PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Progress and Developments in Forecasting Outbreaks of the African Armyworm, a Migrant Moth [and Discussion]

P. O. Odiyo, R. Day, D. E. Pedgley, A. G. Gatehouse, D. J. W. Rose and R. C. Rainey

Phil. Trans. R. Soc. Lond. B 1990 **328**, 555-569
doi: 10.1098/rstb.1990.0127

Phil. Trans. R. Soc. Lond. B **328**, 555–569 (1990)

Printed in Great Britain

Progress and developments in forecasting outbreaks of the African armyworm, a migrant moth

BY P. O. ODIYO

Desert Locust Control Organization for Eastern Africa and Kenya Agricultural Research Institute, P.O. Box 30023, *Nairobi, Kenya*

This paper describes the development of the forecasting service since 1977 by highlighting the results of various attempts that have been directed at elucidating the origins of primary populations of *Spodoptera exempta* over eastern Africa. The dates between the last outbreak of each season and the first outbreak of the next season (off-season period) provided a mean number of days for estimating dates of potential onset of primary outbreaks. The development of computer-based data processing routines (database management) and of an expert system for forecasting the occurrence of outbreaks in East Africa are described, as examples of decision-support tools in pest management.

1. INTRODUCTION

The African armyworm *Spodoptera exempta* (Walk.) (Lepidoptera: Noctuidae) is a major pest of cereal crops, sugar cane and pasture grasses in Africa south of the Sahara and in southwestern Arabia. At times it causes damage comparable with that of locusts: for example, 5% loss of maize, wheat and rice in Kenya and Tanzania alone can be worth some U.S. $50 million and on rangeland, over one square kilometre, an infestation at 100 larvae per square metre can consume as much vegetation as 100 head of cattle (Odiyo 1979); in the Yemen Arab Republic up to 11000 ha† of intensively cultivated areas were treated with chemicals in 1974 and another 60000 ha in 1984, at considerable cost (Moharram & Nasseh 1989).

The moths migrate at night for tens or even hundreds of kilometres from their emergence site to the next breeding area (Rose *et al.* 1985), on winds commonly over 3–4 m s^{-1} (11–14 km h^{-1}). This is likely to bring them into zones of wind convergence (and therefore areas of potential rainfall) such as the African Rift Convergence Zone (ARCZ), or the Inter-Tropical Convergence Zone (ITCZ) (Brown *et al.* 1969; Haggis 1971, 1979). At the beginning of the rains, the localized wind convergence associated with storm outflows directly affects the distribution of moths and subsequent outbreaks (Tucker & Pedgley 1983). In the arrival area, females mate before taking up water or dew, ovipositing the next night and this leads to the development of new armyworm outbreaks (Page 1988).

The geographical distribution of outbreaks follows a seasonal pattern, with contemporary but different populations, one generally moving southwards from November or December from Malawi, Mozambique, Zambia or Zimbabwe across southern Africa, and the other moving northwards from Tanzania to affect the whole of East Africa (Uganda, Kenya and Tanzania) and countries to the north as far as the Yemen Arab Republic (Brown *et al.* 1969; Blair & Catling 1974; Haggis 1984, 1986). In East Africa, outbreak seasons usually cover the period November–December till May–June, while June–July to October–November represents the

† 1 hectare = 10^4 m^2.

'off-season' period, when no outbreaks are reported; there are often infestations in Ethiopia, Somalia and southwestern Arabia during these months (Brown *et al.* 1969; Haggis 1984, 1986).

In some years there is evidence that the early outbreaks in southwestern Tanzania were produced by moths originating in Zambia and brought eastwards by a movement of the ARCZ (Odiyo, in Rainey 1979; Rainey & Joyce 1990). More frequently, the first outbreaks of the season in East Africa are reported in east-central Tanzania and eastern Kenya (Odiyo 1979, 1981; Tucker *et al.* 1982). The sources of the moths that produce them was long debated (Rose 1979); the current view is that they generally come from scattered populations that survive the dry season in favoured localities in eastern Kenya and eastern Tanzania, probably near the coast (Tucker 1984*b*), although in some years there is evidence that they were produced by moths originating in neighbouring countries (Brown *et al.* 1969; Tucker 1984*b*; Rainey & Joyce, this symposium).

Outbreaks for which the parent moths cannot be traced to previously known outbreaks are now termed 'primary outbreaks' (Rose 1984; Rose *et al.* 1987; Pedgley *et al.* 1989); these outbreaks are usually small and scattered. Moths that develop from the 'primary' sources spread out over increasing areas with subsequent generations, producing series of secondary outbreaks (Odiyo 1975, 1981; Pedgley *et al.* 1989); as these are often more serious and expensive to control (Rose 1984), the concept of 'strategic control' has been proposed (Rose *et al.* 1987) and is being evaluated.

In the past, the sudden appearance of outbreaks could take farmers by surprise and the larvae were often in their late instars before control could be organized (Brown & Odiyo 1968). Forecasting where and when infestations might occur was seen as a key contribution to overcoming many of the problems of timely control (Brown 1970). The development in East Africa of the armyworm forecasting service from the trial period of 1969–70 to the full-scale permanent service since the 1970–71 season has been reported (Odiyo 1972, 1979; Betts 1976). While much progress has been made in understanding moth migration and behaviour, the main gap in knowledge remains the carry-over from one season to the next. Studies which could facilitate timely prediction and early detection of primary outbreaks could therefore greatly improve the capacity for effective control of *S. exempta* larvae in eastern Africa.

This paper briefly reviews progress in forecasting since 1977 (Odiyo 1979; Rose 1979), and introduces the data base and expert system, which are being developed as potentially useful forecasting decision-support tools.

2. Advances in forecasting

Early evidence of an association between armyworm outbreaks and storms (Rose & Law 1976) and of severe outbreaks following drought (Hattingh 1941; Brown 1962) has been followed up in studies on East African data.

Tucker & Pedgley (1983) studied the most likely egg-laying dates at 53 outbreak sites in East Africa in the 1973–74 and 1974–75 seasons in relation to the occurrence of rainstorms (20 mm or more a day), and found that in these seasons mass egg-laying by moths was more closely associated with the occurrence of rainstorms during the drier period of the season (January–March) than in April–May, when the long rains usually occur. Real-time monitoring of the distribution of very cold clouds by Meteosat satellite imagery is now being used for the third season to provide evidence of convective weather activity for pin-pointing potential breeding areas early in the season.

From studies of records of outbreaks in eight areas of Kenya and Tanzania and rainfall in October–December in 21 seasons (1960–61 to 1980–81), Tucker (1984*a*) also found an inverse relationship between the numbers of armyworm outbreaks and early season rainfall. This tendency for a bad armyworm season to follow low rainfall in October–December, and *vice versa*, has offered the possibility for a seasonal forecast to be issued early in the calendar year.

Monthly summaries of armyworm occurrences in administrative units (Districts and Provinces) in Tanzania, Kenya and Uganda for 20 years (1960–1979), showed that the onset and durations of infestations in each country tend to follow certain geographical patterns, which can be monitored through the use of insect traps and data from Agricultural Extension services (Odiyo 1984). To compare events occurring between the off-season months of July–October and the start of outbreak seasons from November–December, Odiyo (1981) studied occurrences of *S. exempta* larvae for 19 years (1961–1979) and records of moth catches between southern Kenya and east-central Tanzania (1–8° S and 34–41° E) for 16 years (1963–1978) and concluded that moths emerging from low density and scattered larvae in October–November in southern Kenya and northern Tanzania had probably been spreading and breeding over increasing areas of Kenya and Tanzania.

In studying the redistribution of armyworm populations in East Africa during the 1973–74 and 1974–75 seasons, Tucker *et al.* (1982) compared wind trajectories with known outbreaks before and after nights of sudden increase in moth catch, and concluded that some outbreaks, especially early in the season, were probably derived from unreported sources, which in these seasons were most likely to have been in eastern Kenya or eastern Tanzania.

Areas where the first outbreaks of the season most often occur had already been identified (Odiyo 1979). Backtracks calculated for the oviposition periods of first outbreaks in 14 seasons between 1965–66 and 1981–82 showed that the parent moths generally came from the eastern parts of Kenya and Tanzania, to generate infestations in Kenya and in eastern and southeastern Tanzania, though for outbreaks in Kenya and in southwestern Tanzania sometimes there may also have been immigration from neighbouring countries (Tucker 1984*b*). Networks of pheromone traps are now set up annually in the suspect source areas to monitor for increases in moth numbers several weeks before the anticipated start of the outbreak season.

3. Use of historical data

Patterns in the incidence of armyworm outbreaks have been analysed, as indicated above, from which 'rules of thumb' have been derived to assist with forecast production by synthesizing the accumulated years of experience customarily exercised in manual forecasting. For example, historical data from Kenya and Tanzania were used to develop a system for forecasting the occurrence of primary outbreaks from the dates of secondary infestations at the end of the preceding season. Using the records archived at Muguga, Kenya, for the 25 seasons from 1962–63 to 1986–87, dates of the last outbreaks (secondary outbreaks) of each season were listed with all dates of the first outbreaks in the following season. The number of inter-season days (between successive seasons) was counted for each of the 24 years to obtain an annual mean figure. The mean figure was then added to the last date in each season to produce 'predicted' dates for the onset of potential primary outbreaks. These were tabulated against

TABLE 1. PREDICTED DATES OF FIRST OCCURRENCE OF *S. EXEMPTA* LARVAE IN TANZANIA BASED ON THE MEAN NUMBER OF DAYS (247) BETWEEN DATES OF THE LAST (SECONDARY) AND THE NEXT (PRIMARY) OUTBREAKS OF THE SEASONS

outbreak season	date first outbreak predicted to occur	date first outbreak reported	location of first outbreak by district	difference in days between prediction (2) and occurrence (3)	last date larvae reported in this season
1962–63	—	—	—	–	06/04/63
1963–64	12/12/63	20/12/63	Kilosa	+8	31/01/64
1964–65	04/10/64	06/01/65	Kilosa	+94	03/03/65
1965–66	05/11/65	10/12/65	Kilosa	+35	03/05/66
1966–67	05/01/67	26/12/66	Kilosa	−10	10/05/67
1967–68	12/01/68	07/01/68	Kisarawe	−5	16/04/68
1968–69	19/12/68	04/11/68	Mbeya	−45	01/04/69
1969–70	04/12/69	22/12/69	Kilosa	+18	21/05/70
1970–71	23/01/71	28/11/70	Tunduru	−56	13/02/71
1971–72	18/10/71	28/12/71	Morogoro	+71	04/04/72
1972–73	07/12/72	06/05/73	Kisarawe	+150	30/05/73
1973–74	01/02/74	01/01/74	Lindi	−30	15/06/74
1974–75	14/02/75	03/01/75	Ulanga	−42	03/05/75
1975–76	05/01/76	01/01/76	Kilosa	−3	04/05/76
1976–77	06/01/77	21/12/76	Mpwapwa	−16	16/04/77
1977–78	19/12/77	01/01/78	Masasi	+13	12/02/78
1978–79	17/10/78	28/11/78	Mbozi	+42	19/04/79
1979–80	22/12/79	Nov. 1979	Kilimanjaro	?	27/05/80
1980–81	29/01/81	11/12/80	Kilosa/Pare	−49	27/04/81
1981–82	01/01/82	21/11/81	Nachingwea	−42	26/05/82
1982–83	28/01/83	26/12/82	Kilosa	−33	?
1983–84	?	15/12/83	Mpwapwa	?	19/05/84
1984–85	21/01/85	26/11/84	Kilimanjaro	−56	14/04/85
1985–86	17/12/85	16/12/85	Kilimanjaro	−1	23/03/86
1986–87	27/11/86	17/11/86	Kilosa/Mbeya	−10	?

the actual dates of first outbreaks of the next season, to give the difference in days (±) between actual and predicted dates. The results are summarized in tables 1 and 2.

In this analysis of Tanzanian dates, 12 out of 23 predictions (52%) were confirmed between 1 and 35 days (within about a month) from the dates of actual outbreaks, 6 (26%) of them within 10 days. Accurate 'predictions' were made for all 13 Districts with primary outbreaks, all located in the areas outlined in Figure 2 of Odiyo (1979). For Kenya, only 4 out of 19 predictions (21%) were confirmed between 4 and 36 days from the actual dates of outbreaks, and accurate predictions were made for only Taita-Taveta and South Nyanza Districts, which border northeast and northwest Tanzania, respectively.

This system of prediction may complement existing expertise in forecasting early outbreaks in Tanzania, where first outbreaks of the season develop mainly in November, December and January (Odiyo 1981, 1984). In Kenya, however, outbreaks may start between October and February. The final outbreaks of the season have been recorded in Tanzania predominantly in April–May (range January–June), while those in Kenya were predominantly in June (range March–August).

Table 2. Predicted dates of first occurrence of *S. exempta* larvae in Kenya based on the mean number of days (202) between dates of the last (secondary) and the next (primary) outbreaks of the seasons

outbreak season	date first outbreak predicted to occur	date first outbreak reported	location of first outbreak by district	difference in days between prediction (2) and occurrence (3)	last date larvae reported in this season
1962–63	—	—	—	—	27/06/63
1963–64	13/01/64	?	—	–	?
1964–65	?	Feb. 1965	Narok	–	16/03/65
1965–66	02/10/65	mid Nov. 65	Laikipia	–	22/06/66
1966–67	08/01/67	05/04/67	Machakos	+87	12/06/67
1967–68	29/12/67	16/05/68	Laikipia	+138	16/05/68
1968–69	02/12/68	?	—	–	?
1969–70	?	22/12/69	Machakos	–	08/06/70
1970–71	25/12/70	04/11/70	Lamu	–51	28/06/71
1971–72	14/01/72	19/02/72	Taita-Taveta	+36	19/02/72
1972–73	06/09/72	30/12/72	Kisumu	+115	30/12/72
1973–74	18/07/73	late 02/74	South Nyanza	—	09/07/74
1974–75	25/01/75	26/02/75	Taita-Taveta	+32	11/08/75
1975–76	27/02/76	02/03/76	Taita-Taveta	+4	24/07/76
1976–77	09/02/77	10/12/76	Kajiado	–61	17/06/77
1977–78	03/01/78	20/02/78	South Nyanza	+48	20/02/78
1978–79	08/09/78	04/01/79	Kiambu	+118	21/04/79
1979–80	08/11/79	12/02/80	Machakos	+96	07/07/80
1980–81	24/01/81	22/10/80	Kwale	–107	07/07/81
1980–81	24/01/81	03/11/80	Meru	–82	07/07/81
1981–82	24/01/82	09/02/82	South Nyanza	+13	22/06/82
1982–83	08/01/83	20/10/82	Taita-Taveta	–80	20/10/82
1983–84	08/05/83	13/01/84	Machakos	+250	27/06/84
1984–85	31/01/85	05/10/84	Kitui	–118	20/05/85
1985–86	06/12/85	10/02/85	Taita/Machakos	–299	26/05/86
1986–87	12/12/86	18/10/86	Taita-Taveta	–55	12/06/87

4. Computer database

The need to improve both the regional and national control strategies and to strengthen the Desert Locust Control Organization for Eastern Africa (DLCO-EA) armyworm forecasting service, requires that data from current and historical field records of armyworm occurrence, weather and vegetation be re-organized for rapid access and utilization. To do this, the warning system which was developed in East Africa in 1969 for forecasting seasonal occurrence of outbreaks has been computerized.

Reports of armyworm infestations vary greatly in quality and detail, coming from farmers, agricultural extension workers, trap operators, national pest control services or from the public or the press. Every effort is, however, made at the monitoring and forecasting centre to collate all the information, which is then recorded on a standard data sheet, mapped and archived at Muguga. The data sheet was specially designed to select key factors relating to outbreaks of larvae, and to arrange them in order of priority. Records of outbreaks of larvae for the period 1963–1989 have been transcribed onto the special data forms before being stored on computer. Historical records of trap catches of moths, being more uniform in format, have been entered without transcription to the dBASE IV system of database management.

A key part of the database development has been the design of a system specification to identify the set of operational requirements to be met by the system, and prepare precise and detailed statements of what the computer system is to do. The main components of the dBASE IV system control database maintenance and utilization. Software, code-named WORMBASE (Day 1987), has been developed to accommodate a range of data types and functions which are summarized in table 3.

TABLE 3. THE MAIN COMPONENTS AND FUNCTIONS OF THE DATABASE

data types	forecast types
light trap records	short term, e.g. weekly
outbreak records	medium term e.g. monthly
pheromone trap records	long term e.g. quarterly/seasonally
weather summaries	
data handling functions:	data analysis functions:
entering	data presentation
viewing	current
editing	historical
printing	data analysis
mapping	comparisons
summarizing	analogue searches
	forecast generation (expert system)
	forecast printing

The WORMBASE data entry programmes have been tested using imaginary data. This practical exercise proved valuable, enabling learning through trial and error by the operator, and suggesting corrective measures to the programmer. The tests showed the way the programme is likely to be used most of the time in East Africa, but also included ways that will not arise very often, but which may pose different operational problems. Grossly erroneous data (as might occur in mistakes) were deliberately entered as a test for safety checks, and logical problems were created to see if the system might assign a wrong number or inaccurately prompt 'No data' when some item was entered. Other practical benefits from these tests were that the system was thoroughly checked for typographical errors, and situations which might elicit 'problem error messages' on the screen; the wording on displays, menus etc. was checked for clarity of messages; menus were scrutinised for superfluous or incomplete items; the messages displayed in the status bars were verified, and extra help/information suggested which might be useful at any point for the benefit of the inexperienced user.

5. EXPERT SYSTEM

Expert systems are computer programmes that attempt to mimic human experts in identifying solutions to problems. They provide a framework for accessing quantitative information in databases and are particularly useful for problems that have qualitative components (Frenzel 1987; Waterman 1986). An expert system uses information; the reasoning is arranged in rules consisting of conditions and consequent actions. A rule can be a regulation or statement defining a particular attribute, such as the behaviour of a moth.

Expert system development for the armyworm database management programme encompasses both prescriptive problem solving, whereby a user answers a series of questions and receives a recommendation, and provision of information which is relevant to a problem to help the user make a better decision, by linking to the database for searching, analysis and presentation of historical information. Preliminary development of the more prescriptive components has utilized an expert system shell (Exsys 1985) which allows knowledge to be coded by using a rule-based format:

'IF ⟨conditions⟩ THEN ⟨conclusions⟩ ELSE ⟨other conclusions⟩'.

For example, IF moth influx in an area is primary/secondary AND the cereal crops are in a vulnerable stage AND the period is within the outbreak season AND the area has had outbreaks of larvae in the past AND weather elements (rain and wind) have been favourable THEN a warning of impending pest attack should be issued. Or, as another example, IF young maize, sugarcane or grazing is infested AND the larval density looks threatening AND natural enemies are not reducing the population AND the loss is likely to be economically unacceptable THEN control of the pest with insecticides is necessary ELSE IF older maize, sugarcane or grazing is infested AND only a few larvae are observed AND damage is unlikely to be serious THEN chemical control is not economical to apply.

In the above examples, the IF and the AND parts state the conditions, and the THEN part suggests necessary actions. The expert system may already have access to information concerning the conditions of a rule; if not, appropriate questions will be asked of the user. If all the conditions of a rule are satisfied, the rule is then selected, and the search continues from rule to rule until the programme reaches a final conclusion.

The armyworm forecasting problem is a suitable application for expert systems for a number of reasons. Firstly the problem can be well defined, as it involves describing the interactions between the key factors of time (of moth catch, larval infestation or rainfall), location (of trap site, outbreak or raingauge), size (of catch, outbreak or precipitation) and the history of such occurrences over the years (from the database). Also the problem is one that occurs frequently. Finally, the end-users are well defined (e.g. pest control services, farmers, government funding departments etc.).

The armyworm forecasting expert system was structured to address the problem of decision making by evaluating four components: the breeding potential of moths in current and recent catches at a trap representing an administrative district; the risks to be posed by different stages in the life of the insect (larvae, for current damage; pupae, as potential sources of new moths; moths, as potential parents for new larvae at near or distant sites); the degree of influence likely to be exerted on moths, larvae or pupae by the prevailing weather, especially rainfall, winds and temperature; and the lessons to be learned from the comparison of current with previous (analogous) population structures and levels.

The forecasting process, made explicit in the expert system, proceeds as a series of levels. An influx of moths intercepted at a trap site forms the first factor for making a decision in armyworm forecasting (Odiyo 1989). Forecasting considerations at level 1 are therefore based solely on current moth catches from the trap network in each country. The development of populations is assessed consecutively from week 1 at the anticipated start of the outbreak season to week 35 or more at the end of the season. Rule building at forecast level 2 would therefore include moth catches for weeks 1 and 2. The magnitude of moth catches, that is, peak numbers in a night, can vary according to locality, altitude, time of year, prevailing weather conditions and trap efficiency. Categories of peak moths catches (based on experience) may at certain times of the year be defined for high-catching stations, namely, Muguga in Kenya, Tengeru and Arusha in northern Tanzania, as:

1–100 moths per night = low catch (category 1),
101–500 moths per night = medium catch (category 2),
more than 500 moths per night = high catch (category 3),

and for low-catching stations, i.e. all others:

1–10 moths per night = low catch (category 1),
11–100 moths per night = medium catch (category 2),
more than 100 moths per night = high catch (category 3).

Consultation with the programme is structured to follow the usual sequence considered by the forecaster: (*a*) current peak moth catches from the light or pheromone trap network; (*b*) reports of current outbreaks of larvae in the country from pest control services; (*c*) synoptic weather summaries from the meteorological departments, and (*d*) access to the historical data from the archives (database). The computer will first ask the operator to identify the trap site and indicate whether this week's catch is known. The operator is then asked to enter the number of moths caught, whose value will be interpreted by the computer according to the in-built rules on moth catch category. Next, the preceding week's catch is entered as the actual catch or, if appropriate, as 'catch unknown'. The programme then moves to questions about conditions of known outbreaks during the current week, and so on, until all items are covered.

The final output at the end of the run (i.e. prediction and recommendation) is structured in the range:

1. 'Forecast impossible' when there is no information from the field on which to base a decision.
2. 'Forecast, none expected' when available reports are mostly of zero values.
3. 'Forecast low probability' when only minor infestations could result from known source areas.
4. 'Forecast medium probability' where larger populations of larvae might be discovered in the district.
5. 'Forecast high probability' when the occurrence of fresh outbreaks is imminent.

Examples of forecasts based on catches in week 1 are shown in table 4. For the following week, at forecast level 2, the relationship would be as shown in table 5. Output from the programme is in the form of text, maps, graphics and explanatory notes.

TABLE 4. RANGE OF FORECASTS POSSIBLE ON BASIS OF MOTH CATCHES IN FIRST WEEK OF SEASON

IF: catch category is	THEN: Forecast probability of outbreaks is
moth catch unknown	forecast impossible
moth catch zero	forecast none expected
moth catch category 1	forecast low probability
moth catch category 2	forecast medium probability
moth catch category 3	forecast high probability

Table 5. Range of forecasts available on basis of moth catches in first and second weeks

IF catch in weeks 2 (current week) is	AND catch in week 1 (last week) was unknown	zero	category 1	category 2	category 3
	THEN forecast probability of outbreaks (level 2) is				
unknown	impossible	none	low	low	medium
zero	none	none	low	low	medium
category 1	low	low	low	low	medium
category 2	low	low	medium	medium	high
category 3	medium	medium	high	high	high

6. Discussion

Putter & Van der Graaf (1988), of the Food and Agriculture Organization of the United Nations, identified broad objectives about information for plant protection in terms of: the type of information required (e.g. text, map, photographs); the end-users who need the information (e.g. farmer, pest control officer); how the information is to be managed at the central office (e.g. as database, expert system, archive); why the information is needed (i.e. what purpose will it serve?) and what is the value i.e. cost-effectiveness of the information in the management/decision-making process? The development of the Armyworm Forecasting Service in East Africa has been in full awareness of these criteria, particularly in terms of how it has incorporated research findings and experience for improving its mandate. Areas of research have included biology, ecology, biometeorology and biogeography; management of the service at the national and regional levels (Odiyo 1985); and the economics of control (Brown 1970; Rose 1984; Iles 1986).

Operation of the service faces continuing challenges in several key areas: specific problems related to armyworm biology include the nocturnal behaviour of the moths, which necessitates the use and maintenance of light and pheromone traps for monitoring changes in moth distribution throughout the year, and the survival of larvae on very widely distributed host plants, which makes investigation and detection of low-density larvae expensive and practically impossible at the farm level. Management problems include detection of early larval instars, which requires massive inputs of labour, transport and the installation of monitoring devices, while reduced vigilance during the off-season, or years with few outbreaks can only be countered by adopting strategic monitoring policies. Economic problems hinge, for example, on the magnitude and frequency of attacks and therefore whether control of larvae on farms and grasslands should be based on strategic or crop protection control policies, especially where limited funds have to be disbursed on competing priorities at the farm or district level.

Encouragement for successful future development comes from the strengthening of national pest monitoring and forecasting services (in Kenya and Tanzania), continuing support for the regional monitoring and forecasting service under the auspices of the DLCO-EA, based in Nairobi, and the involvement in and support for collaborative research and development exemplified by the ODA/EEC/DLCO-EA Armyworm Project.

A well structured monitoring and forecasting system can provide various types of information, such as text which describes the general situation at a particular time and expected developments from the current combination of factors (Betts 1976; Odiyo 1979); a map showing the positions and intensities of current or recent outbreaks, with a short text explaining potential changes which might result from known situations; and short warnings delivered by the quickest possible means (e.g. telex, facsimile, radio) to reach end-users for immediate action.

To maintain and build on progress already achieved, training of personnel at all levels (e.g. trap operators, extension officers, country coordinators) is essential for effective collaboration and exchange of data and information needed for balanced decision-making.

The database and expert system described here, in combination with real-time satellite monitoring of rainfall, and rapid communication of reports of current distributions and concentrations of moths and larvae, especially from primary outbreak areas, will facilitate the formulation of appropriate pest reports and improve forecasting for armyworm outbreaks, for the application of strategic control of larvae.

Records of *S. exempta* kept at the National Agricultural Research Centre (NARC) of the Kenya Agricultural Research Institute (KARI), Muguga, which in turn came from routine data provided by the National Armyworm Coordinators/Pest Control Officers for Tanzania and Kenya in support of the Regional Armyworm Forecasting Services for eastern Africa, have formed the main base for this paper. I am therefore grateful to these officers and to former scientists in East and Southern Africa, especially E. Lewes of the Meteorological Department, Dagoretti (Nairobi). My grateful thanks also go to the Directors of NARC & KARI and the Director General, DLCO-EA, for support and permission to publish this paper; to Dr R. C. Rainey and Miss M. J. Haggis of the Centre for Overseas Pest Research (now Overseas Development Natural Resources Institute), U.K. for encouragement; Dr D. J. W. Rose of the EEC/ODA/DLCO-EA Armyworm Project in Nairobi and Dr R. Day of the Silwood Centre for Pest Management, U.K. for criticisms and useful comments.

References

Betts, E. 1976 Forecasting infestations of tropical migrant pests: the Desert Locust and African armyworm. In *Insect Flight* (ed. R. C. Rainey) *Symp. R. Ent. Soc. Lond.* **7**), pp. 113–134. Oxford: Blackwell.

Blair, B. W. & Catling, H. D. 1974 Outbreaks of African armyworm, *Spodoptera exempta* (Walker) (Lepidoptera, Noctuidae), in Rhodesia, South Africa, Botswana and South-west Africa from February to April 1972. *Rhod. J. agric. Res.* **12**, 57–67.

Brown, E. S. 1962 *The African armyworm, Spodoptera exempta (Walker) (Lepidoptera, Noctuidae): a review of the literature.* (57 pages.) London: Commonwealth Institute of Entomology.

Brown, E. S. 1970 Control of the African armyworm, *Spodoptera exempta* (Walk). – an appreciation of the problem. *E. Afr. agric. For. J.* **35**, 237–245.

Brown, E. S., Betts, E. & Rainey, R. C. 1969 Seasonal changes in distribution of the African armyworm, *Spodoptera exempta* (Walk.) (Lep.: Noctuidae), with special reference to eastern African. *Bull. ent. Res.* **58**, 661–728.

Brown, E. S. & Odiyo, P. 1968 The rate of feeding of the African army worm *Spodoptera exempta* (Walk.) and its significance for control operations. *E. Afri. agric. For. J.* **33**, 245–256.

Day, R. K. 1987 Armyworm forecasting: *Report of a visit to Kenya, May-June, 1987*. T C Fellowship X158, Project A1736. Imperial College, Silwood Park, Ascot, U.K.

Exsys Incorporated, 1985 *Expert system development package users manual.* Albuquerque. New Mexico.

Frenzel, L. E. Jr. 1987 *Understanding expert systems.* Indiana: Haward W. Sams & Company. (A Division of Macmillan, Inc.)

Haggis, M. J. 1971 Light trap catches of *Spodoptera exempta* (Walk.) in relation to wind direction. *E. Afr. agric. For. J.* **37**, 100–108.

Haggis, M. J. 1979 African armyworm *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae) and wind convergence in the Kenya rift valley, May 1970. *E. Afr. agric. For. J.* **44**, 332–346.

Haggis, M. J. 1984 Distribution, frequency of attack and seasonal incidence of the African armyworm *Spodoptera exempta* (Walk.) (Lep., Noctuidae), with particular reference to Africa and southwestern Arabia. (116 pages.) *Rep. Trop. Dev. Res. Inst. Lond.* **L69**.

Haggis, M. J. 1986 Distribution of the African armyworm, *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae), and the frequency of larval outbreaks in Africa and Arabia. *Bull. ent. Res.* **76**, 151–170.

Hattingh, C. C. 1941 The biology and ecology of the army worm (*Laphygma exempta*) and its control in South Africa. (50 pages.) *Sci. Bull. Dep. Agric. For. Un. S. Afr.* **217**.

Iles, M. J. 1986 An economic assessment of the African armyworm, with special reference to Tanzania: Research proposals following a visit to Tanzania and Kenya, April–May, 1986. (26 pages.) *Rep. Trop. Dev. Res. Inst.* **R1380** (R).

Moharram, I. A. & Nasseh, O. M. 1989 Distribution and seasonal incidence of African armyworm *Spodoptera exempta* (Walker) (Noctiuidae-Lep) in Yemen Arab Republic. *Report of 3rd Arab Congress of Plant Protection, Al-Ain, United Emirates University, 5–9 December* 1988.

Odiyo, P. O. 1972 Reliability of the first full-scale (Armyworm) forecasting service. *Rec. Res. E. Afr. agric. For. Res. Org. 1971*, pp. 200–202.

Odiyo, P. O. 1975 The biology of armyworm outbreaks in East Africa. *Ken. entomol. Newsl.* **2**, 2–6.

Odiyo, P. O. 1979 Forecasting infestations of a migrant pest: the African armyworm, *Spodoptera exempta* (Walk.). *Phil. Trans. R. Soc. Lond.* B **287**, 403–413.

Odiyo, P. O. 1981 Development of the first outbreaks of the African armyworm, *Spodoptera exempta* (Walk) between Kenya and Tanzania during the 'off-season' months of July to December. *Insect Sci. Appl.* **1**, 305–318.

Odiyo, P. O. 1984 A guide to seasonal changes in the distribution of armyworm infestations in East Africa. *Insect Sci. Appl.* **5**, 107–119.

Odiyo, P. O. 1985 The development and operation of an armyworm forecasting service in East Africa. *Proceeding of the seminar on agrometeorology and pest forecasting*, 24–28 *June*, 1985, *CTA/TDRI, Fulmer Grange*. pp. 56–72.

Odiyo, P. O. 1989 An expert system for forecasting outbreaks of the African armyworm, *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae.). M.Phil. Thesis, University of Wales, Cardiff.

Page, W. W. 1988 Varying durations of arrested oocyte development in relation to migration in the African armyworm moth, *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae). *Bull. ent. Res.* **79**, 181–198.

Pedgley, D. E., Page, W. W., Mushi, A., Odiyo, P., Amisi, J., Dewhurst, C. F., Dunstan, W. R., Fishpool, L. D. C., Harvey, A. W., Megenasa, T. & Rose, D. J. W. 1989 Onset and spread of an African armyworm upsurge. *Ecol. ent.* **14**, 311–333.

Putter, C. A. J. & Van der Graff, N. A. 1988 Information needs in plant Protection. *Pl. Prot. Serv. FAO, Rome.*

Rainey, R. C. 1979 Control of the armyworm *Spodoptera exempta* in eastern Africa and southern Arabia: report of a mission to formulate an inter-regional project. *FAO-AGPP: Misc*/32.

Rose, D. J. W. 1979 The significance of low-density populations of the African armyworm, *Spodoptera exempta* (Walk). *Phil. Trans. R. Soc. Lond.* B **287**, 393–402.

Rose, D. J. W. 1984 Current views on the epidemiology of the African armyworm outbreaks and strategies for control. In *Working papers of the seminar on the African armyworm, Spodoptera exempta* (Walker) (Lepidoptera Noctuidae) 4–5 September 1984, *Trop. Dev. Res. Inst. Lond.* pp. 31–35.

Rose, D. J. W., Dewhurst, C. F., Page, W. W. & Fishpool, L. D. C. 1987 The role of migration in the life system of the African armyworm. *Spodoptera exempta. Insect Sci. Appl.* **8**, 561–569.

Rose, D. J. W. & Law, A. B. 1976 The synoptic weather in relation to an outbreak of the African armyworm, *Spodoptera exempta* (Wlk.). *J. ent. Soc. Sth. Afr.* **39**, 125–130.

Rose, D. J. W., Page, W. W., Dewhurst, C. F., Riley, J. R., Reynolds, D. R., Pedgley, D. E. & Tucker, M. R. 1985 Downwind migration of the African armyworm moth, *Spodoptera exempta*, studied by mark-and-capture and by radar. *Ecol. ent.* **10**, 299–313.

Tucker, M. R. 1984*a* Forecasting the severity of armyworm seasons in East Africa from early season rainfall. *Insect Sci. Appl.* **5**, 51–55.

Tucker, M. R. 1984*b* Possible sources of outbreaks of armyworm *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae) in East Africa at the beginning of the season. *Bull. ent. Res.* **74**, 599–607.

Tucker, M. R., Mwandoto, S. & Pedgley, D. E. 1982 Further evidence for windborne movement of armyworm moths, *Spodoptera exempta*, in East Africa. *Ecol. ent.* **7**, 463–473.

Tucker, M. R. & Pedgley, D. E. 1983 Rainfall and outbreaks of the African armyworm, *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae). *Bull. ent. Res.* **73**, 195–199.

Waterman, D. A. 1986 *A guide to expert systems.* Reading, M.A.: Addison-Wesley.

Discussion

R. Day (*Imperial College, Silwood Park, Ascot, U.K.*). Mr Odiyo has raised the subject of so-called 'strategic control'. The idea of this approach is that by controlling all the primary armyworm outbreaks, or at least those which are critical in the sense that they lead to subsequent or secondary outbreaks, the extent and thus the cost of secondary outbreaks will be greatly reduced. The idea is certainly attractive, but there are a couple of possible problems with the approach that I think would merit closer investigation.

Strategic control is based on the theory that most of the moths causing secondary outbreaks have arisen from primary outbreaks. There is certainly good circumstantial evidence that secondary outbreaks are caused by moths that have come from the area of primary outbreaks, but what is difficult to show is that the majority of the moths causing secondary outbreaks have come from primary outbreaks themselves. If at the same time that immigrant moths cause primary outbreaks there are significant numbers that are not concentrated in the outbreak area, low density, but extensive synchronous populations could be established in the vicinity of the outbreak. These would emerge at roughly the same time as the moths from the primary outbreaks, and might appear to arise from the outbreak site, but would escape strategic control. The important question is thus what proportion of moths causing a secondary outbreak actually come from the primary outbreak site itself?

A second area of strategic control that needs to be considered is the problem of finding a significant proportion of primary or critical outbreaks. Primary outbreaks are often smaller than secondary outbreaks, and so more difficult to detect, particularly if they are in areas where human habitation is sparse. In this case the costs of monitoring and detecting the primary outbreaks become much greater. An economic analysis comparing strategic and tactical control (if that is the opposite), would be useful, so that the sensitivity of the method to the critical assumptions could be tested.

A second area of interest is Mr Odiyo's analysis of the number of days between the last outbreaks of one season and the first outbreaks of the following season. His examination of this statistic implies that there might be some suggestion that the outbreaks at the start of one season are related to those at the end of the previous season. This recalls the continuous gregarious populations debate, which I thought had been closed, at least for African armyworms.

What are the relative merits of forecasting by statistical methods and forecasting by mechanistic methods? Obviously there is overlap between the two, but my feeling is that the models and statistics that we use in forecasting should be based on mechanistic explanations or hypotheses, rather than simple statistical correlations. On the other hand, it would be folly not to use an inexplicable correlation if it provided a better forecast than a mechanistic model.

D. E. Pedgley (*ODNRI, Chatham, U.K.*). Regarding what Dr Day said on whether one can estimate the proportion of secondary outbreaks that come from primary outbreaks, one way is by examining a large number of armyworm seasons and backtracking, from wind-field maps, to make best estimates of where the parents came from which produced the secondary outbreak and compare these with the known primary outbreaks at the time when moths are likely to have taken to the air. This work is on-going, but as far as I can recall the majority of secondary outbreaks seem to result from moths which have come from primary outbreaks; I would not like to put a figure on it, but perhaps in two years time we will be able to answer the question.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

A. G. Gatehouse (*University of Wales, Bangor, U.K.*). Dr R. Day expressed some doubt that the proportion of moths responsible for secondary outbreaks, which originate in primary outbreaks, is likely to be high. He suggested that many of them are likely to arise from undetected low-density populations in the same general area. This question is of crucial importance for the current approach to strategic control, which depends on the effective control of primary outbreaks as a means of interrupting the sequence of infestations developing from them.

We need some means of distinguishing moths from high- and low-density phase larvae, and methods based on possible biochemical differences are being assessed. However, I think there is reason to suppose that, in years when outbreaks are severe and frequent, the large majority of moths responsible for secondary infestations do indeed originate in primary or critical outbreaks (Rose *et al.* 1987). It is now well established that seasons of severe armyworm outbreaks in East Africa are associated with partial failure of the early or short rains. When this happens, suitable larval habitat, which is absolutely dependent on rainfall, is present only where rain storms have occurred and is therefore patchy and widely scattered. The only larval populations likely to be established under these circumstances are those resulting from the concentration of flying moths (originating from low-density populations in the dry season habitats) by intense convergent airflow associated with these storms, i.e. the primary outbreaks. In these seasons, the patchy distribution of rainfall means that suitable habitat to support low-density infestations of larval offspring of moths escaping such concentration is just not available.

There now seems little doubt that *Spodoptera exempta* breeds continuously through the dry season, surviving at low densities in areas where there is sufficient off-season rainfall or other sources of moisture to permit continued growth of its host grasses. Pheromone traps deployed in such areas, coastal regions of Kenya, for example, catch moths throughout the year but give no indication of a build-up of these populations towards the end of the dry season to levels expected if they are the sources of moths initiating the primary outbreaks. As the latter occur regularly on the eastern slopes of the first hills inland from the Kenya and Tanzania coasts and as back-tracking studies have shown, unequivocally, that the moths causing them originate from the east, these consistently low catches could be no more than a consequence of the problems inherent in monitoring the insects at extremely low population densities, a measure of the success of their 'low density strategy' (Gatehouse 1987). However, Mr Page of the Kenya National Armyworm Project has suggested that another mechanism may be involved.

Moth concentration leading to primary outbreaks very often occurs on the very first rains in these areas, irrespective of their precise timing. This requires the assumption, on the basis of current knowledge, that adequate numbers of moths leave the dry season coastal habitats every night at the end of the dry season and beginning of the rains, to account for the infestations following the first rainstorms. If this were happening, moths would also be available for concentration by rainstorms subsequent to the first ones but the evidence suggests that they are not. However, the apparent anomaly would be resolved if moths from the coastal habitats underwent a quiescence induced by the low humidity conditions that they encounter inland after flight, before the first rainfall. Even if this was of limited duration, it would allow accumulation of the insects over time in these regions, to be activated by environmental cues associated with the onset of the first rains and then concentrated by them to initiate the primary outbreaks. Diapause and quiescence, often prolonged, is known in adult noctuids (Oku 1983) and we are now looking into its possible occurrence in the African armyworm.

References

Gatehouse, A. G. 1987 Migration and low population density in armyworm (Lepidoptera: Noctuidae) life histories. In *Recent advances in research on tropical entomology* (ed. M. F. B. Chaudhury) *Insect Sci. Appl.* **8** 573–580.
Oku, T. 1983 Aestivation and migration in noctuid moths. In *Diapause and life cycle strategies in insects* (ed. V. K. Brown & I. Hodek), pp. 219–231. The Hague.
Rose, D. J. W., Dewhurst, C. F., Page, W. W. & Fishpool, L. D. C. 1987 The role of migration in the life system of the African armyworm *Spodoptera exempta*. In *Recent advances in research on tropical entomology* (ed. M. F. B. Chaudhury). *Insect Sci. Appl.* **8**, 561–569.

D. J. W. Rose (*EEC/ODA/DLCO-EA Armyworm Project, Nairobi, Kenya*). Twelve years have passed since Mr Odiyo presented his paper at the previous symposium on migrant pests, convened by the Royal Society in 1977 (Odiyo 1979). That paper described the Armyworm Forecast Service which had been developed for the three countries of the East African Community by using light traps to monitor moth populations. Since then, the forecast service has been extended to the Desert Locust Control Organisation for Eastern Africa (DLCO-EA) and the national armyworm coordinators in seven member countries, and much greater use has been made of moth pheromone traps in the national networks of each country for the regional forecast issued each week. In addition to this service, relatively dense networks of pheromone traps have been established in the most important primary outbreak areas in Kenya and Tanzania. These are monitored by the local extension officers and are used to locate the first outbreaks of the season so that these can be controlled as quickly as possible before moths spread to continue a succession of secondary outbreaks downwind from the original sites. These networks of pheromone traps, plus the satellite pictures of locations of storms likely to concentrate moths to cause outbreaks, are the most important sources of information for alerting crop protection officers and District Agricultural officers so that major control operations can be mounted. In addition, farmers and extension officers in these previously dry areas are warned to take heed of the first major rain storms of the season and to search for newly hatched caterpillars about a week later. Coloured and illustrated charts showing the stages of armyworm which may be found on specified days after the storms have been prepared for distribution to farms (W. W. Page, personal communication).

The extension of the forecast service with Mr Odiyo as Regional Armyworm Forecast Officer for DLCO-EA, the development of the data bank on computer and the introduction of 'expert system' software for programming forecasts are all exciting developments, which show great promise for the future. Seasonal forecasts of severity of armyworm outbreak years are already possible (Tucker 1984; A. W. Harvey, unpublished). The investigations of possibilities for producing long-term forecasts of the time and place of likely occurrence of primary outbreaks are still at a preliminary stage and no doubt will need to be modified as more data become available. Nevertheless, this possibility must be fully investigated, as prior warning increases the chance of implementing control operations before damage is done.

References

Odiyo, P. O. 1979 Forecasting infestations of a migrant pest: the African armyworm, *Spodoptera exempta* (Walk.). *Phil. Trans. R. Soc. Lond.* B **287**, 403–413.
Tucker, M. R. 1984 Forecasting the severity of armyworm seasons in East Africa from early season rainfall. *Insect Sci. Appl.* **5**, 51–55.

R. C. Rainey, F.R.S. (*Elmslea, Old Risborough Road, Stoke Mandeville, Bucks, U.K.*). During most years for a period of several months from about December to April, dense infestations are absent from the East African countries. Odiyo (in Rainey 1979) directed attention to an incursion of westerly winds at the African Rift Convergence Zone over Zambia in late 1971, which subsequently advanced into southern Tanzania at an appropriate time and area to have probably brought the parents of the first generation of the sequence of heavy infestations which later extended right up to Ethiopia and Yemen. In a number of years Kenya has recorded armyworm infestations coming in with incursions of westerlies.

In 1970, the wind-finding research aircraft recorded, close to the Nakuru light trap, the sharply defined leading edge of such an incursion of westerlies a few hours after the peak light trap catch of the season at this trap, and this catch proved to have sampled the parents of a further generation of armyworm in and around the Nakuru district (Haggis 1979).

It has been suggested that the windshift of such westerlies would be appropriate for experimental searches with the airborne radar for missing moth populations in the off-season.

Any further observations on the effects of westerly incursions on the armyworm could be highly relevant. Odiyo's investigation of 'expert systems' is particularly to be welcomed in the context of 20 years of successful armyworm forecasting.

References

Haggis, M. J. 1979 African armyworm. *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae) and wind convergence in the Kenya rift valley, May 1970. *E. Afr. agric. For. J.* **44**, 332–346.

Rainey, R. C. 1979 Control of the armyworm *Spodoptera exempta* in eastern Africa and southern Arabia: report of a mission to formulate an inter-regional project. *FAO-AGPP*: *MISC*/32.