 m. The RIS collects samples from 15 suction traps throughout England and one each from Wales and Northern Ireland and collates aphid data from five traps in Scotland.

The delay in suction trap samples being collected, sorted, identified and the information being disseminated is five to 12 days. This delay might not be too serious as damaging aphid populations are unlikely to develop until at least one generation after the immigrant aphids have colonized crops and farmers may still have time to examine crops as a result of suction trap warnings and apply an insecticide if needed.

The RIS, in co-operation with the Institute of Horticultural Research, is engaged in a five-year project to relate suction trap samples to crop colonization rates in cereals and subsequent aphid population development. Initial findings suggest that there is a relationship

between aerial populations and initial crop infestations and that, generally, the variation in aphid densities between fields up to 20 miles away from suction traps sites is small. Particular attention is being paid to those fields in which aphid densities are either lower or higher than average to determine the factors responsible for the differences. Between-field differences in natural enemy populations and agronomic practices, such as fertilizer and chemical usage, are currently thought to be the most important factors. Once these factors have been confirmed and quantified, suction trap samples could be used to give an indication of crop populations within a region, which would then be modified by knowledge of these factors operating in individual fields.

D. CROPS

Monitoring of wheat crops for aphids in summer is done by three methods: (i) counting the number of aphids on a pre-set number of shoots, flag leaves or ears (usually 50 to 100), (ii) estimating the percentage of shoots or ears on which there are aphids and then converting this value to a density (Fig. 13), and (iii) using a portable suction sampler. The third method is not practicable for farmers and advisers to use and is not as accurate as visual counting, except at very low aphid densities. Visual counting is also more accurate than converting the percentage of infested shoots to a density but takes longer. Estimating aphid densities from the percentage of infested shoots is used in the Dutch pest and disease monitoring scheme for cereals (EPIPRE), the cereal aphid forecasting scheme on Prestel FARMLINK run by Southampton University and the aphid monitoring research project organised by the Institutes of Arable Crops Research and Horticultural Research. The relationship between density and percentage infested shoots is, however, complex and several mathematical relationships have been proposed. In the one currently used in the three schemes mentioned above, 1 aphid per shoot is equivalent to about 35% shoots infested, three to 64% and five to 75%. Above this last percentage the estimate is less accurate and so the percentage of shoots with ten or more aphids is used. With practice, it is relatively easy to distinguish these shoots without having to count all the aphids present. ADAS has recently adopted a similar system following analyses

of Pest Monitoring Surveys in which aphid densities have been correlated with percentage ears infested.

A possible fourth type of crop monitoring scheme based on a rating scale has not been developed for cereal aphids. In this approach, a score is

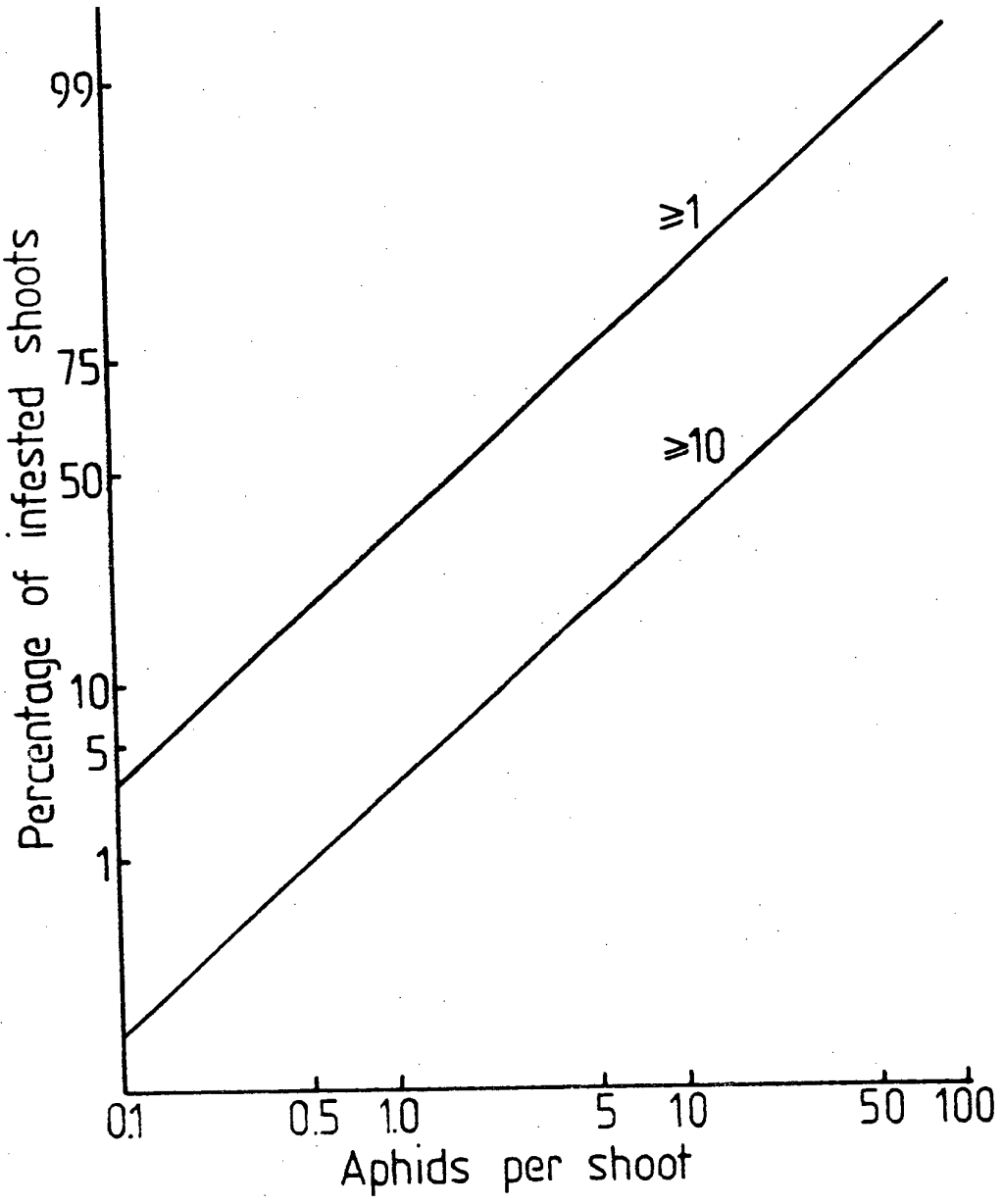

FIGURE 13 The relationships between aphid density (numbers of aphids per shoot on a logarithmic scale) and percentage of shoots with one or more, or ten or more, aphids.

given for the degree of plant infestation. It can be done quickly but the sizes of the categories have to be chosen carefully; too small and the sampler ends up counting all the aphids, too large and information is lost. Rating always gives less information than actual counts and percentages but may prove useful as it is quick to perform.

A detailed study of aphid distributions in cereal fields is needed in order to develop the most efficient and reliable monitoring scheme for use by farmers and advisers.

E. FORECASTING

Forecasts can either be short- or long-term. The former is likely to be dependent on either monitoring of migrants coming into crops or subsequent crop populations and, if control is required, the farmer usually has to respond immediately. Long-term forecasts give the farmer more time to plan his control strategy but are invariably less accurate than short-term forecasts. This is because there is a relatively long time period between the forecast being made and the peak density occurring on crops so that conditions are more likely to change and affect pest population increase. The forecasting scheme for black bean aphid is a series of forecasts, which range from long-term (based on monitoring of aerial populations the previous autumn and egg counts over-winter) to short-term (based on spring counts of aphids on the overwintering host and aerial populations in early summer).

F. SHORT-TERM FORECASTS

The current forecasting scheme for cereal aphids used by ADAS is based on crop monitoring from the start of flowering onwards (Fig. 14) with some complementary information coming from suction trap samples. The scheme recommends that crop monitoring should be continued to at least the milky-ripe stage so that late infestations of both grain aphid and rose-grain aphid can be detected. Hot, dry weather is thought to be particularly important for the development of damaging aphid populations. As weather also affects crop growth and development and the activity of natural enemies, the relationship between aphid population increase and weather is unlikely to be this simple. Indeed, results from a computer model for grain aphids indicate that low

temperatures slow down crop development more than aphid population growth so that the aphids have more time to reach higher levels.

Carter et al. (1982) developed two methods to predict the actual size of the peak population of grain aphid on winter wheat. In the first, the peak aphid population was estimated from the number of aphids at either the end of ear emergence or mid-way through flowering using data from 1976 to 1978 collected in Norfolk and Wageningen (the latter in the Netherlands). In the second, more complex method, the aphid population was assumed to develop at a constant rate, relative to temperature. The monitoring was undertaken up to the middle of the milky-ripe stage when it was assumed that the peak population occurred. These two methods and the Dutch EPIPRE and Southampton University Prestel systems, assume a constant high rate of aphid population growth. Unfortunately in 1980, the first year that Carter et al. (1982) tried out their forecasting methods, in most areas aphid population growth

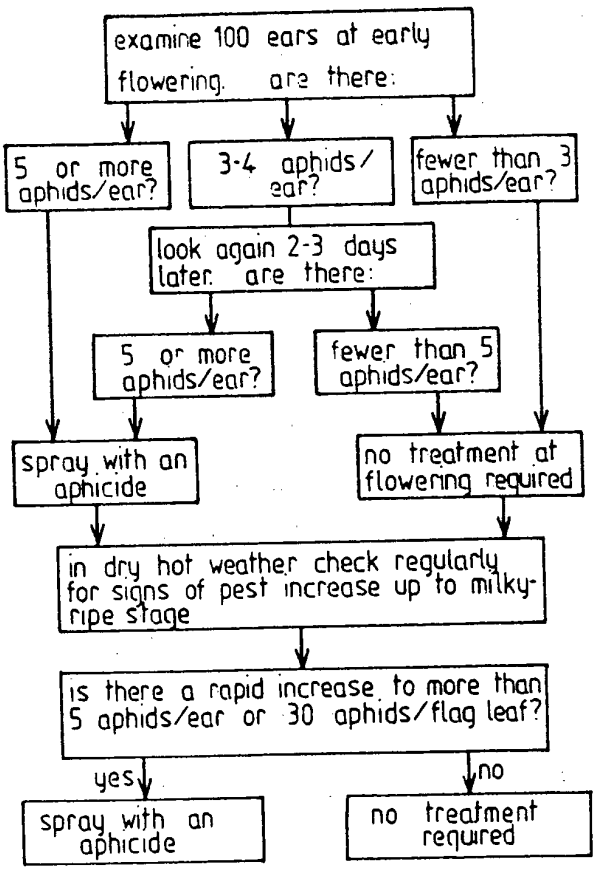

FIGURE 14. ADAS decision flow chart for the need to control grain aphid and rose-grain aphid on winter wheat in summer.

was much lower than predicted and the expected aphid outbreak did not occur, except in Norfolk. The low aphid population growth rates were attributed to the effects of natural enemies and adverse weather conditions.

A more accurate short-term forecasting scheme for grain aphid has been proposed by Entwistle and Dixon (1986) which uses numbers of aphids and the rate of population increase. This latter factor combines the effects of natural enemies, prevailing weather conditions and host plant condition into one measurable value, but requires two samples to be taken. The scheme has the advantage over the ADAS method in that it is able to distinguish those years in which initially low aphid populations will increase rapidly to outbreak levels and when initially high aphid populations, increasing slowly, will not. However, the scheme requires validation by field studies.

For rose-grain aphid, Dixon et al. (1987) found that the time of the peak weekly RIS suction trap sample (which corresponded to the aphid peak on crops) was related to a temperature sum, measured as the daily number of degrees above $1^{o}C$ accumulated over the winter up to the end of May. Thus rose-grain aphid populations peaked earlier after mild winters than after cold ones. If one week's suction trap sample exceeded 100 at least two weeks prior to the predicted peak then an outbreak was possible. Of the 15 years that they examined, it was predicted that there was little risk of an outbreak in seven years but, of the remaining eight years in which an outbreak was expected, in only one did aphid populations reach damaging levels. In addition, the inherent delay in identifying suction trap samples could mean that, in a year with a late build-up of rose-grain aphid, farmers may get less than a week's warning before the peak aphid population. The system will, however, detect some years in which insecticide treatment is not necessary, and do so early enough to be of practical use.

G. LONG-TERM FORECASTS

A survey on the application of insecticides in the summer to control cereal aphids showed that most farmers were applying chemicals after a significant yield loss had occurred (Watt et al., 1984). In some

cases, sprays were applied at the time of the peak population density or during the aphid population decline phase. Farmers were, therefore, responding to high aphid densities rather than using the forecasting scheme. Longer term forecasts would allow them more time to prepare for spraying and perhaps give them greater confidence in the current short-term forecasting schemes. In addition, some farmers apply insecticides as a tank-mix with fungicides at ear emergence which can lead to significant yield benefits in years when aphid populations would otherwise have increased during flowering. Unfortunately, crop monitoring prior to flowering is not a reliable indicator of future population increases so a long-term forecast would also help optimise this early insecticide use.

Dewar and Carter (1984), using data from the late 1970's and early 1980's, showed that outbreaks of grain and rose-grain aphid rarely occurred following small aphid migrations (below 10 and 100 aphids per suction trap sample respectively before the end of flowering). Large migrations of grain and rose-grain aphid (more than 50 and 300 respectively) sometimes led to outbreaks but in other years did not. Natural enemies and possibly adverse weather conditions during the colonization period probably prevented damaging outbreaks occurring. As cold winters generally lead to small numbers of grain aphid which migrate later than usual and to large numbers of rose-grain aphid, an estimate of the likelihood of an outbreak occurring can be made from the weather conditions up until April. However, as Dixon (1987) pointed out, using data from 1945 to 1979, the relationship between peak numbers of grain aphid and winter severity was positive which indicates that outbreaks occurred after severe winters. Perhaps this difference between the findings of Dixon (1987) and Dewar and Carter (1984) is due to the early sowing of cereals in recent years allowing grain aphid to overwinter successfully in mild winters primarily as aphids. Prior to this, crops were sown later and the grain aphid probably overwintered as eggs on grasses. In this latter form, it would be expected that grain aphid would have a similar relationship to rose-grain aphid with regard to peak numbers and winter severity. A clearer understanding of the relationship between winter weather and

numbers of spring migrants is needed, especially the extent of regional variation before winter weather could be used in a practical forecasting scheme.

Also required is more information on the factors influencing aphid population development after crop colonization and how they may be predicted. Vickerman (1977) showed, using field data from the Sussex Downs, that outbreaks occurred following cold springs rather than mild ones. This he attributed to the effects of weather on natural enemies - cold springs delaying natural enemy population development allowing the aphid populations more time to increase to high levels. As with the forecasting of spring migrations, this relationship needs to be tested over more years and in different regions and more biological information sought to verify the suggested explanation before it could be used practically.

It may prove possible to integrate relationships between winter weather and spring migrations and spring weather and peak aphid populations, into a forecasting system as has been done with black bean aphid. Early autumn sampling of cereals and roses would give an estimate of the initial overwintering population reservoir of grain and rose-grain aphid respectively. Winter weather conditions would affect survival of overwintering grain aphid populations and thus influence the size and timing of the spring migration. However, even after mild winters, low initial overwintering populations might not be able to increase sufficiently to result in large spring migrations. Weather conditions during the winter would also influence host plant development, with cold winters slowing down development which would be advantageous to rose-grain aphid populations colonizing crops in early summer. More information is also needed about the locality of aphid sources - are they local or is long-distance migration more important than is currently supposed?

Weather conditions during March and April would affect natural enemy population development such that mild winters and cold springs would be more likely to result in a grain aphid outbreak than a cold winter followed by a mild spring. Rose-grain aphid outbreaks would be most likely to follow cold winters and springs.

Again, these theories would have to be tested extensively before implementation and the relationship may need tuning for different regions. An approach such as this, combined with an accurate short-term forecasting system as developed by Entwistle and Dixon (1986), would give farmers a long-term warning of potential problems and a reliable decision on the need to spray before significant damage is done to crops.

DAMAGE ASSESSMENT

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The main work in Europe on the damage by the grain aphid has taken place in Britain and in the Netherlands. Many meetings in the 1970's and early 1980's held by the International Organisation for Biological Control attempted to co-ordinate the work and come to agreements concerning common thresholds. These meetings were useful but in 1988 nearly every country in Europe has a different interpretation of grain aphid spray strategy!

Work in the UK began in the early 1970's by ADAS. This was followed by Southampton work funded by the AFRC. The Ministry's approach was to use their advisers around the country to find incipient outbreaks of the grain aphid in June and set up replicated spray trials in which sprays were applied at different times or growth stages. The plots were harvested and yield losses were assessed. George and Gair (1979) summarised many of these trials and concluded that when aphid numbers were below 5 per ear at the time of insecticide application, a subsequently high yield loss was unlikely to take place. This led to the ADAS advice, that crops should be sprayed if the grain aphid population exceeds 5 per ear at the time of flowering, the weather is calm and warm and the population increases further a few days later. This threshold did not address the situation of a late aphid population above 5 per ear, developing after flowering. Later modifications covered this situation and spraying crops is advised if grain aphid populations rise rapidly to more than 5 per ear at growth stages after flowering.

The University of Southampton work took a different approach which was more experimental and manipulated grain aphid populations using large field cages (Lee et al., 1981). Because cages reduce wind and raise temperatures slightly, it is possible to guarantee aphid outbreaks most years. It is also possible to use clonal, virus free, single-species

aphids from laboratory cultures and to create outbreaks (and curtail them with insecticides) almost at will. Results from Southampton in the 1970's and early 1980's, on the grain aphid and on the rose-grain aphid (Holt et al., 1984), have been used in the development of a simulation model. This model has identified the important effect of crop growth stage on damage caused by a given number of aphids. In particular, the model has been used to analyse farmers' spraying decisions based on questionnaires in the south and east of England; spraying was not just after the 5 per ear notional threshold was reached but was often at, close to, or even after a peak population of 30 or 40 per ear. Not surprisingly, economic losses were associated with these spray decisions, especially when labour costs were included in the calculations (Watt et al., 1984).

A most recent survey of 100,000 hectares of winter wheat in 1984, carried out jointly between the University of Southampton and the Game Conservancy, revealed that in that year nearly 80 percent of the winter wheat acreage was sprayed with aphicide. Twelve different insecticide active ingredients were used, and the spray period covered ten weeks from late May into early August and many populations were still being sprayed at, near or after the peak. Dimethoate was the commonest pesticide used (50 percent of area treated) in many areas and economic analysis of these results revealed that either advice was being ignored or being interpreted incorrectly. The medium whereby advice is transmitted to the farmer is very important. For this reason Viewdata media such as Prestel FARMLINK (which now incorporates the old ICI system) could have an important role to play. The University of Southampton simulation model, mentioned earlier, now runs on FARMLINK but the farmer accesses it simply through a series of questions and answers concerning his pest numbers, crop growth stage and the economics of spraying on his own land (Mann et al., 1986). Recent analyses have shown that comparing yields and profits derived from using FARMLINK advice with those from a simple threshold decision at flowering (i.e. that taking no account of large populations after flowering) has shown that a higher economic return may be made by using the former advice (Mann and Wratten, 1988).

The FARMLINK package also includes a simple model based on field cage and open field work on the rose-grain aphid and shares with the grain aphid model the concept that there is no single threshold for spraying; rather, there is an infinite number of thresholds because the decision to spray in these models is influenced by biology and economics on a field-by-field basis.

In the Netherlands the EPIPRE system, developed at Wageningen by Zadoks and his colleagues (Reinink, 1984), covers not just cereal insects but cereal pathogens too. It seems to have changed the farmers' awareness of pest and disease problems in the Netherlands to the extent that, although at any one time there are not large numbers of farmers using it, there seems to be a high turnover of farmers employing the system. This suggests that, having learnt the system and found it useful they carry on applying its principles, although no longer using the medium itself. There appears to have been resistance in the UK to acceptance of the EPIPRE system.

Although the University of Southampton and ADAS work in the 1970's and 1980's was extensive, the grain aphid and rose-grain aphid damage pattern is not yet completely understood. For instance, many cultivars have declined from major commercial use in the past decade so the initial yield-aphid number relationships have changed. Certainly much of the earlier emphasis was on the effect of populations at and after flowering, whilst there is some experimental evidence that the lower populations before flowering may cause damage. Dutch evidence that the proportional yield loss caused by a given number of aphids changes with potential yield of the crop is an adjustment that should be made to the FARMLINK package in future.

Knowledge about grain aphid damage in the UK can be summarised as follows:

Grain aphids on the ear or flag leaf can cause yield loss but on the lower leaves they are virtually irrelevant. The way they bring about yield loss appears to be:

a) via direct removal of phloem sap (and therefore carbohydrate) during feeding;

b) by the effects of sooty moulds (growing on honeydew on leaf surfaces) reducing photosynthetic rate (Rabbinge et al., 1981).

As populations usually develop at or after flowering, grain weight is the usual yield parameter affected as grain number is already determined by the plant at this time. Rose-grain aphids on the flag leaf can also occasionally cause serious yield losses; this species rarely feeds on the ear but may be found just below it (above the flag leaf) as ripening approaches late in the season. It seems to be most important in seasons when crops are slow to mature. There is little evidence that the grain aphid and rose-grain aphid differ in the loss caused per aphid at the same growth stage. This is because most of the carbohydrate synthesised by the wheat, which makes up grain starch, is produced by the ear and flag leaf; lower leaves are less important in this respect so aphid populations on these can be discounted as far as direct yield loss is concerned.

The rose-grain aphid feeding on lower leaves has been shown in the laboratory, and occasionally in the field, to reduce grain quality (bread-making in this case) as has the grain aphid feeding on the ear (Lee et al., 1981). However, it has not been shown that bread-making changes take place in the absence of yield losses. Aphid-induced yield and quality changes in spring wheat certainly occur but have hardly been investigated.

More work needs to be done on potential grain quality effects; the way the aphids bring these about is subtle and still poorly understood. The bread-making effects are linked to a reduction in the quantity of glutenin proteins in the grain, low levels of which lead to poor dough quality and poorly risen loaves. Milling quality is affected by the grain aphid too; in this case, more endosperm is left attached to the bran after milling than in grain from uninfested ears, while the resulting flour is darker and exceeds the colour threshold above which chemical bleaching agents are often used.

The model referred to above for grain aphid has been re-worked for rose-grain aphid and now both operate as advisory tools for farmers at the field level. They do not require the farmer to count aphids; rather he assesses the proportion of flag leaves and/or ears with one or more aphids (= 'infested') and the appropriate control action is calculated on the basis of whether or not he will make a profit from spraying. Given that the surveys reveal a considerable extent of uneconomic 'overspraying', the economics and politics of cereal growing in the 1980's point to an urgent need to refine the medium by which farmers are advised. Pragmatic, rapid, field-based advice, founded on the farmer's own circumstances should be the way forward.

OVERVIEW

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In the Introduction, the summer aphid problem was characterised as occasional outbreak years, with widespread damage, separated by several years of very low levels, with little or no damage. Responses to this situation have diverged into either a 'rational' approach of assessing aphid numbers at flowering and treating if a threshold level is exceeded, possibly using a computer model to refine the decision making, or a 'prophylactic' approach of tank-mixing a cheap insecticide with a fungicide applied at about the correct time.

Sadly, surveys have shown that neither strategy is applied correctly in the majority of cases. Rational sprayers tend to assess too little and spray too late, while prophylactic sprayers tend to spray too early, damaging predators and seemingly causing more problems than they prevent. A better application of current knowledge and a wider uptake of currently available intelligence and advice would overcome many of these problems. This approach can be summarised as "directed field scouting" and is detailed below.

For the future, it is recommended that an "integrated control strategy" be developed utilising varietal resistance (as recommended by Professor Dixon) and the reduced-rate application of selective insecticides (developed by Poehling and recommended by Dr Wratten). Difficulties in estimating levels of natural enemies remain but techniques are now available for enhancing their numbers on farmland, consistent with extensification policies.

A. DIRECTED FIELD SCOUTING

This system proposes a formal integration of the monitoring systems currently operating with a wider distribution of the information direct to farmers and the agrochemical trade. Little additional resource would be required to implement the system as close liaison and passage of information already occurs. A charge will be made for direct access

to this information through ADAS or the IACR, but as the advice will be of a general nature and widely applicable, it is likely to pass quickly throughout the industry.

The system proposed would operate in five stages:

1. **Long-term forecasting.** Winter and spring weather observations backed by limited field sampling would be used to produce a general forecast of likely aphid incidence by the end of April. This forecast, if found to be reliable, could be used by chemical manufacturers to adjust stocks of aphicides.

2. **Migration monitoring.** The RIS trap network provides continuous monitoring of aphid migrations. These figures can be related to previous years' experience to produce an estimate of risk, a week or more in advance of the need for treatment. This information can be used to direct advisers and farmers to areas where a risk of aphid outbreak exists.

   In 1987, for example, the RIS aphid commentary for 8 to 14 June advised that "in Essex the number of aphids recorded so far suggests that crops may be at risk". The largest yield response (0.42 tonnes per hectare) recorded in ADAS trials that year was from sprays applied on 24 June to a crop in Essex. The warning was available in time for a crop check to have identified this field as requiring treatment. Two other ADAS sites in Essex had lower aphid numbers at this time and no yield increase was obtained on these.

3. **Crop surveys.** ADAS monitors 40-70 fields under the PMS (Pest Monitoring Scheme) each year in addition to the more intensive RISCAMS (Rothamsted Insect Survey Cereal Aphid Monitoring Scheme) monitoring in the South East. The RISCAMS data is taken into account in the RIS aphid commentaries with ADAS adding the PMS findings and feedback from crop walkers to their Crop Intelligence reports. This intelligence could be used to decide the need for field walking in particular areas and the best time to carry it

out. Given a more detailed knowledge of varietal resistance, crop growth stages, and the influence of agronomic factors, farmers could be directed to the fields at greatest risk.

4. **Crop scouting.** Individual fields would be walked in response to intelligence advice. Farmers wishing to use the Southampton computer model should estimate the percentage of tillers infested, run their data through the programme and follow the advice regarding treatment and re-assessment. The ADAS system has been simplified from June 1988 to require only an estimate of percentage heads infested rather than aphid counts. The flow chart shown in the section on Forecasting and Modelling has been modified so that 66 percent or more heads infested is required to justify a spray and between 50 and 66 percent infested requiring a further check 2-3 days later. These models may be further refined in the future to take account of continuing developments.

5. **Continued vigilance.** Both the ADAS and Southampton systems advise further checks in response to a near miss. The aphid trapping and field survey systems would detect any late migration to, or build-up in, fields and trigger advice for further checks in response, which would be required in a rose-grain aphid year.

It is proposed that this system would be paid for by direct charges to those receiving the advice. Dr Carter has recommended further development of certain parts of the system which if implemented would require central funding.

If seen to be successful, a full acceptance of this system would reduce the desire for insurance spraying by those adopting the pophylactic approach. Realistically, it is unlikely to eliminate it and there is a need to find acceptable alternative sprays which can be applied in place of the cheap broad-spectrum materials currently used. The following recommendations for the development of an integrated control strategy are intended to provide these alternatives.

B. INTEGRATED CONTROL STRATEGY

In the section on aphid biology, Professor Dixon has suggested that reductions of 40 to 85 percent in aphid numbers are possible if available resistance were exploited. The level of resistance would, on its own, greatly reduce the number of occasions on which sprays were required. Further University-based research is needed to elucidate the mechanism of such resistance. Improvements in biotechnology should allow a relatively rapid utilization of this knowledge in wheat breeding programmes.

Utilization of plant resistance, by slowing the rate of aphid population increase, would give natural enemies a greater chance to control aphids and thereby increase their value. It would, therefore, become even more important to use pesticides only where necessary, and use selective chemicals to conserve natural enemies. Within the current range of chemicals there is a wide range of toxicity to natural enemies and it is suggested that these aphicides should be reviewed. Poehling (1987) has shown that reduced rates of application can be used to further enhance selectivity and it is also recommended that this possibility should be investigated under UK conditions. An initial trial is to be carried out at the IHR Littlehampton in 1988. Because of the lack of information on their side effects on non-target species when the early pyrethroids were introduced in the UK, and the possibility of very large areas of cereals being sprayed, the Advisory Committee on Pesticides, following a review of the available data recommended that they should not be used for the control of cereal aphids in summer. More recent UK and continental data suggests that their effect on beneficial species in the field is less damaging parallelling the findings on flowering oilseed rape where bee mortality in the field is much lower than predicted from laboratory tests (Shires et al., 1984; Wilkinson et al., 1986). It is, therefore, recommended that pyrethroid materials be investigated for use in the UK and that safe, low dose rates be established.

The development of varietal resistance, combined with improved forecasting systems and the use of low-dose selective insecticides would allow the development of an integrated control strategy without

any increase in cost to the farmer. The current cost to the farmer of poor control strategies is very difficult to estimate, as chemical costs, and cost of application vary widely, as does the yield loss from year to year. As mentioned in the Introduction, these various factors give a total range of costs from £2 million to £24 million with a median of around £5 million in an 'average year'.

SUMMARY OF CONCLUSIONS

GENERAL STATUS AND POTENTIAL CROP LOSS

1. In the past 12 years there have been four grain aphid outbreak years. In these years, an average of 32% of fields have exceeded the ADAS threshold, with a potential yield loss of 4% of the British wheat Crop. Apart from losses caused by rose-grain aphid in 1979, in the other eight years damage, on a national basis, has been negligible. Given this variation, the average annual loss to the industry of £5 million can range from £2 million to £24 million. Monitoring the incidence of cereal aphids should continue so that their importance can be kept under review.

2. Recent ADAS damage assessment trials have supported conclusions from previous work. Future trials should continue to investigate the economics of preventive spraying and post-flowering treatment of any late build-up, particularly of rose-grain aphid.

BIOLOGY OF THE ROSE-GRAIN APHID AND THE GRAIN APHID

3. Further work is required on the long range migration of cereal aphids. This is probably best achieved as an adjunct to the EURAPHID network of suction traps of which the RIS network is part (See Conclusion No. 12).

4. There is now an urgent need to obtain a clearer understanding of the mechanisms underlying the resistance of cereals to aphids and the mode of inheritance . Such understanding would help plant breeders to incorporate greater levels of aphid resistance into cereals. This fundamental study is most appropriate to University research.

5. There is a need to identify reliable predictors of aphid rates of increase for forecasting purposes. Sequences of population counts of aphids collected over many years are required for this and it is recommended that priority be give to sustaining existing aphid

counting surveys operating under RISCAMS and the PMS (See Conclusion No. 11).

6. The genetics of cereal aphids require further investigation to determine the clonal stability of the offspring and to establish the potential for the development of strains capable of overcoming varietal resistance in wheat or developing resistance to insecticides. This work is appropriate for University of AFRC research.

NATURAL ENEMIES OF CEREAL APHIDS

7. Further work is required on maximising the role played by non-crop habitats in increasing the numbers of predators and enabling them to move into crops earlier. The existing MAFF-funded work should continue.

8. The use of reduced-rate, selective pesticides requires further testing, with a view to developing an IPM package for cereal crops and replacing outdated broad-spectrum pesticides. The extension of existing work for this purpose seems appropriate for consideration by the HGCA.

MONITORING AND FORECASTING

9. Further work is required on the distribution of aphids within cereal fields so that the most efficient monitoring procedures, based either on percentage infestation or rating scales, can be developed. This work is underway as part of the PMS.

10. Existing data sets should be collated to develop and test theories related to weather conditions, overwintering, spring migrations and natural enemies, and peak aphid populations. This work seems most appropriate to the IACR as an extension of the RIS.

11. There should be a systematic, standardised collection of aphid population data on crop and non-crop host plants at various places

throughout Great Britain, throughout the year. At present, data collection is restricted to critical times and whilst detecting overwintered aphids on crops in the spring, the information is too late and sparse for the purpose envisaged.

12. Studies should be conducted on the sources of aphid populations to determine whether they are local or long-distance. This conclusion follows on from Conclusion No. 10, and is most appropriate to work at the IACR in conjunction with the RIS.

DAMAGE ASSESSMENT

13. The means of communicating information to and from farmers needs improving to encourage the adoption of a rational spraying strategy.

OVERVIEW

14. The current monitoring and forecasting systems should be formally integrated and promoted as a guide to "directed field scouting".

15. If the development of reduced-rate, selective pesticides (including pyrethroids) proves successful, the use of broad-spectrum materials should be reviewed.

16. All these developments should be seen as part of an integrated approach and the combined application of them as an IPM system should be tested in specific field trials.

RECOMMENDATIONS FOR FURTHER STUDY

The value of reduced-rate, selective aphicides requires testing to assess their potential for replacing out-dated broad-spectrum insecticides. The following components should be investigated:

1. The effectiveness of control.

2. The implications on development of insecticide resistance.

3. The economics and effects on yield and quality.

4. The effects on natural enemies and any enhancement of their role.

The initial evaluation should be on winter wheat; an extension to spring wheat and other cereals could be considered later.

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