PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Pest Monitoring to Aid Insecticide Use

T. Lewis

Phil. Trans. R. Soc. Lond. B 1981 **295**, 153-162
doi: 10.1098/rstb.1981.0129

Phil. Trans. R. Soc. Lond. B **295**, 153–162 (1981) [153]
Printed in Great Britain

Pest monitoring to aid insecticide use

By T. Lewis
Rothamsted Experimental Station, Harpenden, Herts. AL5 2JQ, U.K.

Careful monitoring of pest populations is necessary to determine the need for, and correct timing of, pesticide applications to ensure efficient control with minimum waste and environmental pollution. The use of physical and attractant traps for short-term monitoring on a regional and local basis is considered.

Extra studies and resources are required to convert current monitoring schemes into a short-term warning system more helpful to farmers. The combined efforts of research and advisory groups could lead to the development of more sophisticated insect detectors, methods of analysis, and communication procedures, to produce a pest monitoring system appropriate in scope and cost for British agriculture.

1. Introduction

Pressures to restrict the use of crop protection chemicals are likely to increase during the next decade with mounting public awareness of the undesirable environmental effects of persistent compounds, the rising costs of materials, more widespread and intense resistance of pests to available insecticides, and the dearth of alternatives (Anon. 1979*a*). In these circumstances, and as agriculture becomes more sophisticated, growers and advisers need better information than is at present available to make decisions on whether pesticide treatments are necessary, and, if so, when they should be applied for maximum effect. Such decisions are especially difficult for mobile airborne insect pests, many of which may spread rapidly and often unexpectedly over areas far larger than those encompassed by individual farms or even counties. In the U.K., adults of most of the serious crop pests fly to crops during the growing season, and this immigration can provide a convenient indicator of impending infestations.

The importance of correct timing of insecticide applications, once the presence of a pest is recognized, is illustrated by three different types of plant–pest relations. The simplest is when populations of an external feeding pest build up gradually until the crop can no longer recover completely from its effects. Increases in the yield of winter wheat resulting from one insecticidal treatment applied at the beginning of flowering against *Sitobion avenae* (Fabr.), when there are 5–10 aphids per ear and a rising population, are about 11.5%. By delaying treatment for a week, yield increases can fall to 3.9% (George & Gair 1979). Correct timing may be even more critical for pests that are only exposed to surface residues for a short time before they bore into plant tissues. Larvae of the pea moth, *Cydia nigricana* Fabr., survive only if they enter young pods within a few hours of hatching. To be effective, a contact insecticide must be present on the vegetation when larvae emerge, which is usually 9–12 days after moths arrive on the crop. This delayed treatment for pea moth contrasts with the prompt treatment required for virus vectors because a small proportion of viruliferous individuals in the immigrant population can seriously infect the crop if not controlled promptly. In sugar beet, a dangerous population level is reached in southern counties when a single green aphid (assumed to be viruliferous *Myzus persicae* Sulz.) is found per four plants (Heathcote 1978).

Forecasts of pest abundance and spread made months ahead of the time when crops may become infested are useful for allocating resources for the coming season, but are too unreliable for planning pesticide applications requiring precise timing because future weather and complex interactions between pests, natural enemies and diseases cannot be predicted accurately enough. Such forecasts are achievable only after many years of study of individual species (see, for example, Way *et al.* 1981). However, continuous or anticipatory monitoring of mobile adults can often provide evidence of population increase, spread and initial infestation of crops soon enough to provide a few days, and for some pests perhaps up to 3 weeks, warning of the need for, and correct timing of, control measures. Ideally, such monitoring could best be done by examining crops at risk; however, there are too few research and advisory entomologists available in this country to provide a comprehensive service, the Agricultural Development and Advisory Service (A.D.A.S.) having only about 100 staff directly involved to some extent with this work. By contrast, an extensive but by no means comprehensive monitoring scheme run by the Ministry of Agriculture and Forestry in Japan employs 10800 part-time observers to inspect and report on the occurrence of pests and diseases in over 2000 fields planted with local crops and cultivars (Yasuo 1971). With no prospect of such resources in this country, and with signs that economies will reduce even the present skilled manpower, it is essential to extend and improve the existing monitoring systems to complement and supplement the limited field inspections that are possible if pesticides are to be used only when necessary and to maximum effect.

This requires the continued development of practices based on a detailed knowledge of the biology and ecology of each key pest species, incorporating methods and information from a wider range of scientific and technological disciplines than has been traditional. Such a scheme is being developed for certain pests, and in particular aphids, from the trapping network already established by L. R. Taylor and colleagues at Rothamsted (Taylor 1973), with the collaboration of the entomological section of A.D.A.S. and the Department of Agriculture and Fisheries for Scotland (D.A.F.S.), which at present are the only organizations able to provide national coverage for a range of crops in Britain. Continuing specialized collaboration will be needed from universities, other A.R.S. institutes, the Meteorological Office, pesticide producers and distributors, farmers, and European organizations that have established trapping systems on the Rothamsted model.

This paper outlines present monitoring and short-term forecasting methods, and suggests how they can be developed in the 1980s to a degree more appropriate for British agriculture. For brevity, consideration is restricted to airborne pests infesting field crops and inflicting direct or indirect damage themselves, or producing offspring that damage the crop within the same growing season. These include most important pest aphids, moths, flies and beetles other than long-lived soil dwellers. The four essential components of the system envisaged are: (i) detection of the pests, (ii) collation, processing and recording of samples, (iii) analysis and interpretation of data as a basis for decisions, and (iv) dissemination of information and advice. A review of progress so far shows how research and advice need to be channelled for improvement.

2. Detection and sampling

(*a*) *Adult immigrants*

The network of 23 suction traps extending over the length and breadth of Great Britain already indicates regions of the country likely to be at risk from certain migrant pests (Taylor *et al.* 1981), especially aphids (Taylor 1977), and thus warns of the need to inspect fields in defined areas. Traps baited with pheromones or plant-attractants can detect the early arrival in crops of certain moths and flies over smaller areas, even on individual farms or fields (Lewis 1977).

Each of these sampling methods has important merits and disadvantages. The fixed suction traps have been carefully standardized (Taylor & Palmer 1972), they operate continuously and can provide a wide coverage. The sample is efficient because the trap is non-selective, but, consequently, catches are laborious to sort, trap density is restricted and the interpretation of samples in terms of crop infestation is at present uncertain. Pheromone traps for moths can be placed in individual crops throughout the vulnerable growing period, and because they are species-specific, catches can be assessed quickly within fields. Unfortunately, efficiency is variable and the traps catch only males, which are not always a good indication of the number of larvae or the amount of damage to be expected from the ensuing infestation. Plant-attractant traps placed in crops catch both sexes, of which the majority are females, thus giving a more direct impression of the damage potential of the immigrant population. They too vary in efficiency and are not as exclusively selective as pheromone traps, often attracting a range of pests for which a given crop is host. For example, traps baited with allylisothiocyanate will attract at least seven of the insect pests of brassicas (Finch 1977). The general advantage of these three types of mechanical or chemical trap is that they detect pests at lower densities than is practical by crop inspection with present manpower (Taylor & Palmer 1972).

Further refinement could minimize some of their disadvantages. With about 300 species of aphids caught annually in the suction traps, 12 of which are major pests and another 20 are of lesser importance, some catches will always need to be examined to identify the species present. However, it may be possible to supplement the coverage provided by the present suction trap system by additional remote detection of the total aerial aphid population at these and at other sites concentrated in areas where most field crops are grown. Upwardly directed, high-resolution, short-range radar with a 3° wide beam can detect small insects up to at least 0.5 km, and by measuring wing-beat frequency and body shape can establish the number of aphids in the air, though not the species (Schaefer *et al.* 1979). Sites with a suction trap and radar could provide estimates of the species present and their absolute density. Sites with radar alone could provide details of abundance and movement on a finer scale than at present.

Chemical detection might be improved by searching for more specific plant attractants (e.g. disulphides and trisulphides for onion pests), for female-attracting pheromones or for oviposition stimulants, which would provide a truer estimate of the numbers of offspring likely to arise from the initial immigrants. It should be possible to design chemical traps containing simple devices to sense and count the number of entrants of the single species attracted, and record them automatically (E. D. Macaulay & C. Wall, personal communication).

(*b*) *Virus vectors*

For potential virus vectors, not only is early knowledge of their presence required but also whether they are viruliferous. Often only a small proportion of a population of vectors carry virus, and this varies between years and regions within a year. For example, for barley yellow dwarf virus between 1970 and 1980 the percentage of infective *Rhopalosiphum padi* (L.) caught at Rothamsted in September to November ranged from 0 to 11.6%; in 1976 a larger proportion was infective at Long Ashton than at Rothamsted, but in 1977 the opposite was true (Plumb

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

1981 *a*). If viruliferous cereal aphids infest an early autumn-sown cereal crop, insecticidal treatment is often worth while.

Until recently, estimation of the proportion of viruliferous individuals in a population was possible only by catching living individuals and testing them for transmission on plants, a slow, but biologically valid procedure. Enzyme-linked immunosorbent assay (Elisa) now enables rapid assessment of the presence of viruses in freshly killed aphids or specimens collected in water (though not necessarily confirming their ability to transmit), but it can as yet only be used on groups. The even newer immunospecific electron microscopy method can detect barley yellow dwarf virus in fresh individuals and promises to be applicable to specimens preserved in alcohol for a few days or perhaps weeks, and to a range of persistent viruses (R. T. Plumb, personal communication). If so, it should be possible to produce an infectivity index (Plumb 1981 *b*) from the pickled suction trap catches (numbers caught multiplied by the percentage that are infective) to give warning of potential virus infection.

(*c*) *Weather data*

The development and movement of insect populations are intimately dependent on weather. It largely determines overwintering survival and so the number of immigrants available to fly to crops in spring. Winter weather may exert its influence months before the short warning period considered in this paper, and it is often a valuable preliminary guide and an essential component of some pest forecasting analyses. When immigrants are available, temperature and wind speed determine whether they fly, and wind direction and speed where they spread (Johnson 1969). On reaching a crop their rate of reproduction and, perhaps, movement between plants are affected by temperature, rain and wind, as well as by population density, predation and parasitism.

The Meteorological Office's Agricultural Service (Anon. 1979 *b*) already provide excellent coverage of past and present weather, but as long as forecasts remain unreliable for more than 2–4 days, so will the accuracy of short-term warnings. The best solution is prompt daily comparison of pest and weather data. The Meteorological Office supplies the Plant Disease Intelligence Unit of A.D.A.S. (Bristol) with daily information on weather likely to favour the spread of certain diseases, and with a slight modification of content and easier access to forecasts and maps it should be possible to develop a complementary pest service. Automatic field weather stations, as already used in disease forecasting, might eventually supplement the present information based on synoptic stations, if a more intensive trapping and detection network were established. On-farm pest monitoring for local infestations with chemical traps does not need to be matched with such sophisticated meteorological records (see §4 *b*).

(*d*) *Crop development*

Data on crop growth stages are often essential for pest control decisions to be made. Field advisers and farmers are the main source of this information, and their participation in this aspect of monitoring needs encouraging (see § 4 *b*).

3. Collation, processing and recording of samples

(*a*) *Retrieval and identification of specimens*

At present, pheromone traps provide the most rapidly countable samples because their catch of target species can be recognized immediately. With experience, the more mixed catches in data probably reflect not only an increase in the number of species of insects with resistant strains as a result of more widespread and prolonged use of insecticides, but also a greater awareness of resistance by the farmers and their attribution of control failure to resistance.

The causes of lack of resistance to insecticides and fungicides are not necessarily analogous, since there is no insecticide acting in the same broad manner as copper against fungi. There are many insecticides besides azinphos-methyl to which insects have not yet developed resistance; why they have not done so is unknown.

A few pests, such as tetranichid mites, *Boophilus microplus*, the housefly and some Noctuidae, have so far developed strains resistant to most of the materials used for their control. It is against such pests that strategies to delay build-up of resistance will be of greatest use.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Automatic logging of catches in chemical traps with programmed radio recall would enable the phone-in service mentioned to be developed further. Advances in mobile radio should allow counts from automatic traps to be accessed directly to local minicomputers or microprocessors for onwards transmission to a central data bank. From a pool of radio channels one frequency could be assigned to the collecting network for the few seconds needed to transmit the information (Owen 1980). Appropriate meteorological records will also need accessing in a form to match the entomological data.

4. Data analysis, interpretation and decision-making

(a) *Analysis and interpretation of catches*

A thorough knowledge of the biology and seasonal cycle of each pest is essential for analysis of the data collected. Hitherto, most analyses have been based upon temperature, or a function of it, such as accumulated day degrees above a threshold necessary for the pest to develop to a vulnerable stage, or to a density meriting treatment.

The timing of spraying dates for pea moth shows how simple maximum–minimum temperature records taken either in growing crops or within at least 8 km of them can be used to predict egg-hatching dates after the number of moths caught by traps has reached a chosen threshold. Lewis & Sturgeon (1978) showed that hatching dates predicted from temperature data after 80% of egg development had occurred were correct to within 2 days on 28 out of 36 occasions. This means that a farmer would be aware of an impending need to spray for about a week before he obtained a more definite indication of the best spraying date, usually 1–2 days ahead.

Catches in the widely spaced suction traps give early warning of the likely arrival of immigrants in crops over a wide area up to 40 km distant from the trap (Taylor & Palmer 1972), but to enhance the usefulness of the system for spray warnings there is an urgent need to establish the relation between catches and immigrant density on crops. This has been achieved for *Aphis fabae* Scop., the only species for which data from crops have been collected for 10 years (Way *et al.* 1977) to match the trap record (Taylor *et al.* 1981).

This aphid has three major seasonal migrations, but flights before mid-June include most of the individuals migrating from the primary host to bean crops. The detection of this migration in a single suction trap by an accumulated catch of five or more alatae before mid-June is correlated with initial infestations of more than 10% of plants, which usually justify insecticidal treatment. Such a cumulative catch should give a few days' warning of the probable need to spray late-sown crops. Collaborative work with field observers in A.D.A.S., D.A.F.S. and the British Sugar Corporation could provide the information necessary to establish this relation for other species and crops, and an opportunity to standardize sampling methods in crops.

For the cereal aphid, *S. avenae*, a complex simulation analysis, using suction trap catches as the initial input, is being developed to give up to 3–4 days warning of the need to control this pest on winter wheat (Carter & Dewar 1981; Carter *et al.* 1981). The principal driving variables are maximum and minimum temperatures from the Meteorological Office's synoptic forecasts, but the effects of early predation in spring need incorporating to achieve the reliability required for advisory work. The extra complexity of the analysis compared with that for *A. fabae* arises because *S. avenae* can overwinter on grasses or autumn-sown cereals. In spring, the suction traps detect only the immigrants flying from overwintering sources but the build-up on cereals may also depend on the overwintering success of the resident population. Several interrelated events before the spring migration affect the size of the early infestation on cereals, so knowledge of the pest's biology and past, present and future weather is necessary to interpret trapping data to give even short-term warnings of rising populations.

A wide geographical spread of trapping sites allied to long-term records offers a complementary input to this type of analysis by allowing pest presence and crop development to be traced progressively over large adjacent regions. The development of an infestation of *Metopolophium dirhodum* (Walker) that reached spectacular densities in East Anglia in 1979 illustrates this. Suction traps in mainland Europe and the U.K. showed that alates first flew at Montpellier (southern France) in early–mid-April and infestations gradually developed in a northerly direction until the first individual was caught in England on 14 May. The first immigrants were detected at Orleans (central France), Broom's Barn (Suffolk) and East Craigs (Edinburgh), progressively 500 km apart in a SSE–NNW direction, successively 1 week later from south to north. This sequence was not caused by long-distance migration of individual aphids, but by relatively local migrations to developing crops from their primary hosts (Dewar *et al.* 1980; Cochrane 1980). With enough experience of this type of situation, warnings based on trap catches, long-term means (Taylor *et al.* 1981), pest distribution maps and weather forecasts, should become increasingly possible and reliable.

Sequential computerized mapping of suction and pheromone trap data based on the SYMAP II program has already provided impressive graphical demonstration of pest distribution and movement (Taylor 1979; Taylor *et al.* 1979). With a gradually expanding data bank, a visual comparison of maps from different years and subsequent infestation levels becomes progressively more useful. More advanced mapping programs such as SYMVU and SURFACE II should provide greater detail and accuracy. Programs and pattern scanners could be devised to speed the comparison of current distribution maps with forecast weather maps and infestation patterns of previous years.

A quite different approach to providing early warnings, worthy of further exploration, would be the recognition of harmless species or minor pests whose presence might portend the arrival or presence of a serious pest having a similar phenology. An example might be *Myzus ascalonicus* Doncaster, which often arrives in potato crops earlier and in larger numbers than the more serious *M. persicae*. There may also be a negative correlation between numbers of *M. ascalonicus* and *S. avenae*; when the former is abundant early in spring on chickweed (*Stellaria media*), there seem to be fewer *avenae* later on cereals (Vickerman 1977). If such relations were confirmed, they would have the advantage of integrating the many factors affecting population growth and spread without the need to define, measure and model them.

(*b*) *Decision-making*

For most pests, farmers and advisers decide intuitively on whether and when to apply control measures, prompted by subjective assessments of the effect of the pest on yield, the efficacy of control measures and the financial returns resulting from different actions. In an attempt to rationalize such decisions, Norton (1976) has identified two types of decision procedure, one based on economic thresholds and requiring specific information on pest attack, the other a prophylactic procedure designed to give information on the probability of infestations occurring. It is within the former context that short-term warning is placed, although the longer a monitoring system were operated the more information would accrue to develop the latter approach.

By the time immigrant pests are detected, several decisions affecting subsequent attack, such as previous cropping, sowing date and cultivar, will have been made irrevocably, leaving only decisions on whether to spray, when and with which pesticide. At this point, information on economic injury levels is required, but unfortunately it is available for only very few pests of field crops. For aphids these include *M. persicae* (≡ green aphids) on sugar beet (Heathcote 1978), *S. avenae* on winter wheat (George & Gair 1979), and *A. fabae* on spring beans (Way *et al.* 1977). There is a provisional threshold for *M. dirhodum* on wheat, and for timing aphid sprays in potato ware crops and moth sprays in dry-harvested peas. For a few other pests, including egg populations of wheat bulb fly (*Delia coarctata* (Fall.)), seed weevil (*Ceutorhyncus assimilis* (Payk.)), and pollen beetles (*Meligethes* spp.) on rape, traditional but controversial criteria are used. Some have arisen more through expediency than careful measurement because it takes laborious observations over a long period, at different growth stages of crops and at many sites, to establish these pest–crop relations. However, more effort must be devoted to this work if pest monitoring data are to be used to full effect.

While interpretation of the more complex regional situations will need to be made centrally by experts, more farmer participation is essential for accurate on-farm decisions. There is a welcome sign that some agrochemical firms are encouraging farmers to rationalize more of their decisions on pest and disease control. Bayer have introduced a 'risk' model by which a simple yes–no answer to a series of operations indicates a course of pesticide action, and on a wider scale I.C.I.'s Wheatrace has some of the same objectives.

5. Dissemination of advice

However rapidly decisions are made from the information collected, short-term warnings will only be useful if advice is available to farmers promptly and if they act upon it. There is a need to retain personal contact between advisers and farmers, but there are not enough advisers in A.D.A.S. or the private sector to convey pest warnings soon enough to all interested farmers individually, so alternative methods are needed and more studies on farmers' responses to the advice received.

At present the T.I.S. operated by A.D.A.S. for pea moth spray warnings in 1980 provides probably the most up-to-date pest advice available. Used by farmers who had caught a threshold catch of moths on their own farm, it gave an estimated spray date and, incidentally, the impression of providing a personalized service (Emmett & Cochrane 1981). The present Pest Intelligence Reports issued by A.D.A.S. on T.I.S., telex, radio, Ceefax and Prestel, compiled from regional observations, provide general current awareness of the pest situation, with 4–7 days delay. The more detailed information from the Rothamsted Aphid Reports is 5–12 days old when transmitted. Press notices and even posted warnings are too slow or unreliable.

The A.D.A.S. Pest Intelligence Unit offers a centralized organization for rapid communication of advice through telex, radio and viewdata systems, providing the information is received promptly from the collectors and analysts. At this stage, these are seen principally as Rothamsted staff helped by A.D.A.S. Regional and Harpenden Laboratories and D.A.F.S. Once a system were developed, other sources of data could be incorporated. A few years hence it should be possible to revise a viewdata system twice weekly for aphids, and perhaps some moths, flies and beetles, and eventually every 1 or 2 days. Further ahead, interactive v.d.u.–teletype terminals may be available whereby farm managers, pesticide manufacturers and spray operators could interrogate a central computer programmed with decision models based on the latest pest situation and factors easily measured on the farm. This type of system is already available in Michigan, U.S.A. (Welch & Croft 1979).

At present farmers receive advice on pesticide use mainly from commerce, A.D.A.S. and specialized organizations such as the British Sugar Corporation (for sugar beet crops) and P.G.R.O. (for leguminous crops) (Steed *et al.* 1980; Mumford 1980). Some do not seek up-to-date information on pests at all, others spray routinely, and yet others accept advice but do not act promptly upon it. A central source of impartial, readily accessible information may encourage more farmers to use it and give them confidence not to spray when it is unnecessary, especially if it is seen to save money. It would also provide pesticide firms and processors with better information on which to recommend spraying, and by improving control through effective timing, enhance the reputation of properly applied products.

6. Conclusions

The development of a more sophisticated system to provide short-term warnings of pest infestation is timely and feasible. Many of the elements required are already established and funded by financially secure organizations. Rothamsted has developed appropriate sampling and analytical methods, which research can extend and refine. In A.D.A.S., there are specialists to supplement and confirm information on pests in the field, and the embryo of an organization to transmit warnings rapidly to users. The Meteorological Office collects information that could be adapted to match the entomological data. Different techniques, many already commonly used in other disciplines, need incorporating into this framework, especially aspects of computing, programming and communication methods, though biological knowledge, obtainable only from long-term studies, must remain the basis of any system The considerable technical and organizational difficulties could be overcome with cooperative effort and appropriate funds.

Compared with the value of the crops that the system would help to protect, and the less quantifiable benefits from a more rational approach to pesticide use, its cost would be trivial. Each year, the total value of cereal and other arable crops exceeds £1500M. They are treated with insecticides at a cost of £15–20M annually (Steed *et al.* 1980). The combined cost of pest monitoring from public funds is a mere 0.02–0.03% of the value of the crops that it could be developed to protect, and about 2% of the cost of present insecticidal treatments. Once established, the system outlined would totally justify investment in it. For example, if pest monitoring could decrease the cost of aphid control by only 10% in such a minor crop as hops, the saving would approximate the entire annual cost of the present suction trap scheme (Bardner *et al.* 1981). An extension of the approach to more important crops would produce huge savings and greatly improve the effectiveness of the pesticides applied.

The development, extension and coordination of the pest monitoring schemes already available should be pursued as an urgent priority.

I am grateful to many staff in the Entomology Department, Rothamsted, to Mr H. Gould and staff in A.D.A.S., to Professor G. W. Schaefer, Cranfield Institute of Technology, and Dr S. Finch, National Vegetable Research Station, for advice in preparing this paper.

REFERENCES (Lewis)

Anon. 1979*a* *Seventh Report of the Royal Commission on Environmental Pollution. Agriculture and Pollution*. Cmnd. 7644 (280 pages.) London: H.M.S.O.

Anon. 1979*b* *Meteorological Office Annual Report 1978*. (158 pages.) London: H.M.S.O.

Arnold, J. 1968 Mechanical sorting and counting of trap catches. *Rothamsted Report for 1967*, p. 198.

Bardner, R., French, R. A. & Dupuch, M. J. 1981 Agricultural Benefits of the Rothamsted Aphid Bulletin. *Rothamsted Report for 1980*, part 2, pp. 21–39.

Carter, N. & Dewar, A. 1981 The development of forecasting systems for cereal aphid outbreaks in Europe. In *Proc. IXth International Congress of Plant Protection*, Washington D.C., August 1979. (In the press.)

Carter, N., Rabbinge, R. & Dixon, A. F. G. 1981 Cereal aphid populations: biology, simulation and prediction. In *Simulation Monograph Series*. (In the press.) Wageningen: Pudoc.

Cochrane, J. 1980 Meteorological aspects of the numbers and distribution of the rose-grain aphid, *Metopolophium dirhodum* (Wlk.) over south-east England in July 1979. *Pl. Path.* **29**, 1–8.

Dewar, A. M., Woiwod, I. & Chopin de Janvry, E. 1980 Aerial migrations of the rose-grain aphid, *Metopolophium dirhodum* (Wlk.), over Europe in 1979. *Pl. Path.* **29**, 101–109.

Emmett, B. J. & Cochrane, J. 1981 An interdisciplinary approach to pest control. In *ADAS Science Service Annual Report 1980*. (In the press.)

Finch, S. 1977 Monitoring insect pests of cruciferous crops. In *Proc. 1977 Brit. Crop Protection Conf. – Pests and Diseases*, pp. 219–226.

George, K. S. & Gair, R. 1979 Crop loss assessment on winter wheat attacked by the grain aphid, *Sitobion avenae* (F.), 1974–77. *Pl. Path.* **28**, 143–149.

Heathcote, G. D. 1978 Review of losses caused by Virus Yellows in English sugar beet crops and the cost of partial control with insecticides. *Pl. Path.* **27**, 12–17.

Johnson, C. G. 1969 *Migration and dispersal of insects by flight*. (763 pages.) London: Methuen.

Lewis, T. 1977 Prospects for monitoring pests using behaviour controlling chemicals. In *Proc. 1977 Brit. Crop Protection Conf. – Pests and Diseases*, pp. 847–856.

Lewis, T. & Sturgeon, D. M. 1978 Early warning of egg hatching in pea moth (*Cydia nigricana*). *Ann. appl. Biol.* **88**, 199–210.

Mumford, J. D. 1980 Farmers attitudes towards the control of aphids on sugar beet. In *Proc. 1977 Brit. Crop Protection Conf. – Pests and Diseases*, pp. 263–270.

Norton, G. A. 1976 Analysis of decision making in crop protection. *Agro-Ecosys.* **3**, 27–44.

Owen, K. 1980 New frontiers on weather forecasts. *Times, Lond.* 28 October, p. 18.

Plumb, R. T. 1981*a* Chemicals in the control of cereal virus diseases. In *Strategies for the control of cereal disease* (ed. J. F. Jenkyn & R. T. Plumb), pp. 135–145. Oxford: Blackwell Scientific Publications.

Plumb, R. T. 1981*b* Cereal diseases. In *Rothamsted Report for 1980*, part 1. (In the press.)

Schaefer, G., Bent, F. & Cannon, R. 1979 The green invasion. *New Scient.* **83**, 440–441.

Steed, J. M., Sly, J. M. A., Tucker, G. G. & Cutler, J. R. 1980 *Pesticides Usage Survey Report* no. 18 (*Arable crops*). London: M.A.F.F.

Taylor, L. R. 1973 Monitor surveying for migrant insect pests. *Outl. Agric.* **7**, 109–116.

Taylor, L. R. 1977 Aphid forecasting and the Rothamsted Insect Survey. (R.A.S.E. Research Medal Paper.) *Jl R. agric. Soc.* **138**, 75–97.

Taylor, L. R. 1979 The Rothamsted Insect Survey: an approach to the theory and practice of pest forecasting in agriculture. In *Movements of highly mobile insects: concepts and methodology in research* (ed. R. L. Rabb & G. G. Kennedy), pp. 148–185. North Carolina State University.

Taylor, L. R., French, R. A., Woiwod, I. P., Dupuch, M. J. & Nicklen, J. 1981 Synoptic monitoring for migrant insect pests in Great Britain and Western Europe. I. Establishing expected values for species content, population stability and phenology of aphids and moths. In *Rothamsted Report for 1980*, part 2, pp. 41–104.

Taylor, L. R. & Palmer, J. M. P. 1972 Aerial sampling. In *Aphid technology* (ed. H. F. van Emden), pp. 189–234. London: Academic Press.

Taylor, L. R., Woiwod, I. P. & Taylor, R. A. J. 1979 The migratory ambit of the hop aphid and its significance in aphid population dynamics. *J. Anim. Ecol.* **48**, 955–972.

Vickerman, G. P. 1977 Monitoring and forecasting insect pests of cereals. In *Proc. 1977 Brit. Crop Protection Conf. – Pests and Diseases*, pp. 227–234.

Way, M. J., Cammell, M. E., Alford, D. V., Gould, H. J., Graham, C. W., Lane, A., Light, W. I. St G., Rayner, J. M., Heathcote, G. D., Fletcher, K. E. & Seal, K. 1977 Use of forecasting in chemical control of black bean aphid, *Aphis fabae* Scop., on spring-sown field beans, *Vicia faba* L. *Pl. Path.* **26**, 1–7.

Way, M. J., Cammell, M. E., Taylor, L. R. & Woiwod, I. P. 1981 The use of egg counts and suction trap samples to forecast the infestation of spring-sown field beans, *Vicia faba*, by the black bean aphid, *Aphis fabae*. *Ann. appl. Biol.* (In the press.)

Welch, S. M. & Croft, B. A. 1979 *The design of biological monitoring systems for pest management*. (77 pages.) Wageningen: Pudoc.

Yasuo, S. 1971 Forecast work of disease and insect outbreak in Japan. In *Japan Pestic. Inform.* no. 6, pp. 5–10.