CROP PROTECTION PROGRAMME

Decision tools to aid armyworm surveillance and outbreak prediction

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Executive Summary

The purpose of the project was to develop population and behaviour models of economically important armyworm outbreaks and to promote improved pest management strategies. This was achieved through the following activities: (1.) The development of a model to describe the dispersal, displacement and re-concentration of armyworm moths; (2.) The development of a mechanistic, rule-based, model of armyworm population dynamics and movement; (3.) An analysis of the behaviour of the model (2. above) for a representative range of initial conditions and weather scenarios, and (4.) The dissemination of findings, and training in use of the forecasting aids. These activities led to the output of the project, the devising of models to aid armyworm surveillance and outbreak prediction. This contributes towards DFID's development goals, particularly Purpose 4 of the semi-arid production system (Population and behaviour models of economically important locust, grasshopper and armyworm outbreaks developed and improved pest control strategies promoted), by reducing the impact of migrant pests on crop production, as more accurate outbreak prediction improves the efficiency of control teams.

Background

Larvae of the African Armyworm moth, *Spodoptera exempta*, are serious pests of cereal crops (e.g. maize, sorghum, millet, wheat, rice, teff) and range-land in many countries, particularly in eastern and southern Africa. In some years the area infested may total several million hectares, with 30% of cereal production lost in outbreak areas (Scott, 1991; Cheke & Tucker, 1995). Chemical control appears to be economically justifiable, but farmers do not generally notice infestations of caterpillars until after their third moult and, as a result, control measures may be initiated too late to prevent serious damage to crops and pastures. The development of methods for monitoring armyworm populations and forecasting outbreaks are, therefore, key requirements for the efficient management of this pest. Forecasts of armyworm outbreaks, made at national centres (e.g. at Pest Control Services (PCS), Arusha, Tanzania) and at regional centres (e.g. the International Red Locust Control Organisation for Central and Southern Africa (IRLCO-CSA, Ndola, Zambia) and the Desert Locust Control Organisation for Eastern Africa (DLCO-EA, Nairobi, Kenya), use the results from several years of research (Rose *et al.*, 1987, 1995; Tucker, 1994, 1995; Cheke & Tucker, 1995). However, the forecasters involved requested help in developing a more structured approach to the utilisation of the research data.

Work on armyworm data management systems and forecasting technologies has already made progress toward this goal. Current elements include: (i.) A computer package known as WORMBASE providing information on distribution and timing of the armyworm outbreaks for use by pest managers to assist in control planning (Day, 1991). (ii.) Trajectory analysis to evaluate probabilities of migration, using weather data (Tucker, 1994, 1995). (iii.) Potential damage estimates based on historical probabilities of likely movements from known sources (Cheke & Tucker, 1995). (iv.) Rule-based models to integrate qualitative understanding with more quantitative data in empirical prediction (Odiyo, 1989) and predictive simulation (Holt & Day, 1993). (v.) Radar observations of armyworm dispersal and re-concentration during migration (Pedgley *et al*., 1982; Riley *et al.,* 1983; Rose *et al.,* 1985).

In Tanzania, where an extensive database of armyworm outbreak records already exists, the data management aspects (element i) have been successfully implemented through the provision of the WORMBASE package. At the start of the project, work on the forecasting (elements ii – v) was at an earlier stage, and had still to be implemented successfully with accessible aids for use in routine forecasting. This was the researchable constraint addressed by the project.

Demand for the project was identified by national and international agencies involved in armyworm control. These included the International Red Locust Control Organisation for Central and Southern Africa (IRLCO-CSA, based in Zambia but with regional responsibilities including Tanzania), and by the Ministry of Agriculture and Co-operatives and their Pest Control Services, United Republic of Tanzania. The latter have a continuing interest and commitment to the research project in general and to armyworm forecasting in particular. In addition, the Food & Agriculture Organization of the United Nations (FAO) expressed its support for the aims of the project.

Project Purpose

The project's purpose was "Population and behaviour models of economically important armyworm outbreaks developed and improved pest management strategies promoted". This was addressed by synthesising knowledge of armyworm dispersal and concentration and probabilities of armyworm movements based on historical events, within a ruled-based model of armyworm population dynamics. The model provides pest control services with the means to improve their forecasting abilities and thus to plan control operations more efficiently, thereby reducing potential crop damage.

Research Activities

1. Modelling the dispersal of African armyworm moths leaving an emergence site.

Radar studies, funded by DFID, have provided data on the flight behaviour of armyworm moths when they leave emergence sites (Riley *et al*., 1983; Rose *et al*., 1985; Reynolds & Riley, 1997), but the contribution of this behaviour to the dispersal of emigrating moth populations had not been quantified. Radar-derived information on moth flight behaviour was used to model this dispersal and to predict the area over which the migrating moths would land.

The model of moth flight paths makes the following assumptions:

- Moths emigrate from an outbreak site, which is very small compared to the area over which they will subsequently fly, meaning that the site is considered to be a point source.

- The *durations* of the moths’ flights can be described by a normal distribution about an appropriate mean value.
- The moths’ *air speeds* and *headings* can be described by normal distributions about their appropriate means.

Because no account was taken of the change of wind speed with altitude, the effects on dispersal of variations in the moths' rates of climb and cruising altitudes were suppressed. The effects of atmospheric turbulence were also neglected, so the dispersal predicted by the model can be taken to be the *minimum* which moths would normally experience in natural conditions. The final dispersion pattern is represented by summing the number of flight trajectories that end in each 5 x 5 km square within a zone downwind of the emergence site.

2. Modelling armyworm population dynamics and movement to make a forecast of outbreak risk one month in advance

African armyworm moths *S. exempta* displace downwind and are concentrated by convergent wind-flows associated with rainstorms (Pedgley *et al.* 1982, Riley *et al.* 1983, Rose *et al.* 1985). They land and breed, sometimes resulting in the occurrence of high-density outbreaks of larvae which cause considerable damage to crops and grassland. Moths emigrating from an outbreak site can then initiate further outbreaks in other locations. Dispersal modelling (Activity 1, above) and trajectory analysis have been used to estimate these downwind migrations (Tucker *et al.* 1982, Tucker 1994).

The forecasting model was developed to predict the fate of moths emerging from an outbreak site. Holt & Day (1993) developed a rule-based simulation model of armyworm population dynamics which in this project was expanded to incorporate moth migration and satellite-derived rainfall information. The model simulates population change from one week to the next and movement over a grid of units of one degree-square each. The model predicts the directions, distances and dispersions adopted by moths, based on prevailing winds. Rainfall is the main driving variable and is estimated from rain gauges or from Meteosat cold-cloud data. Rainfall determines emigration from the source outbreak, and aggregation, fecundity, mortality and food quality at the potential destinations of the displaced moths.

3. Testing the forecasting model for a representative range of initial conditions and weather scenarios

The component of the model that described population dynamics was tested, by examining the probability of occurrence of armyworm outbreaks following different rainfall patterns. Rain gauges in the same degree square as the reported outbreak were used for a comparison which involved 164 outbreaks spanning 11 years and 25 locations in Tanzania (Tucker & Holt 1999).

4. Dissemination of findings and training in the use of the forecasting aids.

Since 1969, the forecasting of armyworm outbreaks by national forecasting units and by the regional Desert Locust Control Organisation (DLCO-EA) (Brown *et al.* 1969, Odiyo 1990) has been based on plotting the changing distribution of outbreaks and trap catches in relation to winds and rainfall. In 1991 a computer database, WORMBASE, was developed to incorporate both historical and current armyworm data, in the form of outbreak reports, light and pheromone trap catches and rainfall data (Knight & Day 1993, Day *et al.* 1996).

The decision process in current use by forecasters at PCS in Tanzania is summarised in Fig. 1. The two central data requirements are moth reports of some sort (outbreaks or trap catches) and rainfall (meteorological station reports, rain gauge or Meteosat data). Cold Cloud Duration data which are used to run the population model are also being used directly in current forecasting procedures. Meteosat has been used to locate nocturnal rainstorms from infra-red images. Rainstorms are identified by the temperature of the cloud-tops as measured by the Meteosat infra-red channel. The software calculates a 'cold-cloud duration' (CCD) image by adding the number of hours that a cloud-top temperature lower than a fixed threshold of -50°C is present for each pixel (data point). Daily (or nightly) CCDs are calculated to identify the presence of individual rainstorms.

All planned activities were carried out.

Outputs

Activity 1. Interpretations of radar data suggest that armyworm moths emigrating from an outbreak site typically fly for 3.5 ± 1 hours, at 3.5 ± 0.5 ms^{-1}, and with their headings represented by a circular normal distribution with dispersion s = ± 30°, about some mean angle relative to the wind, where $s = ((-2 \ln R)^{0.5})/2$ and R is the root of the mean value of the sum of the squares of the sines and cosines of twice the original orientation angles. We present here two examples of the dispersion which the model predicts when using these data, and for mean headings relative to the wind of 0° (Fig. 2) and 40° (Fig. 3). The wind speed is assumed to be 6 ms^{-1} in both examples, and 10,000 moth flight paths were modelled in each case.

The striking feature of both Figures 2 and 3 is the *extreme* degree of dispersion, which they imply. Moths emigrating from an emergence site, which might occupy a square kilometre or less, would become distributed over an area of ~ 16,000 km^2 in the space of a few hours. A consequence of this dispersion is the very low area density at which moths would 'invade' any crops or pasture in the zone downwind of the emergence site. The highest density in the figures is ~ 80 moths per 25 km^2, and while the nightly output from a dense emergence site might be two orders of magnitude higher than the value used in the simulation, the corresponding invasion density would still amount to < 400 moths per km^2. In reality, wind shear with altitude, and atmospheric turbulence would increase dispersion well beyond that shown in the figures, and invasion densities would correspondingly be much lower than one moth per 2,500 m^2.

The implications of these findings are quite profound, because invasions at densities as low as this would simply not lead to troublesome re-infestations. The fact that outbreaks *do* occur in practice thus demonstrates that some re-concentrating effect must be at work. The moths might actively seek out favourable sites in which to land, but there is no radar evidence to support this possibility. Alternatively, migrant populations may be re-concentrated by convergent wind flows whilst in flight and the moths may then land before re-dispersal occurs (Rose *et al.*, 1987). Dramatic linear concentrations of airborne insects seen on radar, (including armyworm moths, Pedgley *et al.*, 1982), have been associated with wind-shift lines, and so there is little doubt that convergent wind flows of one type or another must be a key factor in the production of armyworm outbreaks.

The dispersal footprint, predicted by the dispersal model, provides a basis for the estimation of moth dispersal, which is required in the forecasting model.

Activity 2. To forecast an armyworm generation (*c*. 5 weeks) ahead, historical frequencies of rainfall patterns were used. Repeated sampling of this rainfall frequency distribution in an ensemble forecast allowed a spatial probability footprint of outbreak risk to be calculated. The forecast comprises a prediction of the probabilities of low, medium and high outbreak risk in each degree-square of the grid.

In each degree-square, armyworm population dynamics are simulated. A wide range of outbreak outcomes can occur depending on the pattern of moth arrival and its interaction with rainfall events. The spatial model predicts outbreak risk in the next armyworm generation across a grid of 20 degree-squares following an outbreak in a source square. The parameter input screen of the model (Fig. 4) allows the distance, direction and dispersion of moths leaving the source square, and the frequency of each weather category to be specified. Moths from the source are distributed across the possible destination squares and occurrence of subsequent outbreaks depends upon the weather patterns encountered in each square. When projecting forward to the next armyworm generation, historical probability distributions of rainfall category for different places and times are used. The potential impact of different scenarios, e.g. 'drier than usual', 'wetter than usual', and average, can be examined.

In the example shown in Fig. 5., a general weather forecast of rainstorm probability for a large area of Tanzania was used. Therefore, the same rainfall frequency distribution was taken for all squares and used with an ensemble forecasting technique (Zhang & Krishnamurti 1997), to estimate outbreak risk. Forecasters at PCS describe armyworm risk as low, medium or high and the index of outbreak risk obtained from the model (abundance x aggregation) was categorised similarly. Repeated runs of the model (usually 100) were made for different realisations of the rainfall category distribution and the numbers of occurrences of low, medium and high outbreak risk in each square were recorded to estimate the probabilities of these events (Fig. 5). Model output such as that in Fig. 5 can be used to help judge not only the most likely outbreak risk level in a square, but also to assess the variability associated with this estimate. A major benefit provided was to allow a sensitivity analysis of the outbreak prediction to different armyworm dispersal and rainfall patterns.

Activity 3. Expressing the results as conditional probabilities allowed comparisons to be made with model predictions. Based on historical frequency of occurrence alone, there was, on average, a 6% chance of an outbreak, i.e. the prior probability of an outbreak in any week in any district was 0.06. The conditional probability was greatest (0.24) when widespread rains were followed by dry weather (sequence 4,1; Fig. 5). The probability was higher than the prior probability when isolated storms in the week of moth arrival were followed by any weather category (3, followed by any category), and when widespread storms were followed by dry weather or light rain (4, followed by 1 or 2). Other weather patterns gave conditional outbreak probabilities similar to, or less than, 0.06.

The outbreak risk predicted by the model is also shown in Fig. 6. This is the product of the logarithm of the population size and aggregation level. Thus, the larger and more aggregated the population of late instar larvae the greater the outbreak risk. The data and model appeared to be in reasonable agreement with ‘4,1’ having the highest outbreak probability and ‘1,4’ the second lowest in the data set examined (Fig. 6).

Activity 4. CCD data were summarised for a grid of degree squares (1º latitude x 1º longitude) for each day and this information was sent weekly by electronic mail from the Natural Resources Institute to the Tanzania Armyworm Forecasting Unit at Pest Control Services, Arusha. These data were converted at PCS into a simple geographically referenced image (Fig. 7) which can then be compared with daily trap catch data for the current week. This output supports and develops the short-term forecasting capability.

The forecasting model went a step further. Instead of evaluating the outbreak risk in the current generation of armyworm larvae it projected one generation ahead (about 5 weeks). As future rainfall over the next five weeks was not known, historical data were used, appropriate for different places and periods of the year. From the historical data, the probabilities of each rainfall category over the next five weeks can be obtained. By simulating multiple realisations of these probability distributions in an ensemble forecasting approach, a probability footprint of outbreaks can be projected forward for the moths departing an existing outbreak site. Thus, the model is designed to produce a medium term forecast to complement the short-term forecast. The accuracy of this medium term forecast can be improved as time progresses over the five-week interval from the current armyworm generation to the next one, and as actual rainfall data become available. If real-time data became available, they were substituted for the historical probability distribution. This forecast was designed to provide farmers, extension services and control services with a probability distribution of outbreaks one generation hence.

The anticipated outputs were achieved.

Contribution of Outputs

The outputs have contributed to DFID’s general developmental goal of reducing poverty, and to the specific goal of minimising the impact of migrant pests on resource-poor farmers in semi-arid farming systems in southern Africa, by improving the ability of the Pest Control Services of Tanzania to respond to armyworm infestations. For instance, a recent example of the use of CCD data, sent by email, to aid short term forecasting occurred during February 1999. Areas of cold cloud were observed in Ilonga and Morogoro regions. The frequency and distribution of the CCDs were indicative of isolated rainstorms and, on the following day, there was a large increase in moth catches in the pheromone traps in parts of this region. This combination of events is indicative of high outbreak risk and a forecast was therefore issued and the control teams alerted. A week later, outbreaks occurred in Kilosa and Kilombero districts in Morogoro region. The control teams were by then in a more advanced state of readiness to perform control operations than would have been the case without the forecast.

The model has been made available to the target institution in a form, which can be interpreted quickly by pest control staff after short training sessions. Recommendations can be made based on the model, which can be used by the extension services to improve their responses to outbreak threats. Electronic and printed versions of the model algorithms have been made available for continuing research.

The ‘end-user’ beneficiaries are rural communities in Tanzania, dependent on cereal crop production, who gain from improvements in the efficiency of control methods against armyworm. Similar communities in neighbouring countries will also profit from the control of armyworm sources in Tanzania. Other direct beneficiaries include the personnel responsible for armyworm surveillance and forecasting in Tanzania, and the national and regional control organisations in other armyworm-affected countries in Africa. Follow-up research to promote the findings of the project should include testing and refining of medium-term forecasts based on model outputs with real-time events in Tanzania. If these tests proved to be successful, then the model could be adapted for use in other countries in Africa affected by the pest. However, for the model to be of value in such other countries, it would be necessary to ensure that the countries have capabilities to collect appropriate data, and the institutional strengths to sustain an information gathering and dissemination network.

The following publications have been written, based on project outputs, and which are appended to this report:

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