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Weather and the epidemiology of the African Armyworm (*Spodoptera exempta*) (NRI Bulletin 58)

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Bulletin 58

WEATHER AND THE EPIDEMIOLOGY OF THE AFRICAN ARMYWORM (*SPODOPTERA EXEMPTA*)

Overseas Development Administration

WEATHER AND THE EPIDEMIOLOGY OF THE AFRICAN ARMYWORM (*SPODOPTERA EXEMPTA*)

M. R. Tucker

Bulletin 58

Natural Resources Institute

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Overseas Development Administration

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GLOSSARY

Armyworm phase	Refers to the two discrete morphological types of *Spodoptera exempta; gregaria* and *solitaria*.
Backtracks	Trajectories drawn backwards from armyworm outbreaks to estimate moth sources.
Critical outbreak	An outbreak leading to large numbers of subsequent outbreaks, usually over several generations.
Degree square	An area on a map of one degree of latitude by one degree of longitude.
Development table	A table showing the normal duration of each stage of the armyworm life-cycle, especially of larval instars.
Forward tracks	Trajectories drawn forward from armyworm outbreaks to estimate the possible destination(s) of departing moths.
Gregaria	A distinct morphological type of armyworm caterpillar characterised by black colouring and high activity.
LT (local time)	Local time as distinct from Zulu (or Greenwich Mean Time).
Moth arrival	The most likely date(s) on which moths arrive at a locality and are concentrated prior to mating and oviposition, leading to an armyworm outbreak.
Outbreak	Armyworm caterpillars at high density, usually over a well-defined area.
Primary outbreak	An outbreak originating from moths coming from low-density populations.
Secondary outbreak	An outbreak originating from moths coming from a previous outbreak.
Solitaria	A distinct type of armyworm caterpillar characterised by green or brown colouring and low activity.
Squall-line	A curvi-linear feature over tens of kilometres, where an abrupt change in wind direction and increase in wind speed accompanies the outflow from a convective rainstorm.
Synoptic-scale convergence	A zone where winds converge on a scale of hundreds or thousands of kilometres, caused by large-scale pressure patterns, usually pressure 'troughs'. It is often associated with rainfall.
Trajectory	A line drawn on a map parallel to the windflow (for periods of several days), of a length determined by the windspeed, and used to estimate downwind migration of moths flying at the windspeed.
Windfield disturbance	An area of winds differing from the prevailing winds, usually with a well-defined structure and lasting from one to several days.
Wind rotor	An area of overturning winds caused by the barrier effect of topography, usually over an area of tens of kilometres.
Wind streamlines	Continuous lines on a windfield map drawn parallel to the wind direction and indicating structures in the windfield, such as windfield disturbances and synoptic-scale covergence. Trajectories follow wind streamlines for the appropriate time and location.

Summary

Armyworm reports and weather records for eastern Africa were analysed for armyworm seasons from 1972-88. Relationships between the frequency and distribution of outbreaks and weather (especially wind and rainfall) were summarized for each season separately and compared between seasons.

Outbreaks were classified into those derived from low density populations (primaries) and those from previous outbreaks (secondaries). Trajectory analysis was used to estimate migrations of windborne moths, and the distribution of rainstorms helped to determine the timing of the moth concentration leading to armyworm outbreaks.

First reported armyworm outbreaks in Kenya and Tanzania, from October to December, were usually primary. 'Critical' primary outbreaks, leading to many secondary outbreaks, occurred in east-central Tanzania, east-central Kenya and north-east Tanzania to the adjacent Taveta district of Kenya. Strategic control, to prevent subsequent, downwind outbreaks, is best carried out in these areas.

The direction of migration was determined by seasonally dominant winds, although windfield disturbances were occasionally important. The results confirm previous work showing an association between outbreaks and rainstorms, especially at the beginning of the short and long rains, which indicates that rainstorm distribution following a dry period can be used to help forecast armyworm outbreaks. Weekly forecasting requires rapid acquisition of rainfall data for the whole of eastern Africa, a requirement best served by satellite-derived information.

Three seasons with very low numbers of armyworms had heavy persistent rainfall from October to December leading to high larval mortality. Seasons with large numbers of outbreaks did not always have below average early season rains. The critical factors leading to many armyworm outbreaks are:

(a) the presence of low-density parent populations at the beginning of the season

(b) the occurrence of rainstorms where moths can be concentrated while in flight, leading to high density ovipositions and subsequent outbreaks

(c) the occurrence of dry periods between rainstorms, suitable for the survival of young caterpillars and unsuitable for the spread of larval disease

(d) migration of moths downwind from primary outbreaks into cereal growing areas in eastern Africa.

The work reported in this bulletin will enable armyworm forecasters in eastern Africa to compare present and past seasons, predict how seasons might develop, and improve forecasts. The results are being used to assess the economic viability of strategic control.

Section 1

Introduction

ARMYWORM EPIDEMIOLOGY

The African armyworm is the caterpillar of the moth *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae) which occurs mainly in Africa, south of the Sahara, especially in eastern and southern Africa, but also in Yemen and parts of South-east Asia, Australia and Hawaii. (Haggis, 1984; 1986).

It feeds almost exclusively on cereals and grasses (Gramineae) and occasionally on sedges (Cyperaceae). It is a serious pest on maize, sorghum, millet, rice and wheat and, to a lesser extent, on teff, barley and sugar-cane. It may also cause serious damage to grassland used as animal pasture (Odiyo, 1979). The economic importance of *S. exempta* in eastern Africa has been reviewed by Scott (1991).

African armyworm shows a density dependent phase polymorphism (Faure, 1943). The low density *solitaria* phase is green or brown, inactive and inconspicuous, and does little damage. The high density *gregaria* phase is black, very active and conspicuous, and does much damage. *Gregaria* phase armyworms usually occur in well-defined outbreaks. The name 'armyworm' comes from the behaviour of gregarious caterpillars which, having defoliated one area, will move *en masse* to a new food source. They are also called 'mystery worms' because outbreaks appear suddenly and erratically, and their distribution in space and time varies from one season to another. Forecasting outbreak occurrence is an aid to their control.

Research on armyworm epidemiology in eastern Africa (Brown *et al.*, 1969) made it possible to start a regional forecasting service in 1969 (Odiyo, 1979; 1984). This was based at the East African Agricultural and Forestry Organization (EAAFRO), near Nairobi, which became the Kenya Agricultural Research Institute when the East African Community broke up. The work transferred to the Desert Locust Control Organization for Eastern Africa (DLCO-EA) in 1984. Ethiopia, Kenya and Tanzania maintain their own individual armyworm forecasting units, based in their Ministry of Agriculture Plant Protection or Pest Control Departments.

The need for a regional armyworm forecasting service was based on the realization that armyworm moths migrate long distances, crossing country boundaries and appearing suddenly in previously uninfested areas. This knowledge was originally based on the interpretation of trap catches (Brown and Swaine, 1966) and mapping outbreak distributions (Brown *et al.*, 1969). In many years outbreaks are reported from March to July, progressively further north of Tanzania and Kenya to Ethiopia and Yemen (Haggis, 1984; 1986). Brown *et al.*, (1969) showed that this could be attributed to large-scale moth migration following the seasonal wind change from north-easterly or easterly to south-easterly or southerly. No convincing evidence has been found for a return migration. Although Brown *et al.*, (1969) found an association between the first outbreaks of the season, from October to December, in Kenya and Tanzania, and windshifts from south-easterly to north-easterly (for 1963-67), Tucker (1984a) found from backtracks for 1966-80 that likely sources were usually in the east of these countries, not further north.

Direct evidence of moth migration has been obtained from radar observations and a mark-capture experiment (Riley *et al.*, 1983, Rose *et al.*, 1985). It found that moths flew upwards to a height of several hundred metres from outbreak emergence sites and migrated downwind for distances of 90-147km in one night, and several hundred kilometres over three nights. The duration of moth flight depends on the length of the Pre-Reproductive Period (PRP) (Page, 1988; Wilson and Gatehouse, 1993) and the flight capacity of the individual moths (Woodrow *et al.*, 1987). The PRP is usually one or two days, but some moths have arrested oocyte development, with PRPs of up to six days (Page, 1988). This results in differences in distances covered by migrating moths, which, together with the tendency of air currents to disperse moths during downwind migration, means that for a new outbreak to form there must be a mechanism to reconcentrate the moths before they lay eggs. Radar has shown that rainstorm outflows concentrate flying moths (Pedgley *et al.*, 1982; Riley *et al.*, 1983) and a significant association between outbreaks and rainstorms at the time of moth concentration prior to oviposition has been found (Tucker and Pedgley, 1983).

Rose (1979) using data from Zimbabwe, proposed that the first armyworm outbreaks of a season arise when moths emerging from low density, *solitaria*, populations are concentrated by convergent wind patterns. Some evidence for the persistence of low density, *solitaria*, armyworm populations between outbreak seasons, comes from the occasional capture of small numbers of moths in traps during the 'off-season' (July to October) in Kenya and Tanzania (Odiyo, 1981). Outbreaks suspected of being caused by moths coming from low density populations, especially those at the beginning of the season, have been called primary (Rose *et al.*, 1987; Pedgley *et al.*, 1989) to distinguish them from secondary outbreaks derived from moths coming from previous outbreaks.

A strategy has been developed in eastern Africa to control primary outbreaks, especially 'critical' outbreaks, which, if uncontrolled, lead to many secondary outbreaks in cereal growing areas following downwind migration (Rose *et al.*, 1987).

The present work aims to improve the forecasting of armyworm outbreaks and the control strategy by a better understanding of the causes of differences in outbreak number and locations between seasons. Records for 16 seasons from 1972-88 were used to:

(a) identify primary and secondary outbreaks, their most frequent areas of occurrence and their relation to weather especially, rainfall and winds

(b) examine moth migration between outbreaks

(c) identify critical outbreaks

(d) examine inter-seasonal differences in overall severity in relation to the timing and location of primary outbreaks and early season rainfall

(e) summarize the development of each season to enable them to be compared with future seasons

(f) describe techniques that can be used to improve armyworm forecasting

The findings of this study and the methods used are reported in this bulletin. This information should enable armyworm forecasters to:

- compare present with past seasons in eastern Africa
- see how the season might develop
- improve forecasts by using the summary of results as a set of forecasting 'rules'

It is hoped that the techniques will be useful for armyworm forecasting elsewhere in Africa, and have applications for the forecasting of other migrant moth species.

WEATHER IN EASTERN AFRICA

A basic understanding of the weather in eastern Africa is essential for forecasting armyworm outbreaks. This report includes a brief summary of weather features, and details of particular events affecting armyworm are given in the seasonal summaries in Appendix 1.

Eastern Africa has an equatorial climate, strongly modified by altitude, by its position on the east side of the continent and by the western edge of the Indian Ocean monsoon circulation. Dominant winds are easterly but vary from east to north-easterly from December to February; and from south-easterly to southerly from April to October. The convergence zone between these winds, the Inter-tropical Convergence Zone, is not a clear feature in eastern Africa and is strongly modified by east-west variations and by highlands. Nevertheless, there is a north and south shift of mean wind convergence and associated rainfall following the relative movement of the overhead sun. Near the equator there are two rainy seasons, the 'long rains' from March to May and the 'short rains' from November to December, following the north and south shift of the solar maximum respectively. South of about 6°S there is one rainy season, from November to April.

Figure 1 shows the dominant low-level daytime winds in eastern Africa for the main armyworm season (Tucker *et al.*, 1982). In October (not shown) winds are still largely south-easterly. They back to easterly in November and north-easterly from December to February. South-easterly winds remain in north Tanzania and south-west Kenya, caused by deflection around the highlands, with a large-scale convergence zone in the lee of Kilimanjaro and the Aberdares. This pattern persists until more general south-easterly winds return in April. From May to September, above the surface, there is usually a low-level jet of strong southerly winds over east Kenya. This jet, which is associated with the west boundary of the Indian Ocean south-westerly monsoon, often has winds of 12-20 m/s at 1000 m at Garissa and Voi (Findlater, 1966; 1967; 1969). Another feature, that does not show on the dominant wind maps, is the periodic occurrence of surface westerly winds, usually west of 36°E but occasionally extending further east. The convergence zone between these usually light westerlies and the easterlies is known as the Zaire Air Boundary (Congo Air Boundary or African Rift Convergence). Surface westerly winds are most frequent in the rainy seasons and often associated with rainstorms. In many cases they are the result of mesoscale down-draught outflow winds from storms rather than large-scale westerly incursions. Large-scale westerlies are more frequent above the surface, especially at 2.5-5 km altitude (Nakamuru, 1968). This is above known flying heights of armyworm moths, even over the highlands, and eastward moth movements are only likely when westerlies descend towards the surface.

Table 1 shows mean monthly rainfall, as a percentage of the annual rainfall, at selected stations in Kenya, Tanzania and Uganda (Kenya Meteorological Department, 1984; East African Meteorological Department, 1975). The two rainy seasons in Kenya and north Tanzania and one longer rainy season in south Tanzania, described above, can be clearly seen from the figures. The locations of these stations are shown in Figure 2.

In north and east Kenya and parts of north and central Tanzania, divergent low-level winds result in very low rainfall, such as at Lodwar, Voi, Same and Dodoma. In the west, especially near Lake Victoria, rainfall totals are much higher and some rain falls in all months, although with two peaks, usually in April and November. Rainfall totals exceeding 1000 mm also occur on the Indian Ocean coast, and in parts of the highlands, such as Lyamungu and Amani.

Most rain falls in convective storms. which are often thundery, and the mean frequency of thunderstorm days as shown in Table 2 (Chaggar, 1977) is a good indicator of the distribution of the storms. Thunderstorms occur frequently at Kisumu, Mwanza, Kampala and Tororo, near Lake Victoria, and together with the lake breeze convergence, they produce convergent winds suitable for army-

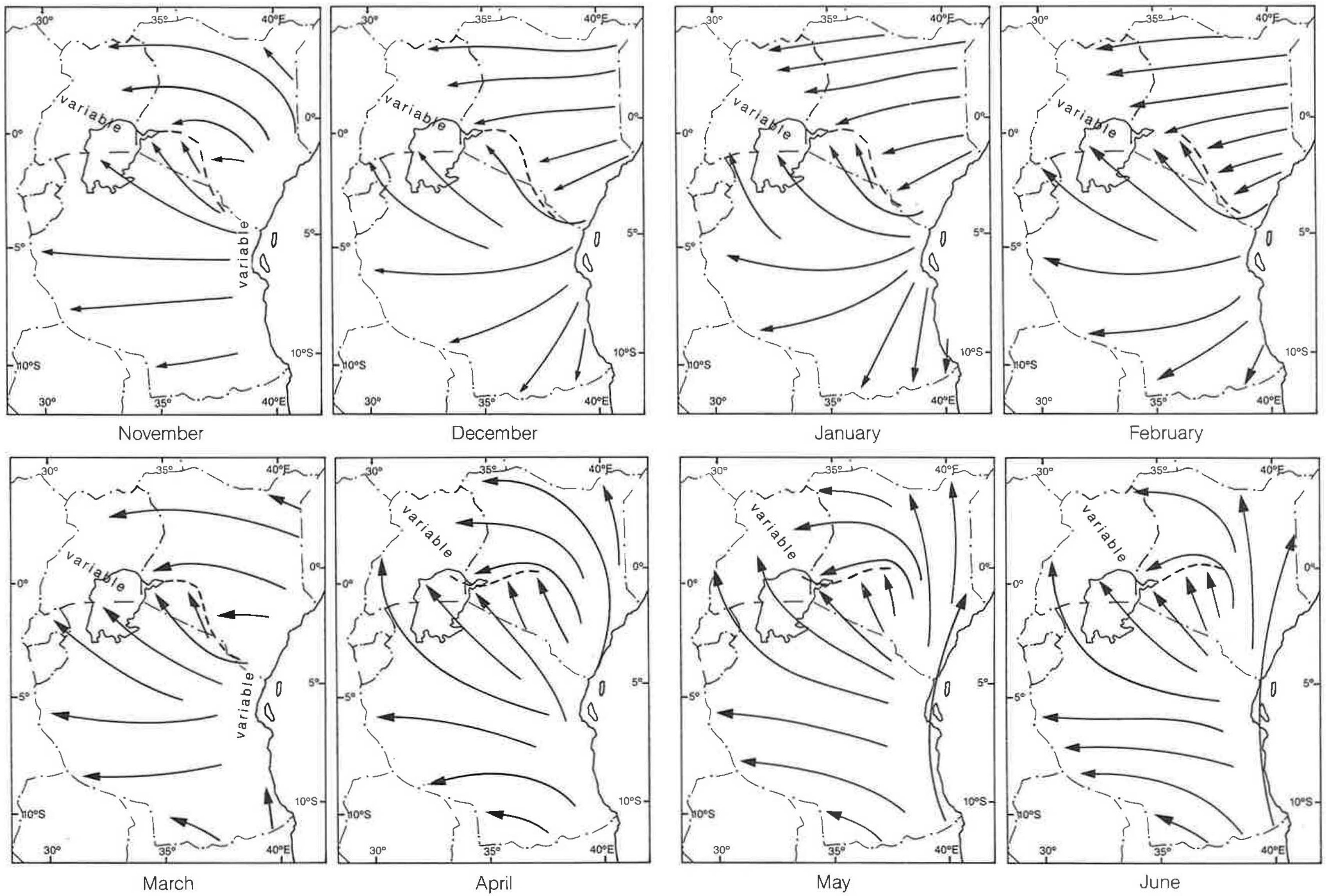

Figure 1 Streamlines of dominant wind directions over eastern Africa, November to June

Key: Dominant winds
Zone of mean wind convergence

0 200 400 600

worm moth concentration in this area. In east and east-central Kenya, on average, there are two to five thunderstorm days in each rainy season month and 4-14 in east and east-central Tanzania. Armyworm outbreaks are particularly associated with these storms and it would be useful for forecasting to know when and where they occur. The moths fly at night so the diurnal distribution of rainfall is also important information. Table 3 (Tomsett, 1975) shows that, away from the coast and Lake Victoria, most rain falls in the afternoon or night (from 1500-0300 local time). So there is a high probability that when a storm occurs, it is during the hours when the armyworm moths are flying.

The mechanism which concentrates armyworm moths near rainstorms is shown in Figures 3 and 4 (Pedgley, 1982; Pedgley *et al.*, 1982). Figure 3 presents a vertical section and plan view of a typical convective rainstorm. Heavy rain falling from the cloud base cools the underlying air, so that a downdraught of cool, dense air is formed. On approaching the ground surface this downdraught spreads out, undercutting the warmer, less dense surrounding air, which is feeding into the rainstorm. An abrupt change in wind direction and increase in wind speed accompanies the outward spreading downdraught. At this squall-line, low level winds are convergent and any insects flying within are concentrated, as shown by radar (Figure 4). The insects appear to resist being carried upwards and into air returning towards the rainstorm (Achtemeier, 1991). As they enter cooler high level air they fly down and may land, with the effect that they are concentrated at the gust front.

Table 1 Monthly rainfall in eastern Africa as percentage of annual rainfall

	J	F	M	A	M	J	J	A	S	O	N	D	Annual total (mm)	Climatic region
Kenya														
*Moyale	2	3	8	10	18	2	2	2	3	15	12	6	705	Northern
Lodwar	5	4	11	25	13	5	10	5	2	5	9	6	193	
Eldoret	4	6	4	12	13	11	15	17	6	4	6	2	1063	Western
*Kisumu	5	7	12	16	13	7	5	7	6	6	9	8	1323	
*Nakuru	4	4	6	14	12	8	9	11	8	10	10	5	883	Rift Valley
*Narok	10	11	14	19	13	4	2	3	3	3	8	10	743	
*Nairobi, JKA	6	7	9	19	17	3	2	2	3	5	18	10	762	Highlands east
Machakos	8	8	13	23	8	2	1	1	2	5	20	10	775	of Rift Valley
*Makindu	7	5	13	18	5	0	0	0	0	5	28	19	612	Eastern
*Garissa	4	2	11	19	6	2	1	2	2	7	22	22	352	
*Voi	6	5	14	18	5	1	1	1	3	5	19	21	555	
*Lamu	1	0	3	14	36	18	8	11	8	9	9	5	919	Coast
*Mombasa	4	2	5	15	22	7	8	6	7	9	9	7	1049	
Tanzania														
*Mwanza	9	10	14	16	7	1	1	2	3	7	13	15	1083	Lake
*Arusha	8	9	16	27	7	2	1	1	1	3	15	11	927	Northern
Lyamungu	3	4	7	32	27	7	4	2	2	2	6	5	1637	Highlands
Amani	4	4	9	18	17	6	5	5	6	7	9	7	1919	
*Same	8	11	15	22	12	1	1	2	2	5	9	12	567	
*Tanga	2	3	8	19	20	5	5	6	6	8	12	6	1339	Coast
*Dar es Salaam	7	7	13	24	13	3	3	2	2	5	11	10	1134	
*Morogoro	10	11	18	24	10	3	2	1	2	3	7	9	908	East-central
*Dodoma	25	20	21	9	1	0	0	0	0	1	4	19	566	
*Tabora	15	15	19	15	3	0	0	0	0	2	12	19	894	Central
*Iringa	23	17	23	12	2	0	0	0	1	1	5	16	743	South-central
*Mtwara	18	17	15	17	4	1	1	0	4	2	5	16	1166	South-eastern
*Nachingwea	20	19	20	16	2	0	1	0	1	1	7	13	934	
*Songea	21	22	21	8	1	0	1	0	0	1	5	20	1149	South-western
Mbeya	22	19	18	12	2	0	0	0	0	2	6	18	905	
Uganda														
Kampala	9	8	8	14	7	5	4	10	11	9	12	5	1123	Lake
Tororo	4	5	9	15	15	8	7	8	8	9	7	5	1470	Eastern

Notes: * Stations used to calculate October-December rainfall index (see Results)

Table 2 Mean frequency of thunderstorm days in eastern Africa

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Kenya													
Lodwar	1	1	2	5	2	1	1	1	0	1	1	1	17
Eldoret	1	2	3	6	8	11	14	18	11	4	2	2	82
Kisumu	12	14	18	23	24	19	16	19	23	23	20	14	225
Nakuru	2	3	7	13	14	10	10	13	12	11	7	4	105
Narok	9	8	11	10	5	4	2	2	3	4	7	7	72
Nairobi (JKA)	2	2	5	4	3	1	0	1	1	1	2	1	23
Makindu	1	2	4	5	1	0	0	0	0	0	2	2	17
Garissa	1	0	3	4	1	0	0	0	0	1	5	2	17
Voi	1	1	6	5	0	0	0	0	0	1	3	3	20
Lamu	0	1	3	4	1	0	0	0	0	0	2	2	13
Mombasa	2	1	6	6	1	0	0	0	0	0	3	4	23
Tanzania													
Mwanza	17	17	18	19	10	4	3	6	9	17	18	20	158
Arusha	8	9	13	4	0	0	0	0	0	3	8	9	54
Same	3	5	7	3	0	0	0	0	0	1	3	3	25
Tanga	3	3	7	5	1	0	0	0	0	0	2	4	25
Dar es Salaam	5	6	12	8	1	0	0	0	0	0	2	6	40
Morogoro	12	11	14	8	1	0	0	0	0	1	4	10	61
Dodoma	11	10	10	3	0	0	0	0	0	0	2	8	44
Tabora	16	16	16	10	2	0	0	0	1	3	11	17	92
Iringa	11	11	13	5	1	1	0	0	0	1	4	11	58
Mtwara	8	12	15	7	1	0	0	0	0	0	2	8	53
Songea	19	17	16	4	0	0	0	0	0	1	6	15	78
Mbeya	21	20	21	13	2	0	0	0	2	8	16	20	123
Uganda													
Kampala	15	15	18	21	20	18	18	20	22	24	20	15	226
Tororo	11	13	18	23	23	15	16	21	23	26	18	14	221

Source: Chaggar (1977)

Table 3 Percentage of annual rainfall falling in each three-hour period of the day in eastern Africa

	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24
Kenya								
Lodwar	5	10	28	22	21	8	4	2
Eldoret	10	4	3	2	15	29	21	16
Kisumu	8	3	1	0	3	23	41	21
Nakuru	4	2	1	1	22	44	19	7
Narok	7	5	2	1	13	34	26	12
Nairobi (JKA)	18	16	9	5	7	16	14	15
Makindu	21	15	8	5	7	9	15	20
Garissa	7	7	6	8	10	22	23	17
Voi	8	8	6	7	13	27	22	9
Lamu	10	12	15	17	14	12	11	9
Mombasa	13	16	18	18	15	7	6	7
Tanzania								
Mwanza	10	16	17	18	21	6	4	7
Lyamungu	19	19	14	7	9	8	9	15
Amani	9	9	9	9	18	23	13	10
Dar es Salaam	7	11	12	22	27	11	5	5
Dodoma	16	14	10	6	7	16	16	14
Tabora	8	6	9	8	12	24	20	13
Uganda								
Kampala	12	20	16	12	22	11	3	4
Tororo	6	4	2	1	14	38	26	9

Source: Tomsett (1975)

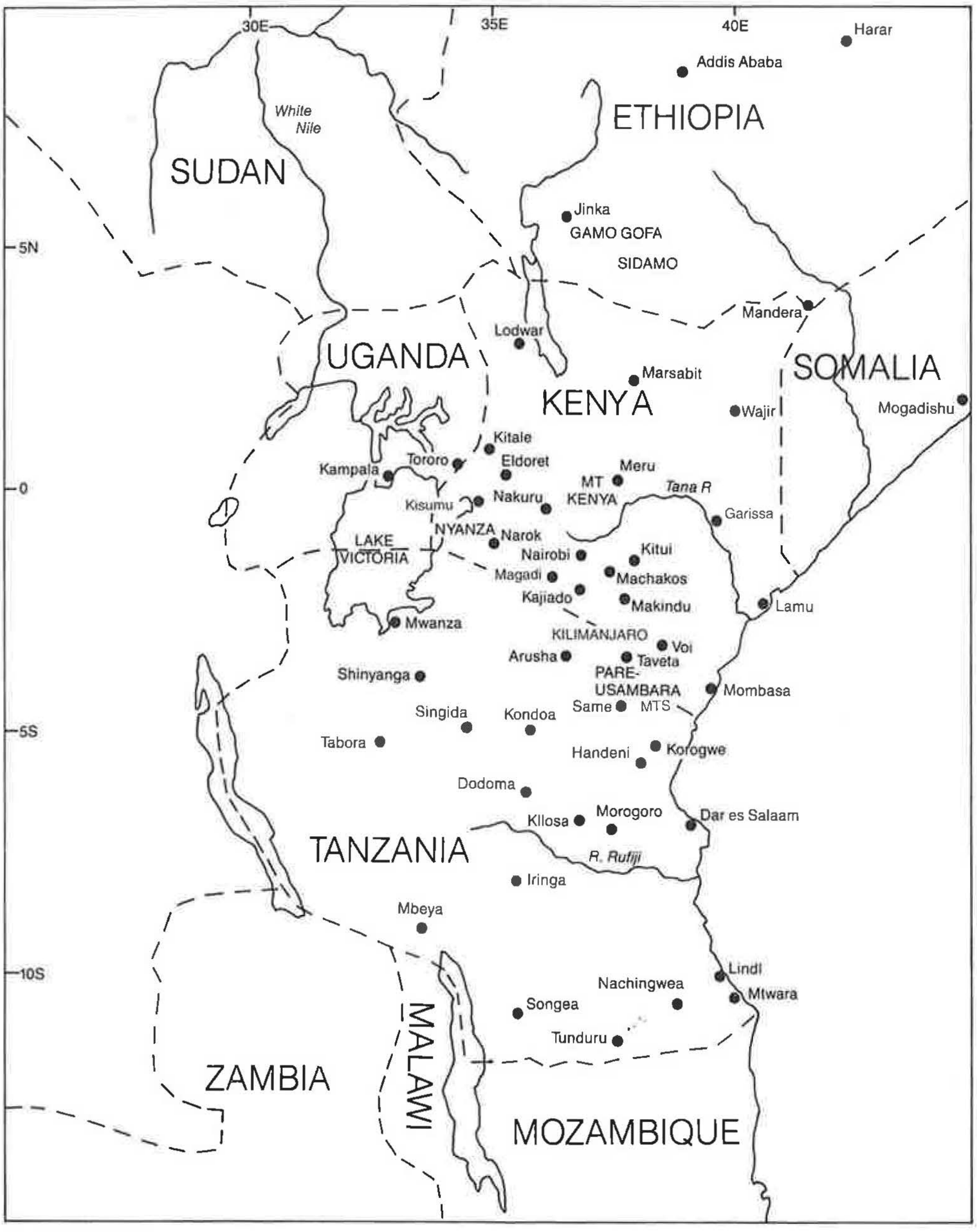

Figure 2 Location of places mentioned in the text

In addition, moths are concentrated in topographically induced wind rotors (Pedgley *et al.*, 1982). A vertical section through one half of such a rotor is similar to that for the storm outflow (Figure 4) and moths are concentrated in the same way. The frequency of such rotors is not known, but they have been observed downwind of particular topographic features such as the Rift Valley escarpment (Pedgley *et al.*, 1982).

Insects are also concentrated by sea or lake breezes (Drake and Farrow, 1988). These are density currents with a similar cross-section to the rainstorm outflow. They are caused by the differential heating of land and water, with cool dense air moving inland at low levels in the afternoon, undercutting air warmed by daytime heating. The warm air rises and moves towards the sea, or lake, at an altitude of several kilometres to complete the circulation. The frequent occurrence of thunderstorms near Lake Victoria in the afternoon or evening, is partly caused by low-level convergence along the lake breeze front. Over the lake at some coastal stations (e.g. Entebbe) a night-time or early morning maximum of thunderstorms occurs, caused by the reverse land breeze (Lumb, 1970). Armyworm moths may be concentrated near coasts either by the sea breeze/land breeze circulations or by associated rainstorms.

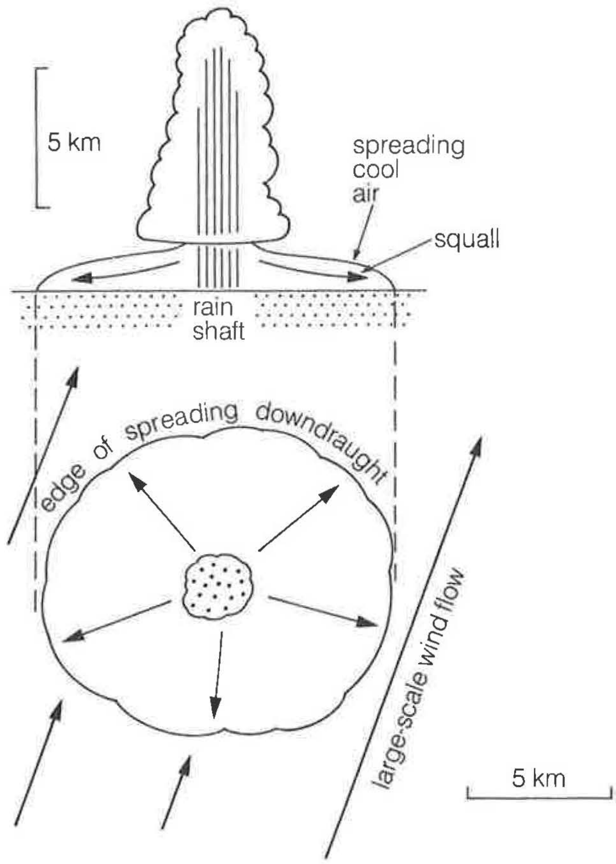

Figure 3 Section through a rainstorm outflow (Pedgley, 1982)

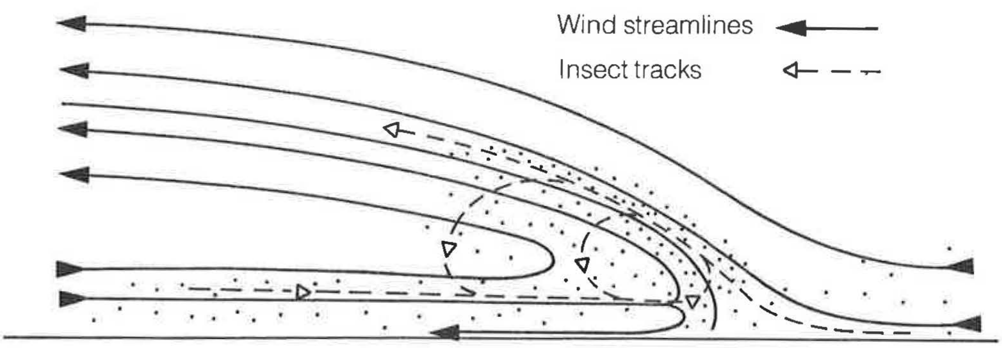

Figure 4 Windflow and insect tracks in the nose of a rainstorm outflow (Pedgley *et al.*, 1982)

TEMPERATURE AND ARMYWORM DEVELOPMENT RATES

Knowledge of the rate of armyworm development is needed to estimate timing of moth concentration, oviposition, damaging caterpillar outbreaks, pupation and moth emergence. It depends on the air temperature which, in eastern Africa, varies with altitude and cloud cover. Brown (1962) found that *S. exempta* could not be reared in the laboratory at temperatures of less than 65°F (18°C). In Kenya, the 18°C mean daily isotherm lies at about 2000 m in most months, and this does appear to be the maximum altitude at which outbreaks occur. The most detailed study of development rates in the field (Page in Pedgley *et al.*, 1989) produced a linear regression of head capsule width (or instar) against number of days after moth concentration which is taken as three days before first oviposition (Figure 5). It gave a development time from first oviposition to moth emergence of 36 days, which agrees with earlier unpublished estimates for the Nairobi area as used by Tucker and Pedgley (1983). Figure 5 also shows the error range of the estimated age, which increases with the size of the caterpillar. Page's regression can be used for outbreaks at altitudes from 1200 to 2000 m, but outbreaks at lower altitudes often develop more rapidly (Rose, 1975; Persson, 1981; Page and Dewhurst (personal communication)). Both Rose and Persson found development periods, from oviposition to moth emergence, of about 30 days at altitudes of about 1000 m, and Persson found a development period of 23 days on the Kenya coast.

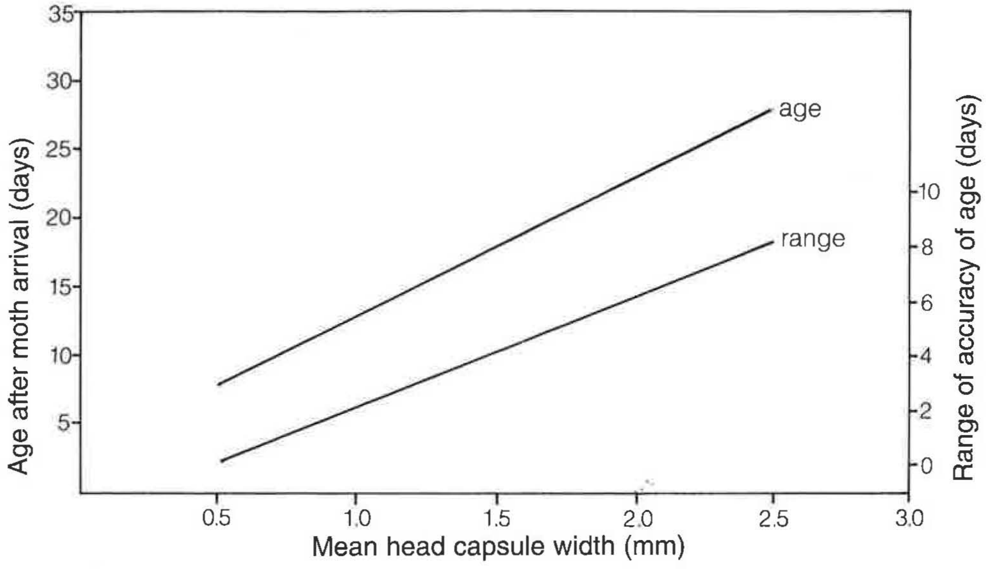

Figure 5 Armyworm head capsule width compared with age after moth arrival (Pedgley *et al.*, 1989)

Section 2

Data and methods

ARMYWORM DATA

Reports of armyworm outbreaks and moth catches in light and pheromone traps, are sent to the National Plant Protection Services of Ethiopia, Kenya, Somalia, Tanzania and Uganda. Regular reporting has been established for about 30 years in Kenya and Tanzania, but it has been irregular in the rest of eastern Africa. Reports are used by National Armyworm Forecasting Services and by the Regional Armyworm Forecasting Service, now run by the Desert Locust Control Organization for Eastern Africa (DLCO-EA), Nairobi.

Armyworm data for 1972-88 were extracted from records at DLCO-EA and the Kenya Armyworm Forecasting Service at the National Agricultural Research Centre NARC, Muguga, and supplemented by additional data from the Tanzanian Armyworm Forecasting Service and the Ethiopian Ministry of Agriculture. The data consisted of reports of armyworm outbreaks from farmers and district agricultural officers, together with information from special surveys carried out in Kenya and Tanzania from 1978, and light and pheromone trap data. Some light trap data were available for the whole period of the study. Pheromone trap data were available from 1978, following the development of an artificial female sex-attractant pheromone (Campion *et al.*, 1976). From 1982 there were additional pheromone trap records from local networks installed in areas where primary outbreaks often occur. At the Armyworm Forecasting Centres in Kenya and Tanzania, most of this data are now available on 'Wormbase', a computerized armyworm database and forecasting system (Day, 1991). Control measures against armyworm were sometimes reported but these data were not used because there was no information on the effectiveness of control. Crop loss data were generally not available.

WEATHER DATA

Synoptic surface winds were obtained from routine daily windflow charts plotted by the Kenya Meteorological Department (available at NARC, Muguga) and from the meteorological services of Ethiopia, Kenya and Tanzania. Although these charts were sometimes incomplete, they were readily available for the large number of days required. Where necessary the charts were re-analysed to give streamlines suitable for trajectory construction.

Figures for daily, weekly and monthly rainfall were obtained from the meteorological services of Ethiopia, Kenya and Tanzania and from NARC. Daily rainfall data were obtained from rain gauges within approximately 50 km of outbreak sites for all early season armyworm outbreaks and some later ones. The density of rain gauges varies across eastern Africa, but data were obtainable from at least five gauges in each of these areas. If not, then rain gauges within 100 km were used. Detailed analysis of rainfall distribution in relation to outbreaks was possible for Kenya, where data from a much denser network of rain gauges were available for many of the outbreak locations.

METHODS OF ANALYSIS

Outbreaks

For each armyworm season, defined as the period from October to the following July, outbreaks were tabulated chronologically and by district, with information on date, location, instar (or head capsule width) of the caterpillars, size and density of the outbreak, host plant, damage assessment, caterpillar mortality and control.

For each outbreak the time of moth arrival and concentration preceding oviposition was then estimated, taking account of development rates. For all outbreaks above 1200 m altitude Page's regression of head capsule width (or instar) against number of days after moth arrival (Figure 5) was used. Below 1200 m, development rates were assumed to vary from 23 days on the coast to 30 days at 1000 m and 36 days at 1200 m (Table 4) (from Rose, 1975; Persson, 1981). *Gregarious* armyworm caterpillars are usually reported after they turn black in the fourth or fifth instar (Pedgley *et al.*, 1989) so when the caterpillar age was not reported, they were assumed to be in IV-VI instars. 'Moth arrival' is the term used to define the timing of outbreaks in the following account, unless otherwise stated, and is short-hand for moth arrival and concentration, either at the end of moth migration, or at the end of short post-emergence flights. The convention for using moth arrival is based on Pedgley *et al.*, 1989. The date of first oviposition can be obtained by adding three days to the moth arrival date.

Table 4 Estimated oviposition and emergence dates for *Spodoptera exempta* in eastern Africa

Altitude	1000 m			Coast		
	Days from oviposition	Instar	Days to emergence	Days from oviposition	Instar	Days to emergence
		Egg			**Egg**	
	3		27	2		20
		1			**1**	
	6		24	5		18
		2			**2**	
	8		22	6		16
		3			**3**	
	10		20	8		15
		4			**4**	
	12		18	9		13
		5			**5**	
	15		15	12		11
		6			**6**	
	20		10	16		7
		Pupa			**Pupa**	
	30		0	23		0
		Moth			**Moth**	

Source: Brown, 1962; Rose, 1975; Persson, 1981.

Trap catches

Pheromone and light traps were used to monitor moth influx. Light trap efficiency varies with moon phase and cloud cover, and there is a monthly cycle of catches due to the lunar effect (Bowden, 1973; 1982; Bowden and Church, 1973). Because of this variation only five-fold increases or more in nightly catch were taken to indicate moth influx. The same criterion was applied to catches from pheromone traps. A large increase in light-trap catch within an estimated moth arrival period was evidence of the arrival of parent moths. An increase in pheromone trap catch (which often occurred up to four days later) was evidence of, either synchronous mating by large numbers of moths, or that most females had mated so the trap was the dominant source of pheromone (Page, personal communication). Large increases outside estimated moth arrival periods indicated unreported outbreaks, moths emigrating or *in transit.* A long sequence of small catches suggested a persistent low density population.

Rainstorms

The association between rainstorms and moth concentration (Pedgley *et al.*, 1982; Tucker and Pedgley, 1983; and Pedgley *et al.*, 1989) was used to help refine estimated moth arrival dates in the following way. Days with heavy rain (defined as >10 mm) were plotted for rain gauges within 50 km of the outbreak site (e.g. Table 12). When rainstorms occurred at or near the outbreak site during the estimated moth arrival period, it was likely that parent moths were concentrated on these days. The distribution of rainstorms before and after the most likely moth arrival period was also examined. If rainstorm frequency was significantly different on many occasions in the moth arrival period from the preceding or subsequent periods, then potentially this difference could be used as an indicator of possible outbreaks in the absence of reports.

Trajectory analysis

Possible sources of outbreaks were estimated by backtracking, beginning on nights in the likely moth arrival period. This was done using daily surface windflow maps, assuming downwind movement at the daytime surface wind speed, for 10 hours a night, and for a period of one to four nights (Figure 6). As discussed by Tucker *et al.*, (1982) and Tucker (1984a), these daytime surface winds are representative of night winds at the height of moth migration (200-400 m above the ground, Riley *et al.*, 1983). Each trajectory segment was for a five-hour period and was drawn along the appropriate wind streamline for a distance determined by the wind speed.

The duration of moth flight depends on the length of the PRP and the flight capacity of the individual moths (Page, 1988; Parker and Gatehouse, 1985a,b). Under good conditions moths are unlikely to fly for more than two or three nights but under poor breeding conditions they may fly for longer.

Forward tracks were estimated in a similar way. They were ended after three nights or if they entered a zone of light variable winds, such as those associated with synoptic-scale convergence.

The use of backtracking and other techniques for studying insect migration is discussed by Pedgley (1982). The analyses were carried out from October to April in each season. After April overlapping generations made analysis difficult except where new outbreaks occurred in regions or countries previously reported clear, e.g. Ethiopia, usually in April or May.

Classification of outbreaks

Outbreaks were classified as primary or secondary. A primary outbreak originates from a low density population of moths where there is no previous outbreak. Early primary outbreaks occur from October to December and late ones from January to May. Secondary outbreaks occur as a result of a previous outbreak which may be primary or secondary.

Seasonal summaries

The distribution of primary and secondary outbreaks, and migratory interactions for the 16-year period covered by this report were mapped for each armyworm season. These maps, together with rainstorm analyses, formed the basis of summary descriptions for each armyworm season. The role of the weather as a factor in the development of each season was examined, and critical outbreaks identified. Frequencies of association between winds and moth migrations, and

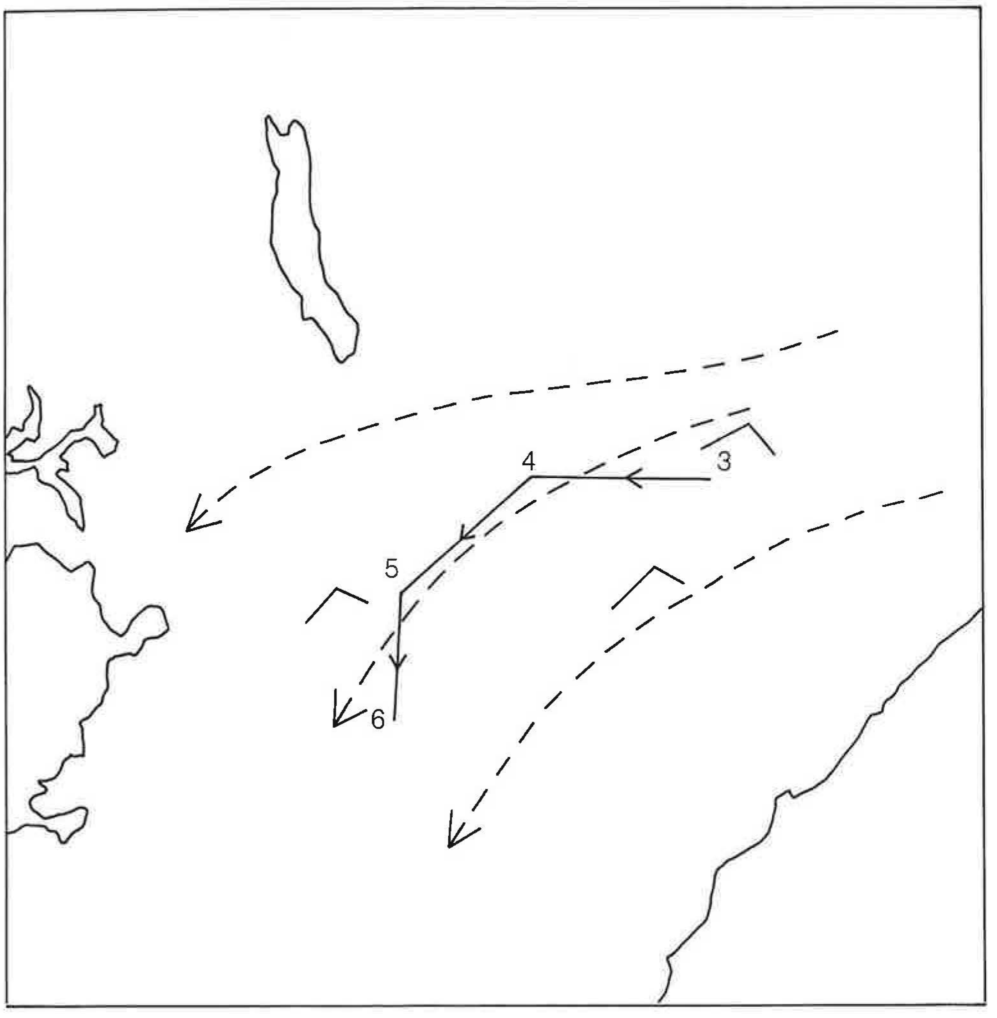

Figure 6 Construction of trajectories

Key: Trajectory is continuous line
Numbers are dates at 00 local time
Wind streamlines for 1500LT on 4th are dashed
Station wind arrows indicate wind speeds of 5m/s
Calculation of length of trajectory segment

Length of segment = wind speed × duration
Segment 4-5 = 5 m/s (18 km/hr) × 10 hr = 180 km

rainstorms and outbreak occurrence were examined, over all seasons, to see if the relationships were statistically significant. Seasons were compared to see if differences in severity were correlated with differences in rainfall.

Comparison of seasonal severity

The severity of armyworm seasons can be defined and assessed in several ways. The farmer and economist will be most interested in the crop loss attributable to armyworm, while the entomologist is more interested in the population size.

Armyworm reports give estimates of areas covered by outbreaks which vary in accuracy and reliability, e.g. where a qualitative estimate such as 'whole district infested' has been converted to a hectarage, such an estimate is likely to be inaccurate and the large area involved will bias seasonal totals.

Severity defined by the number of outbreaks, however, may give a bias towards many small outbreaks, perhaps of only a few hectares, compared with a few, large damaging outbreaks.

Neither of these measures of severity are satisfactory and it was decided to use the 'number of degree squares with outbreaks' as the measure. This gives a conservative estimate that does not vary in accuracy from season to season, even though it measures how widespread outbreaks are, rather than the total population size.

Section 3

Results

INTRODUCTION

In eastern Africa the timing and location of primary outbreaks were important factors in determining the differences between armyworm seasons. The number of seasons that had early primary outbreaks in each degree square are shown in Figure 7. The areas of most frequent occurrence are stippled, and are, in order of frequency, east-central, north-east and south-east Tanzania and east-central Kenya. These areas are referred to as primary outbreak areas. The arrows show the main early season moth migrations. Comparison with Figure 1 shows that they follow the dominant wind streamlines for November and December. Backtracks were from the direction of the coasts of south Somalia, Kenya and Tanzania, while forward tracks were towards central and western areas of Kenya and Tanzania.

The results of individual armyworm seasons were analysed and are presented in the Appendix, together with maps of primary and secondary outbreaks, likely migration paths and examples of trajectory and rainstorm analyses. These analyses were used to compare armyworm seasons from 1972-88.

COMPARISON BETWEEN ARMYWORM SEASONS

Seasonal summaries are useful for armyworm forecasting if the differences between seasons are understood. This section summarizes the main similarities and differences and relates them to windfield disturbances and rainfall on a daily and seasonal basis.

Seasonal severity

The number of degree squares with armyworm outbreaks in Kenya and Tanzania for each season in the period 1972-88 are shown in Table 5. Ethiopia, Somalia and Uganda were not included because data were incomplete. Seasons can be divided into three distinct classes based on the totals for Kenya and Tanzania together:

- severe (>33 degree squares)
- moderate (15-25)
- low (<6)

There were nine severe seasons (underlined in Table 5, column 1), four moderate seasons (1974-75, 1975-76, 1978-79 and 1980-81) and three low seasons (1972-73, 1977-78 and 1982-83).

When the degree squares with outbreaks are separated for Kenya and Tanzania (Table 5) it shows that seasons tended to be severe or low in Kenya and Tanzania, with five exceptions. 1973-74, 1980-81, 1984-85 and 1985-86 were much more severe in Kenya than Tanzania (when the smaller size of Kenya is taken into account) and 1986-87 was much more severe in Tanzania.

The very low seasons (1972-73, 1977-78 and 1982-83) were at five-year intervals suggesting a population cycle but this has not continued in recent years,

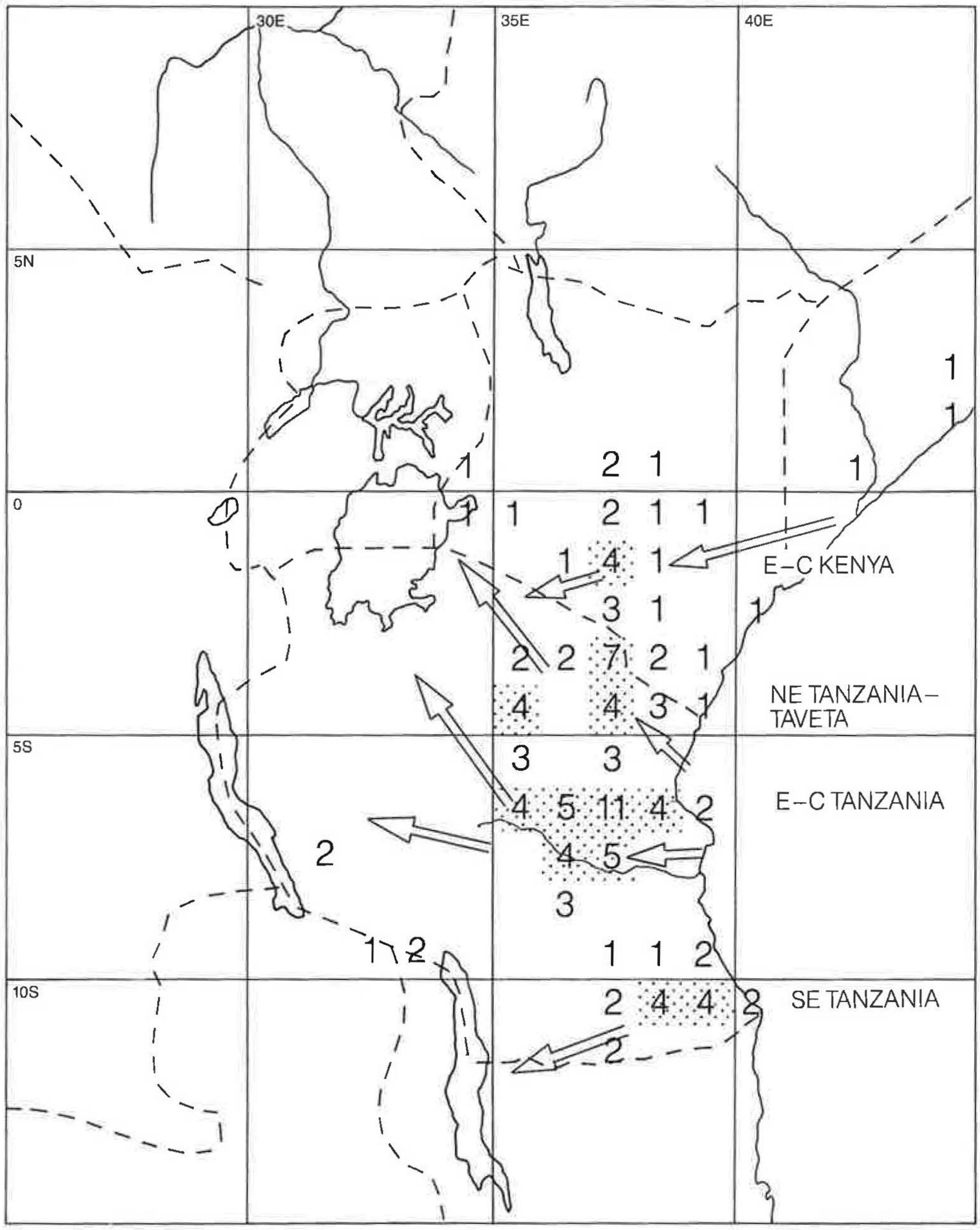

Figure 7 Frequency of early primary outbreaks 1972-88 by degree square and main early season moth migrations.

Key: Degree squares with >3 seasons with primary outbreaks are stippled.
Arrows show direction of main early moth migrations to and from primary outbreaks.

as 1987-88 was a severe season. Both 1977-78 and 1982-83 followed severe seasons but 1972-73 followed a season that was low in Kenya, but not in Tanzania.

Critical primary outbreaks

All seasons, except two very low ones, had primary outbreaks in one or more of the three main primary outbreak areas (see Figure 7 and Table 5). In Table 5 seasons are grouped by the country in which there were critical primary outbreaks and the regions in which these outbreaks occurred are listed in column 2. Critical primary outbreaks occurred in Tanzania in 10 seasons, most frequently in east-central Tanzania (seven seasons, especially Morogoro region), and north-east Tanzania (seven seasons, especially Kilimanjaro region). They occurred in Kenya in seven seasons, most frequently in east-central Kenya (six

Table 5 Seasonal severity in Kenya and Tanzania in relation to location and timing of critical primary outbreaks

Season†	Critical primary outbreaks (location and timing of moth arrival)	Rains associated with critical outbreaks	Seasonal severity: Number of degree squares with: Primary outbreaks		Secondary outbreaks	
			Kenya	Tanzania	Kenya	Tanzania
Seasons with critical primary outbreaks in Tanzania						
1973-74	E-C Tanzania (mid-late Dec)	Late start to rains (mid-Dec)	2	7	16	12
1974-75	NE Tanzania (late Dec)	Late start to rains (mid-Dec)	0	7	8	4
1975-76	E-C Tanzania (mid-Dec) NE Tanzania (Feb)	Late start to rains (mid-Dec) Isolated rainstorms (Feb)	1	3	9	13
1981-82	E-C Tanzania (Nov) NE Tanzania (Dec)	Isolated rainstorms end Oct, Nov Late start to rains (mid-Dec)	1	5	16	30
1986-87	E-C Tanzania (Oct-Nov) NE Tanzania (Nov)	Isolated rainstorms late Oct Main rains mid-Nov	1	14	9	24
1987-88	E-C Tanzania (Nov-Dec) NE Tanzania (Dec)	Isolated rainstorms late Nov	1	16	18	21
Seasons with critical primary outbreaks in Kenya						
1980-81	E-C Kenya (Oct)	Start of rains mid-late Oct (Kenya)	2	4	11	6
1984-85*	E-C Kenya (Oct)	Early start to rains in Kenya (early Oct)	6	5	13	22
1985-86	E-C Kenya (late Oct, mid-late Nov) SE Kenya (mid-late Nov)	Rains started late Oct	10	4	18	10
Seasons with critical primary outbreaks in Tanzania and Kenya						
1976-77	E-C Tanzania (mid-Nov) E-C Kenya (mid-Nov, Jan)	Isolated rainstorm late Nov (Tanzania) Kenya rains started mid-Nov Isolated rainstorm Jan	2	1	20	23
1978-79	NE Tanzania (Dec) E-C Kenya (mid-Dec)	Rains started mid-Nov	2	12	7	5
1979-80	NE Tanzania (Nov, Dec) E-C Kenya (Jan)	Isolated rainstorms mid-Nov Late start to rains (mid-Dec) Rainstorms in dry season (mid-Jan)	4	12	21	13
1983-84	E-C Tanzania (early Dec) Kenya coast (April, May)	Rains started early-mid Dec Long rains started April	6	9	13	17
Seasons with no critical outbreaks (<6 degree squares with outbreaks)						
1972-73	W Kenya (Dec) E-C Tanzania (May) NE Tanzania (May)	Rain started by mid-Oct Long rains started April	1	4	0	0
1977-78	W Kenya (Feb)	Persistent rains Oct-May	1	0	0	0
1982-83	SE Kenya (early Oct) E-C Tanzania (end Nov-early Dec)	Rains started mid-Sept, heavy to Dec	1	2	0	2

Notes: * 1984-85 armyworm data from Pedgley *et al.*, (1989)
† severe seasons (>33 degree squares with outbreaks) underlined

seasons). These included four seasons with critical primary outbreaks in both countries. When critical primaries occurred in north-east Tanzania, they also occurred in either east-central Tanzania or east-central Kenya.

Although critical primary outbreaks, by definition, led to many secondaries, they did not necessarily lead to an overall severe season. Six out of seven seasons with critical primaries in east-central Tanzania were severe, as were four out of seven with critical primaries in north-east Tanzania and four out of six seasons with critical primaries in east-central Kenya. Critical primary outbreaks occurred from October to December except for one in east-central Kenya in January 1980 and those on the Kenya coast in April, May 1984.

Long-distance moth migration

Long-distance moth migration occurs over a distance of more than 100 km. It is the most important factor in changing the distribution of outbreaks during a season. Table 6 shows long-distance downwind migrations, deduced from trajectory analyses, together with the months and number of seasons in which they occurred, and the winds associated with the migrations.

From November to March long-distance migrations occurred on the dominant easterly winds. These were easterly to north-easterly in Kenya but easterly to south-easterly in Tanzania (Table 6). Migrations out of the primary outbreak areas in east-central Tanzania, north-east Tanzania and east-central Kenya towards the east or north-east were particularly important when they were followed by further west or north-westerly movement in the next generation. These migrations often led to outbreaks in cultivated areas near Lake Victoria in north-west Tanzania, west Kenya and south Uganda. Migrations in east-central and central Kenya were relatively short-distance (<100 km), so the frequency of long-distance migration was lower than in other primary outbreak areas.

Migration from outbreaks in southern Somalia was likely to have been the cause of the first outbreaks of the season in east-central Kenya in December 1978. In November to December of 1980 and 1985, similar migrations may have added to armyworm outbreaks already present in east-central Kenya.

A windfield disturbance, leading to an unusual armyworm migration, occurred in south Tanzania in December to January 1976-77, when westerly winds brought moths from Malawi to south-east Tanzania (Figure 15, page 40).

A migration from Kenya to Burundi in 1984-85, deduced from armyworm rather than wind data (Pedgley *et al.*, 1989), probably occurred on unusually strong east to north-east winds that extended across Lake Victoria above the lake/land breeze circulation. The very large source population could have resulted in enough moths surviving the long migration to form an outbreak.

Migration from north-east Tanzania to east-central Kenya occurred in March 1982 and 1988 associated with disturbances that brought rainstorms to Kenya together with southerly (1982) or south-westerly (1988) winds (Figure 30, page 68).

In April and May the dominant winds shift to south-easterly or southerly (Figure 1, page 4), and long distance migration often occurs towards the north. In eight seasons migration north from northern Tanzania, east-central Kenya or the Kenya coast covered from 800-1000 km and led to outbreaks in south Ethiopia. The onset of the low-level southerly jet stream (see page 3) made these migrations possible when the moths flew at heights of several hundred metres above the ground.

Outbreaks and rainstorms

The individual outbreaks were analysed in relation to the daily distribution of rainstorms, measured within 50 km of the outbreak site to provide a comparison of outbreak occurrence and rainstorm distribution over many seasons. Daily

Table 6 Long-distance moth migrations between outbreaks

Months	Seasons	Migration	Aprox. distance (km)	Associated winds
Nov-Dec	1978-79 1980-81 1985-86	S Somalia to E-C Kenya	600	Strong easterlies to north-easterlies
Nov-Dec	1976-77	E-C Kenya to NE Tanzania	150	Temporary northerlies
Nov-Dec	1984-85	E-C Kenya to Burundi	770	Strong north-easterlies
Nov-Feb	1978-79 1979-80 1980-81 1984-85	E-C Kenya to C Kenya	150	Easterlies to north easterlies
Nov-Feb	1976-77 1979-80 1980-81 1984-85 1985-86 1986-87	Kenya to W Kenya/ N Tanzania	300	Easterlies
Nov-Feb	1973-74 1975-76 1976-77 1981-82 1984-85 1986-87 1987-88	E-C Tanzania to C Tanzania	450	Easterlies to south-easterlies
January	1976-77	Malawi to SE Tanzania	600	Temporary westerlies
Jan-Mar	1973-74 1975-76 1976-77 1979-80 1981-82 1986-87 1987-88	C Tanzania to N Tanzania/Uganda	650	South-easterlies
Jan-Mar	1975-76 1976-77 1978-79 1979-80 1981-82 1986-87 1987-88	NE Tanzania to N Tanzania/W Kenya	450	South-easterlies
Mar-May	1981-82 1987-88 1973-74 1974-75	NE Tanzania/SE Kenya to E-C Kenya	250	Temporary southerlies in March Southerlies in April-May
Apr-May	1973-74 1974-75 1975-76 1976-77 1979-80 1987-88	E-C Kenya/NE Tanzania to S Ethiopia	800	Strong southerlies
Apr-May	1981-82 1987-88	S Kenya coast to N Kenya coast/S Somalia	450	Southerlies to south-westerlies
Apr-May	1976-77 1981-82 1983-84 1987-88	Kenya coast to N Kenya/S Ethiopia	950	Strong southerlies

rainfall data were available for a total of 160 outbreaks (over all seasons). The likelihood of rainstorms occurring at or near the outbreaks during an 11-day moth arrival period (estimated from armyworm data) was compared with the likelihood of rainstorms in the previous and subsequent 11-day periods. A high likelihood of a rainstorm was defined as: at least one day with >10 mm rain at a gauge within approximately 10 km of the outbreak site, or daily totals of >10 mm rain recorded from at least half the rain gauges within 50 km of the outbreak site.

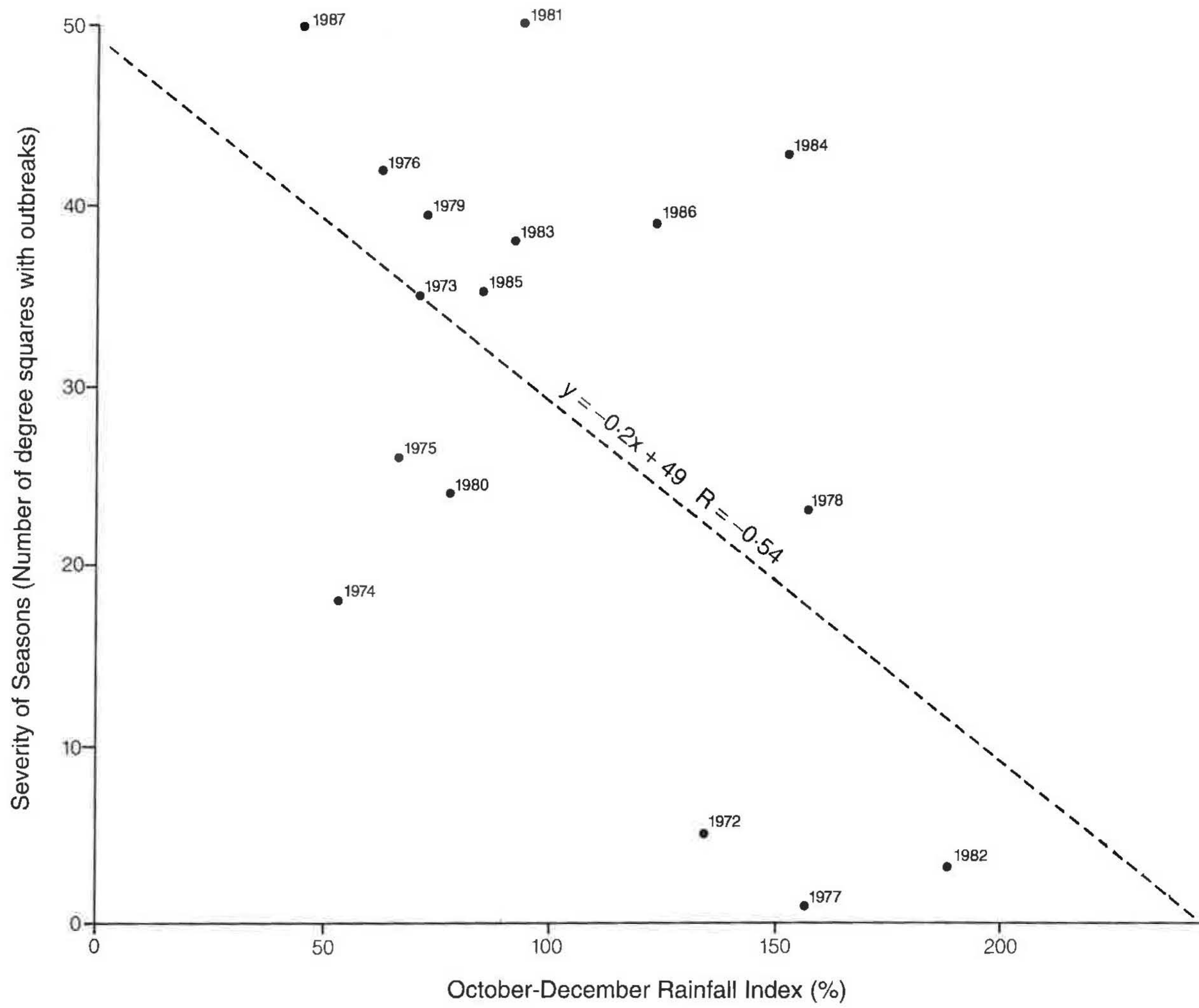

Figure 8 Severity of armyworm season compared with October-December rainfall index

When rainstorms were less frequent or absent the likelihood was considered moderate or low.

Eighty percentage of the 160 outbreaks had a high likelihood of rainstorms at or near the site during the estimated moth arrival period, compared with 34% and 47% for the previous and subsequent 11-day periods respectively. The lower percentage preceding the moth arrival period partly reflects the frequent occurrence of outbreaks at the beginning of the short or long rains, and may be associated with isolated rainstorms preceding these rains.

Seasons with many outbreaks often had rainstorms separated by dry periods of about 10-14 days, in the rainy seasons. This was true for seasons with heavy short rains (e.g. 1984-85) and light short rains (e.g. 1987-88). Associated outbreaks were also preceded and followed by dry periods.

Seasonal severity and early season rainfall totals

An index of October to December rainfall was calculated, using data from 10 synoptic stations in Kenya and 12 in Tanzania (Table 1). This was designed to detect any association between seasonal severity and early rainfall. The October to December total for each station was expressed as a percentage of the mean total, taken from climatological tables (East African Meterological Department 1975, Kenya Meterological Department 1984). The mean percentages for all stations in Kenya and Tanzania were calculated to give an overall rainfall index.

A regression of the October to December rainfall index against number of degree squares with outbreaks, for all seasons, was calculated (Figure 8). There was a significant ($P<0.05$) inverse linear relationship ($R = -0.54$), but this depended strongly on the three very low armyworm seasons (1972-73, 1977-78 and 1982-83), which all had very high October to December rainfall indices (>130%). Three other seasons had October to December rainfall indices of >120%, two of which (1984-85 and 1985-86) were severe and one (1978-79) was moderate. Two seasons had very low October to December rainfall; 1987-88 was very severe and 1974-75 was moderate. In most seasons rainfall was within about 30% of the mean and, in this range, there was no clear inverse correlation between rainfall and seasonal outbreak severity. Seasonal severity ranged from 23-50 degree squares with outbreaks, for this narrow range of total rainfall.

Seasonal relationships between rainfall and armyworm outbreak occurrence may have been masked by considering Kenya and Tanzania together. East-central Kenya had six seasons with early primary outbreaks and 10 without. The possibility that early season rainfall totals were different for these two sets of seasons was investigated. Rainfall totals for October-December from Nairobi (J K International airport) and Makindu synoptic stations were used because data were available for the 16-year period. The rainfall totals for Makindu were positively skewed, so the non-parametric Mann-Whitney test was used. Seasons were ranked by rainfall total and seasons with and without early primary outbreaks were compared. Taking all seasons together, there was no significant difference in rainfall; but when the three very low seasons (1972-73, 1977-78 and 1982-83) were removed, the seasons with early primary outbreaks were significantly wetter at Nairobi ($P<0.05$) than those without. No difference was apparent for the Makindu data. Rainfall data for Machakos for 1980-87, although not adequate for a statistical test, showed the same trend as Nairobi. These results suggest, tentatively, that early primary outbreaks occur in east-central Kenya with moderate October to December rainfall, but that both widespread, heavy rains and very low rains led to an absence of primary outbreaks.

SUMMARY OF RESULTS

- First reported armyworm outbreaks in Kenya and Tanzania from October to December were usually primary i.e. derived from low density populations, and only rarely came from moths migrating from outbreaks in Somalia or Malawi. Most outbreaks later in the season were secondary.
- In seven seasons early primary outbreaks occurred in east-central Kenya. Six of these were critical leading to many secondary outbreaks in central or west Kenya from November to January.
- In nine seasons early primary outbreaks occurred in the north-east Tanzania-Taveta, Kenya area. These were critical in seven seasons, leading to outbreaks in west Kenya and north Tanzania in January or February. In three seasons populations persisted in north-east Tanzania until March or April, when migration north to central Kenya resulted in many late season outbreaks.
- In thirteen seasons there were early primary outbreaks in the Morogoro area of east-central Tanzania. Seven of these were critical leading to extensive secondary outbreaks in central and north-central Tanzania, and sometimes in Uganda.
- Location and control of outbreaks in these critical primary outbreak areas at the beginning of the season should reduce the incidence of secondary outbreaks.
- Early primary outbreaks occurred in south-east Tanzania in nine seasons but, although they were sometimes severe, they did not lead to secondary outbreaks elsewhere in Tanzania, so were not critical.

- Outbreaks east of the Kenya highlands, on the Kenya coast, or in north-east Tanzania in April or May provided a source for migration north to south Ethiopia, on strong southerly winds.
- Trajectories showed that moth migration between outbreaks occurred on winds close to the seasonally dominant windflow i.e. west (or north-west in north Tanzania) from October to March; and north-west or north (especially in east Kenya) from April to July.
- Large-scale windfield disturbances occasionally affected moth movements. Westerly incursions limited spread west and in one season brought moths from Malawi to south Tanzania.
- Outbreaks, especially early primaries, were usually associated with rainstorms often preceded, and followed, by dry periods.
- The three seasons with very low populations all had heavy October to December rainfall which caused high larval mortality.

Section 4

Discussion

LOW DENSITY ARMYWORM POPULATIONS

The role of low density armyworm populations during the season has not been considered in the Results because of lack of data, but needs to be discussed.

The results indicated that moths causing early primary outbreaks came from low-density armyworm populations near the coasts of Kenya and Tanzania, where grass may remain green during the dry season. There was no evidence for moths migrating south to Kenya, as would be expected if early season outbreaks came from previous outbreak populations. These results support previous work by Rose (1979); Rose *et al.*, (1987) and Tucker (1984a).

Low-density armyworm populations are likely to be present in source areas throughout the year, but the proportion of the population that remains at low density is not known. Strategic control of critical outbreaks, aimed at preventing outbreaks in the next generation, would not be successful if large sources of low density armyworm persisted during the season. The occasional occurrence of large primary outbreaks on the coast between November and May, suggests that low density populations persist there during the season.

Gatehouse (1986; 1987) suggested that such populations would not remain at low density if they migrated inland, because they would encounter a patchy habitat where successful breeding would depend on the moths being concentrated by rainstorms, when outbreaks would form. Occasional primary outbreaks in the west of Tanzania and Kenya indicate that low-density populations may persist in these areas, because of widespread rains, which help low-density survival but are generally unsuitable for primary outbreak formation. Low-density populations also persist in south-east Ethiopia, which then becomes a source area, but where primary outbreaks may also occur.

In seasons when early rains were heavy and widespread (1972-73, 1977-78 and 1982-83), armyworm remained at low density and any outbreaks that did occur, as in 1982-83, suffered high mortality from excessive rain. In moderate or severe seasons light and pheromone trap catches showed strong peaks associated with moth emergence and migration from outbreaks. Few moths were caught between generations and this supports the hypothesis that most armyworm live in outbreaks, not in low density populations.

After the beginning of the season, outbreaks were often backtracked to earlier ones, supporting the hypothesis that most armyworm populations occur in outbreaks. This justifies the use of forward tracks from outbreak moth emergence, to areas where wind convergence may result in further outbreaks, as a method of forecasting armyworm occurrence.

ARMYWORM OUTBREAKS AND SEASONAL RAINFALL

The results of this study suggest that the inverse relationship between early season rainfall and numbers of armyworm outbreaks found by Tucker (1984b), was due to a few very low armyworm seasons associated with very heavy early rains.

The analysis of seasonal rainfall for east-central Kenya, indicated that moderate early rains, with rainstorms separated by dry periods, were most often associated with primary outbreaks. These results are consistent with the hypothesis that armyworm outbreaks occur in association with rainstorms, followed by dry periods that allow high rates of larval survival. Seasonal armyworm forecasts must consider both total early season rainfall and the distribution of rainfall on a daily basis.

ARMYWORM OUTBREAKS AND RAINSTORMS

The positive association between armyworm outbreaks and isolated rainstorms, especially at night, at the beginning of the season, is used in forecasting to locate early primary outbreaks in areas where they are likely to be critical. Rainstorm data must be available within a week of occurrence if they are to be used to forecast damaging armyworm outbreaks. Rain gauge data are patchy and not available quickly, but satellite data can be obtained almost immediately using a ground receiving station. At DLCO-EA, Nairobi, satellite data are received at a primary Meteosat Data User Station. Infra-red imagery is used to identify large convective clouds. Each night a cold-cloud duration map is constructed automatically showing where rainstorms occurred during the night to a precision of approximately four kilometres, for the whole of eastern Africa. The success of this method in monitoring rainstorms and predicting the likelihood of armyworm outbreaks is being assessed. It should prove useful in forecasting critical primary outbreaks which must be located for strategic control.

The areas where critical primary outbreaks are most likely to occur cover about 10 degree squares in Kenya and Tanzania. This is a large area to monitor either by trapping or ground surveys. Information on the location and timing of rainstorms likely to be associated with armyworm outbreaks within these areas should considerably reduce the cost of ground surveys.

Section 5

Conclusions

Analysis of 16 African armyworm seasons has provided substantial evidence to support the classification of infestations into primary and secondary outbreaks. In addition, it supports the theory that the development of armyworm seasons starts from low-density populations and continues through a sequence of outbreaks linked by downwind moth migration. Implicit support is given to the concept of regional strategic control, although this has not been assessed directly. Further evidence has been provided to support the use of rainfall analyses for armyworm forecasting both seasonally and over short periods of a few weeks.

The seasonal summaries will be a useful source of analysed data, which can be compared with current seasons in eastern Africa. These analyses are currently being used in work at the Natural Resources Institute (NRI) to help test the economic viability of strategic control. The techniques used in the analyses of African armyworm epidemiology and associated weather, will be applicable elsewhere in Africa where *S. exempta* is a major pest.

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Appendices

APPENDIX 1

Seasonal summaries

Armyworm seasons are summarized in maps marked in degree squares for each season. Primary and secondary outbreaks, are recorded by the month in which the first outbreak occurred. Later outbreaks in that degree square are not shown, for reasons of clarity. Moth migrations between outbreaks are depicted with solid arrows where they are indicated by trajectory analysis, and by broken arrows where the data were inadequate for such analyses and the results were uncertain. The seasons were divided into three distinct classes:

- severe (>33 degree squares)
- moderate (15-25 degree squares)
- low (<6 degree squares)

as defined on page 15.

The text summarizes the occurrence of primary and secondary outbreaks for each season and the associated rainfall, windfields and deduced moth migrations. Tables 12 and 13 in Appendix 2 give examples of the distribution of rainstorms in relation to particular outbreaks. Examples are given of particular moth trajectories and windfields. The aim is to facilitate the direct comparison of armyworm seasons and to highlight some of the main features of each season. This appendix may also give guidance to the armyworm forecaster in the analysis of current armyworm seasons.

1972-73

Brief summary

A low armyworm season, with only one early outbreak and heavy early rains. There were unusual late season armyworm outbreaks in east-central and north-east Tanzania (Figure 9).

Primary outbreaks

There were no early outbreaks in the main primary outbreak areas, but there was a single primary outbreak (of 60 ha) near Kisumu (west Kenya) in December.

In areas where early season outbreaks usually occur (Kenya south of the equator and eastern and central Tanzania) rainfall was well above average in October and November (Table 7). In December it was above average in most of

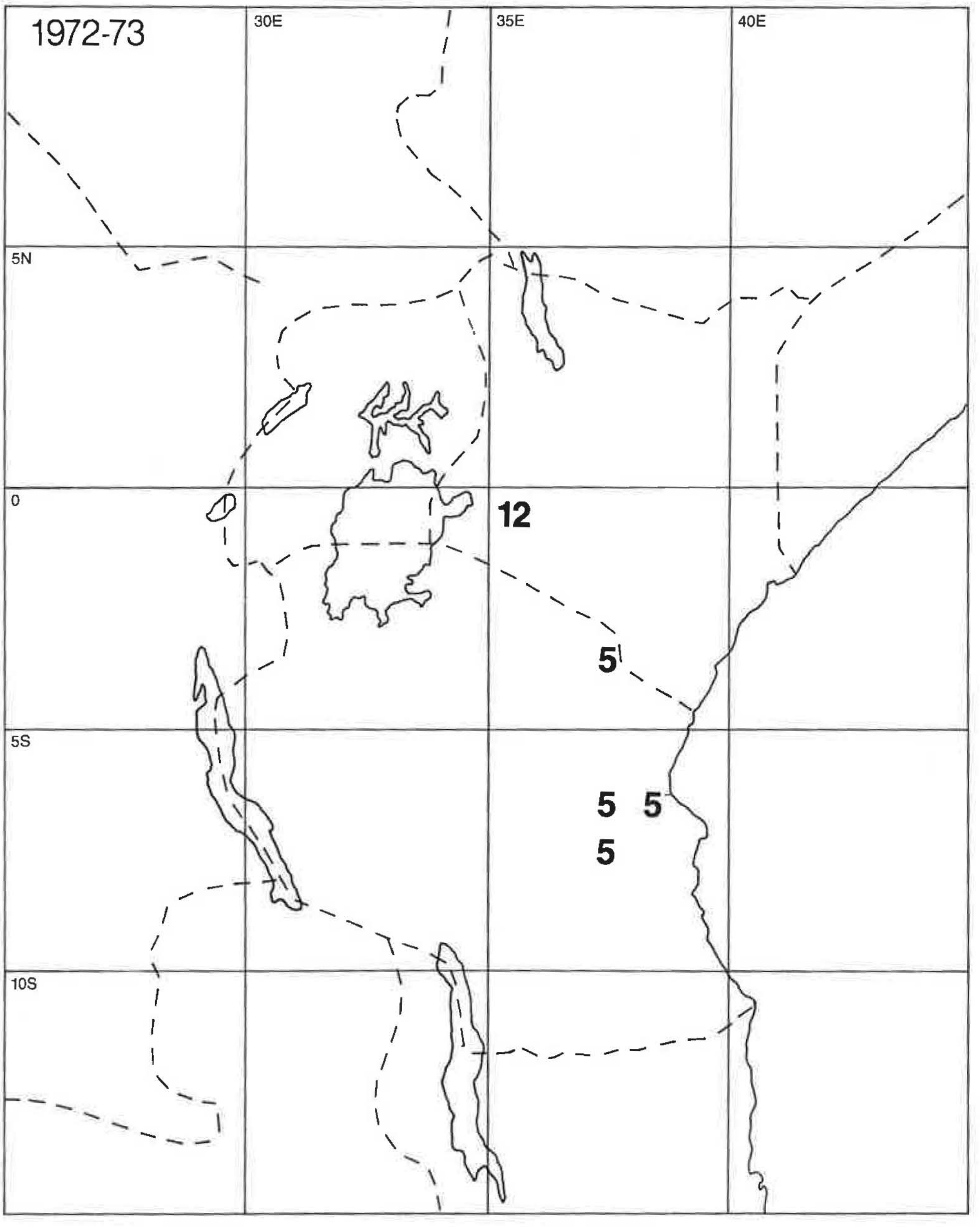

Figure 9 Summary map for 1972-73 season showing primary outbreaks

Key: Figure = month in which outbreak occurred
Bold figure = primary outbreak

Table 7 Monthly rainfall October-December 1972

	October			November			December		
	Monthly mean (mm)	1972 % of mean	1972 Rain days	Monthly mean (mm)	1972 % of mean	1972 Rain days	Monthly mean (mm)	1972 % of mean	1972 Rain days
Kenya									
Mombasa	96	341	11	95	88	9	70	80	6
Voi	26	42	5	106	202	11	119	97	9
Makindu	28	11	3	172	137	10	115	65	6
Machakos	52	331	11	193	81	12	122	49	8
Nairobi	38	426	9	134	72	10	74	34	7
Kisumu	75	203	14	120	188	17	100	62	6
Tanzania									
Arusha	25	44	3	139	143	13	98	52	7
Same	30	140	5	53	228	12	67	72	7
Dar es Salaam	60	220	11	122	144	11	108	125	7
Morogoro	29	286	7	61	116	8	78	137	6
Kilosa	33	303	4	96	238	8	139	99	5
Dodoma	4	350	1	20	195	4	107	191	5
Mtwara	21	119	6	53	70	5	192	166	16
Nachingwea	7	14	0	70	127	6	126	133	11

Tanzania except the north but not in Kenya. However nearly all the Kenyan stations had 10 or more rain days in November and these frequent rains may have caused poor larval survival.

Armyworm at low density were present from December 1972 to February 1973 judging by moth catches at Muguga and the National Agricultural Laboratories, Nairobi, in Kenya and at Tengeru, Arusha TPRI and Ilonga, in Tanzania. Following very low catches in March and April, catches increased at Tengeru, Ilonga and Morogoro on 8 May and these were associated with outbreaks near Moshi (north-east Tanzania), Ilonga, Morogoro (east-central Tanzania) and Kisarawe (near Dar es Salaam) in May. These unusually late Tanzanian outbreaks may have been caused by local build-up or moth migration on southerly winds. Although no outbreak sources were known in southern Tanzania, an increase in trap catches at Mbeya (south-west Tanzania) from 27 April shows that armyworm were present there.

Secondary outbreaks

None occurred this season.

1973-74

Brief summary

A moderate season, starting late in Tanzania with migrations from central Tanzania to Uganda in March, and north Tanzania to east-central Kenya and south Ethiopia in May (Figure 10). In Kenya and Ethiopia outbreaks were most severe in May-June, but there were also widespread outbreaks in south-east Tanzania at the beginning of the season. Rains starting late in December, in Tanzania, and a dry spell in May during the long rains in Kenya, helped armyworm survival and contributed to large outbreaks.

Primary outbreaks

The first outbreaks occurred in Kilwa, Lindi and Nachingwea districts (south-east Tanzania) and near Dar es Salaam (central Tanzanian coast) in mid-late December. The south-east Tanzanian outbreaks were large, although the reported total area of >600 000 ha was probably an exaggeration. Outbreak sources were probably local, low density populations, because the winds were onshore easterlies with a brief incursion of westerly winds confined to south-west Tanzania.

Four outbreaks in Morogoro region (east-central Tanzania, about 400 ha) and one on Mafia Island (central Tanzanian coast, 1000 ha) in early January were probably also primary, because those in the Morogoro region were too early to be derived from the December coast primary, and the latter was south-east of that outbreak, while winds were towards the west.

Rainfall was below average in east Tanzania in October and November. December outbreaks were associated with isolated rainstorms in the middle of the month, and moths leading to early January outbreaks were probably concentrated by widespread rainstorms in the Morogoro region on 14 January (Table 12, Appendix 2).

Late primary outbreaks (about 300 ha) occurred in south Nyanza (west Kenya) in mid-February, associated with isolated rainstorms, and at Meru (east-central Kenya, about 25 ha) in March, associated with the beginning of the long rains on 19 March. Backtracks from south Nyanza came from north Tanzania, and those from Meru from east Kenya. There were no known earlier outbreaks in either source area.

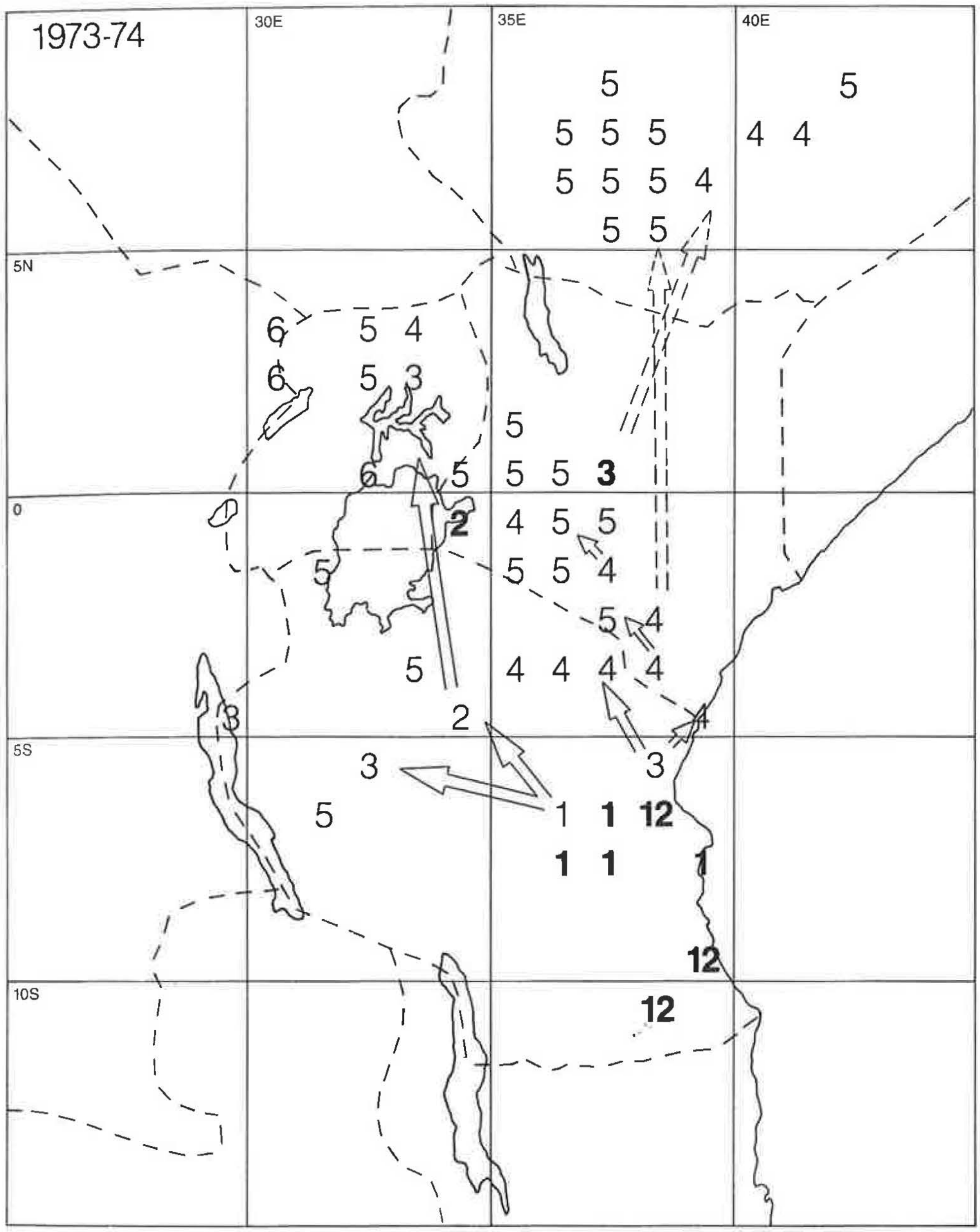

Figure 10 Summary map for 1973-74 season showing primary and secondary outbreaks

Key: Figure = month in which outbreak occurred
Bold figure = primary outbreak
Roman figure = secondary outbreak
Arrows show likely migration between outbreaks (See Seasonal Summaries, Page 29)

Secondary outbreaks

An outbreak at Mpwapwa (east-central Tanzania) in late January probably originated from moths flying west from the Dar es Salaam primary. Outbreaks in Singida and Morogoro regions in February came from moths migrating north-west from Morogoro (Figure 10). Subsequent migrations west from east-central Tanzania gave rise to a small outbreak at Tabora, and southerly winds on 21-22 March near the coast may have taken moths to the Tanga region where there were two outbreaks with moth arrival in late March.

From the Singida outbreaks, trajectories indicated migration north across Lake Victoria to Uganda, with high moth catches near Mwanza accompanied by strong south-easterly winds across the lake. Widespread outbreaks (>3000 ha) in Uganda in mid-March probably originated from this migration. On a few days south-easterly winds may have brought moths from the February primary outbreaks in west Kenya. Further outbreaks in north Uganda from April-June were derived from these March outbreaks.

In April there were many outbreaks (total area >8000 ha) in the Arusha and Kilimanjaro regions (north-east Tanzania) and Taita-Taveta and Kwale districts (south-east Kenya). Winds indicated that parent moths may have come from Tanga outbreaks.

These outbreaks were sources for moths invading east-central Kenya in mid-May on southerly winds. Their arrival was marked by high moth catches in the Nairobi area from 9-30 May. At this time there were approximately 75 outbreaks in east-central Kenya covering an area of about 50 000 ha, and other outbreaks in north-west Kenya including one of 145 000 ha.

Large, severe outbreaks occurred in south Ethiopia in late April and May. Strong southerly winds could have brought moths from outbreaks at Meru from 20-30 April and from Taveta or Kilimanjaro in early and mid-May.

There was good armyworm survival in central Kenya in May, associated with below average rainfall. This lead to further outbreaks in central and west Kenya in June. High moth catches persisted into July even though there were no further outbreaks.

1974-75

Brief summary

A moderate season starting in late December in south-east and east-central Tanzania. Moths migrated north from north-east Tanzania to east-central Kenya and possibly south Ethiopia (Figure 11). Outbreaks remained in Kenya until June or July associated with persistent long rains. There were no reported outbreaks in central and west Tanzania, west Kenya or Uganda, possibly due to dry weather in late January and February in central Tanzania, and successful control measures of the primary outbreaks in Morogoro region.

Primary outbreaks

Primary outbreaks occurred in Mtwara and Lindi regions (south-east Tanzania), in Morogoro region (east-central Tanzania) and south of Handeni (north-east Tanzania) in late December, associated with a late start to the rains. Outbreaks totalled 2500 ha in south-east Tanzania and approximately the same in east-central Tanzania. They were severe in places and control was carried out.

Secondary outbreaks

No secondary outbreaks resulted from south-east or east-central Tanzania, probably because of very dry weather when the moths emerged in late January, but possibly because the control measures were successful. Outbreaks were recorded in Kilimanjaro district (north-east Tanzania) and Taita-Taveta (south-east Kenya) in February, most likely derived from moths migrating on south-east winds from the Handeni outbreak. Further outbreaks near Karatu (Arusha region) occurred in March, and in Kilimanjaro region in April, probably derived from the February, Kilimanjaro outbreaks. As in 1974 these late outbreaks in north-east Tanzania were followed by moth migration to the north resulting in outbreaks in Kajiado, Machakos, Nairobi and Nakuru districts of central Kenya in May, and possibly at Neghele in south Ethiopia at the end of April. The migration into central Kenya was recorded by large increases in catches at the Muguga light trap, associated with rainstorms from 11-16 May, and winds shifting from a north-easterly to south-easterly direction on 12 May. Moths were caught earlier at Muguga, in mid-April, possibly coming up the Rift valley from Karatu, on local southerly winds, but there were no outbreaks.

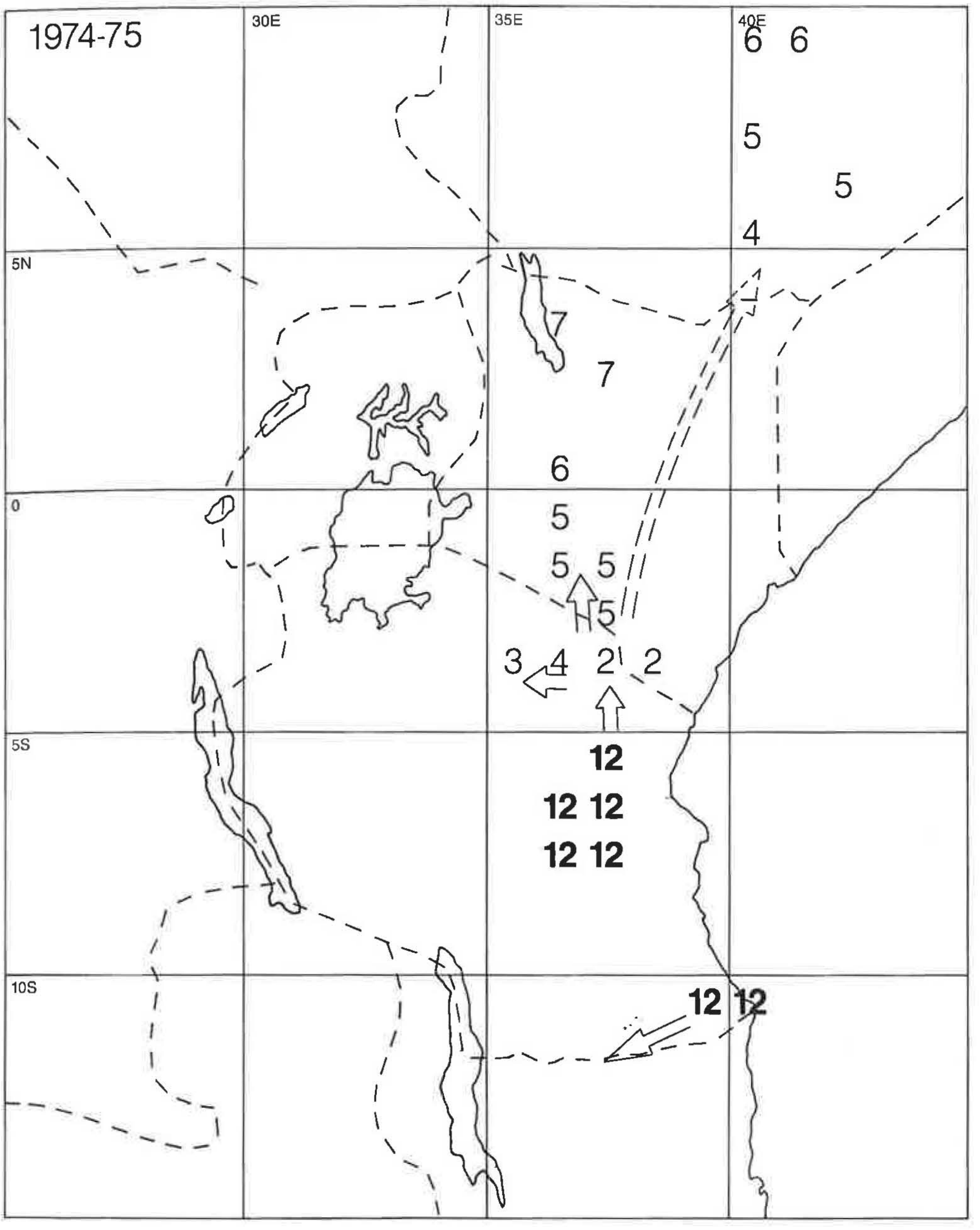

Figure 11 Summary map for 1974-75 season showing primary and secondary outbreaks

Key: See Figure 10

The May outbreaks in Kenya were on wild and ornamental grasses rather than crops, but some were large (6400 ha in Nakuru district and 2200 ha in Machakos district). Moths emerging from these outbreaks flew north to give rise to even larger outbreaks in the Samburu district in June. Above average rains in June and July were associated with persistent high moth catches at Muguga light trap until mid-July, and exceptionally late outbreaks in north Kenya in July. The presence of south-westerly winds suggest that further outbreaks in east Ethiopia in June may have been derived from outbreaks at Neghele.

1975-76

Brief summary

The season was of moderate severity and was associated with below average October to December rains in both Kenya and Tanzania. In Tanzania the rains started late in mid-December. Primary outbreaks were also late, and few in number, but gave rise to widespread secondaries in central Tanzania and Uganda (Figure 12). The largest number of reported outbreaks was in west Kenya where they may have originated from unreported outbreaks in north-east Tanzania. Large outbreaks in east-central Kenya in March and April may have originated from Taveta and were associated with isolated rainstorms. Two outbreaks in May in south Ethiopia could have originated from these outbreaks but the sources of two outbreaks in central Ethiopia in April are unknown.

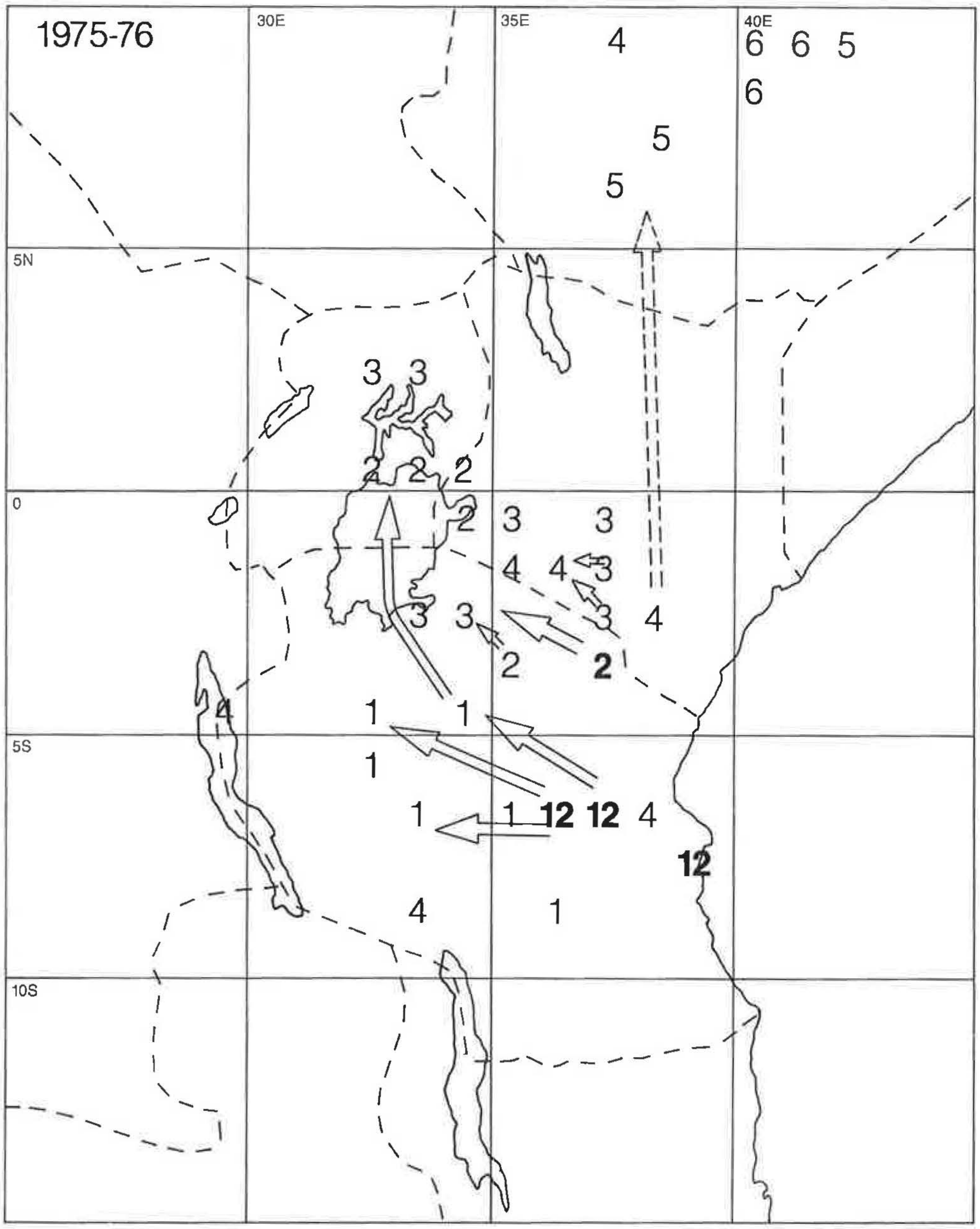

Figure 12 Summary map for 1975-76 season showing primary and secondary outbreaks

Key: See Figure 10

Primary outbreaks

Primary outbreaks occurred over approximately 320 ha in Kilosa district (east-central Tanzania) in mid-December associated with the beginning of the rains and following two dry weeks; and on the Tanzania coast, south of Dar es Salaam, in late December, about a month after the first rainstorms.

In north-east Tanzania, moth catches at Tengeru light trap, near Arusha, increased in late-December and early-January associated with isolated rainstorms. No outbreaks were reported until February, when there was a small outbreak in Kilimanjaro region and a larger one (260 ha) in the adjacent Taveta district of south-east Kenya. These appeared to be primary, but may have been derived from unreported outbreaks in the same areas associated with moth catches and isolated rainstorms in January.

Secondary outbreaks

In mid-January, outbreaks occurred in the Dodoma, Tabora and Singida regions of central Tanzania, downwind of the December primaries. The outbreaks were largest in Singida region (about 2000 ha), and forward tracks (Figure 13) together

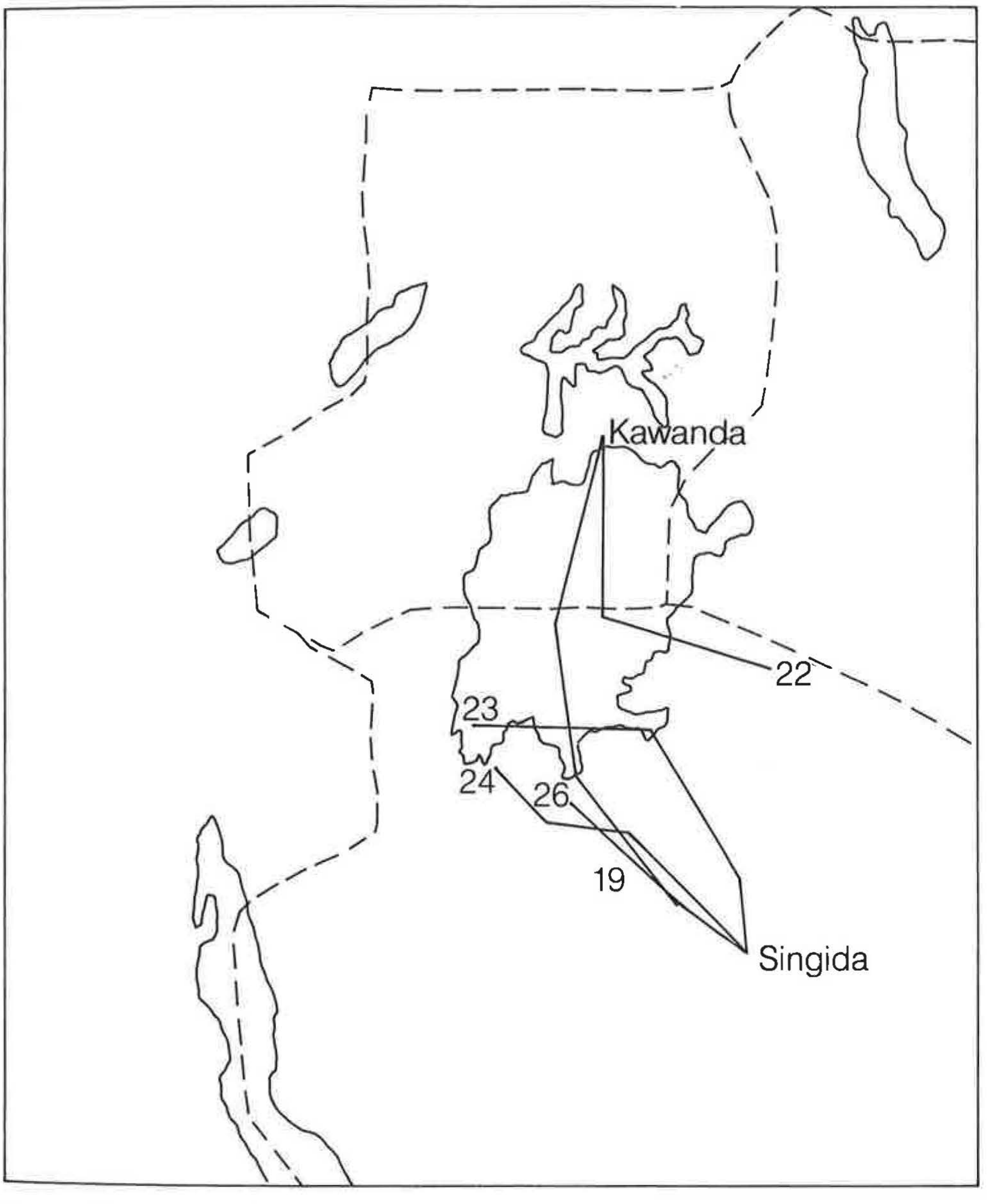

Figure 13 Backtracks from Kawanda and forward tracks from Singida 18-24 February 1976

with a high trap catch at Ukiriguru (south of Lake Victoria) on 25 February, suggest that the Singida outbreaks were the sources of the outbreaks near Kawanda (central Uganda) in late February.

Scattered outbreaks over a very large area (50 000 ha) at Karatu, west of Arusha, in early February may have originated in east-central Tanzania, but it is more likely that unreported outbreaks in north-east Tanzania were the source. Backtracks indicated that outbreaks in west Kenya in February (over about 3000 ha), may have come from the same source. These Kenya outbreaks gave rise to many large outbreaks in the same areas of west Kenya in March (over about 30 000 ha).

Further east, outbreaks in Machakos district of east-central Kenya in late March were associated with large increases in moth catch in the Nairobi area (at Jacaranda, NAL and Muguga light traps) and isolated rainstorms. These were probably derived from moths migrating on south-easterly winds from Taveta.

Large outbreaks, in total area approximately 40 000 ha, occurred in Machakos and Kitui districts in late April. These were derived from the late March outbreaks and were associated with isolated rainstorms. Widespread rainstorms in early April were not associated with outbreaks because moths had not emerged from late March outbreaks. Moths emerging in May could have migrated north on strong southerly winds, and been the source of outbreaks in south Ethiopia (Figure 12). The late outbreak at Athi River (near Nairobi) in June came from local outbreaks, which were the only known sources.

1976-77

Brief summary

This severe season was associated with the late start to the rains in Tanzania. Armyworm outbreaks spread across Tanzania to Uganda from December to February following a single primary in November (Figure 14). It is probable that the large outbreaks in south-east Tanzania in January resulted from the unusual, large-scale moth migration from Malawi. An initial primary outbreak in east-central Kenya in November was followed by a sequence of outbreaks in Kenya, through the dry season to March. These resulted in widespread outbreaks during the long rains, and subsequent migration to Ethiopia.

Primary outbreaks

In November a primary outbreak occurred in Kilosa district (east-central Tanzania) possibly associated with an isolated rainstorm on 25 November in a dry month. In Kajiado district (east-central Kenya) a primary outbreak on pasture was associated with the beginning of the short rains on 20 November.

There was a late primary outbreak at Nyeri (east-central Kenya) in January, associated with a rainstorm and a large increase in moth catch at Mwea Tebere light trap on 14 January. Moderate trap catches in mid-December indicated that a low density population was present the previous month. Backtracks were from the east or north-east while the only known earlier outbreak was in Kajiado, to the south.

Secondary outbreaks

Some of the moths emerging from the Kajiado primary outbreak at the end of December or beginning of January migrated south on northerly winds (Figure 15), giving rise to outbreaks that were reported west of Kilimanjaro in north-east Tanzania. Other moths gave rise to secondaries in Kajiado and Machakos districts (east-central Kenya) but not to the Nyeri outbreak which was too far north. In January, outbreaks were reported over an area of about 16 000 ha in the Nachingwea and Tunduru districts of south-east Tanzania. There were no known local sources, but westerly winds from 31 December to 3 January (Figure 15)

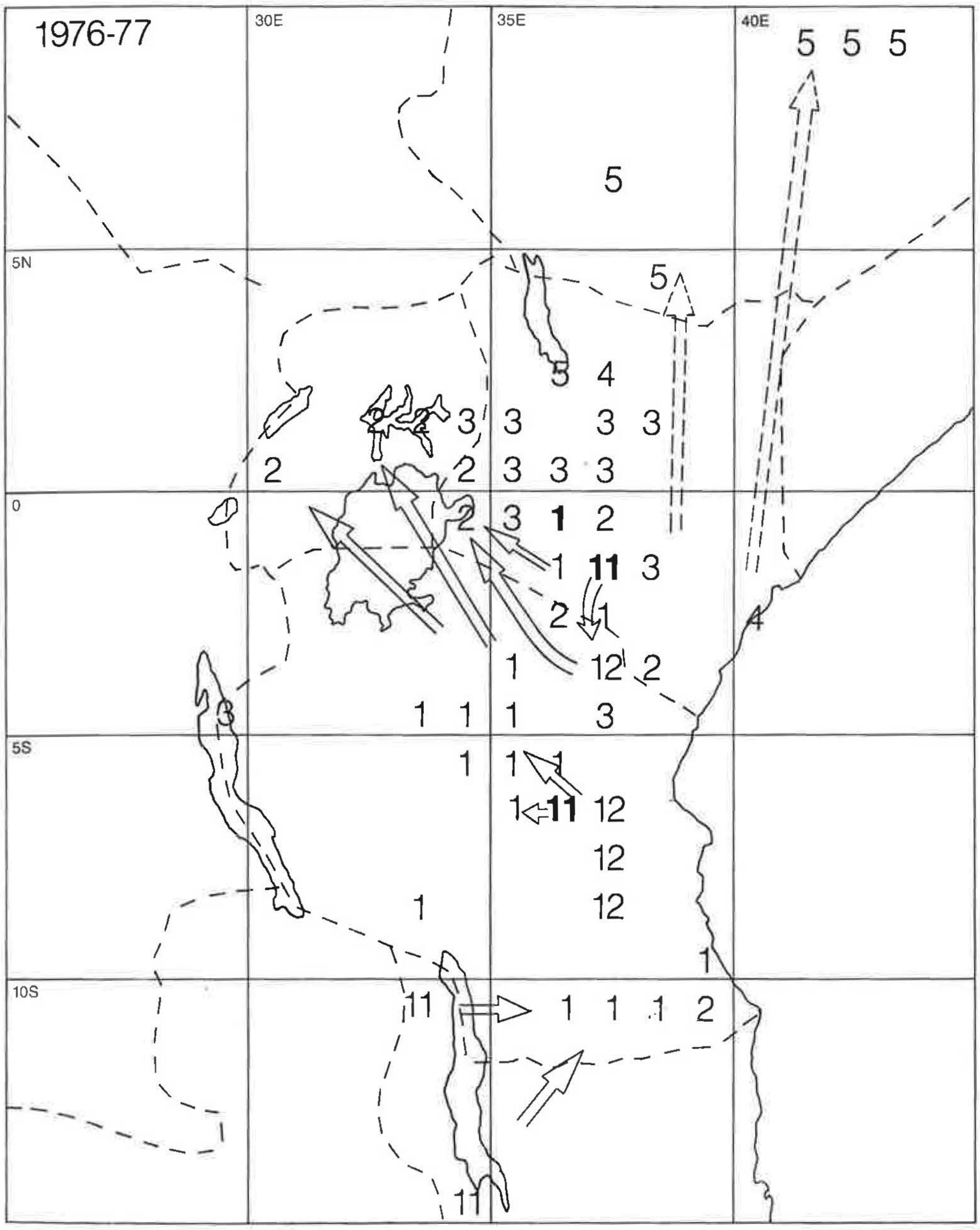

Figure 14 Summary map for 1976-77 season showing primary and secondary outbreaks

Key: See Figure 10

could have brought moths from Malawi, where there were many large outbreaks in November and December.

From the Kilosa primary in November about 20 secondary outbreaks (over 8000 ha) occurred in east-central Tanzania in late December, when moths were concentrated by storms at the beginning of the rains. Subsequent downwind migration resulted in outbreaks in the Mpwapwa, Singida and Kondoa districts of central Tanzania from mid-January to early February. Moths emerging from some of these outbreaks in mid-February migrated north-west towards Uganda, judging by trajectories, an increase in moth catch at Ukiriguru (south of Lake Victoria) on 17 February and subsequent outbreaks in Uganda.

Outbreaks in west Kenya (Nyanza and Busia districts) in February may have originated from moths migrating on south-easterly winds from north-east Tanzania or Kajiado (east-central Kenya). This migration is supported by the

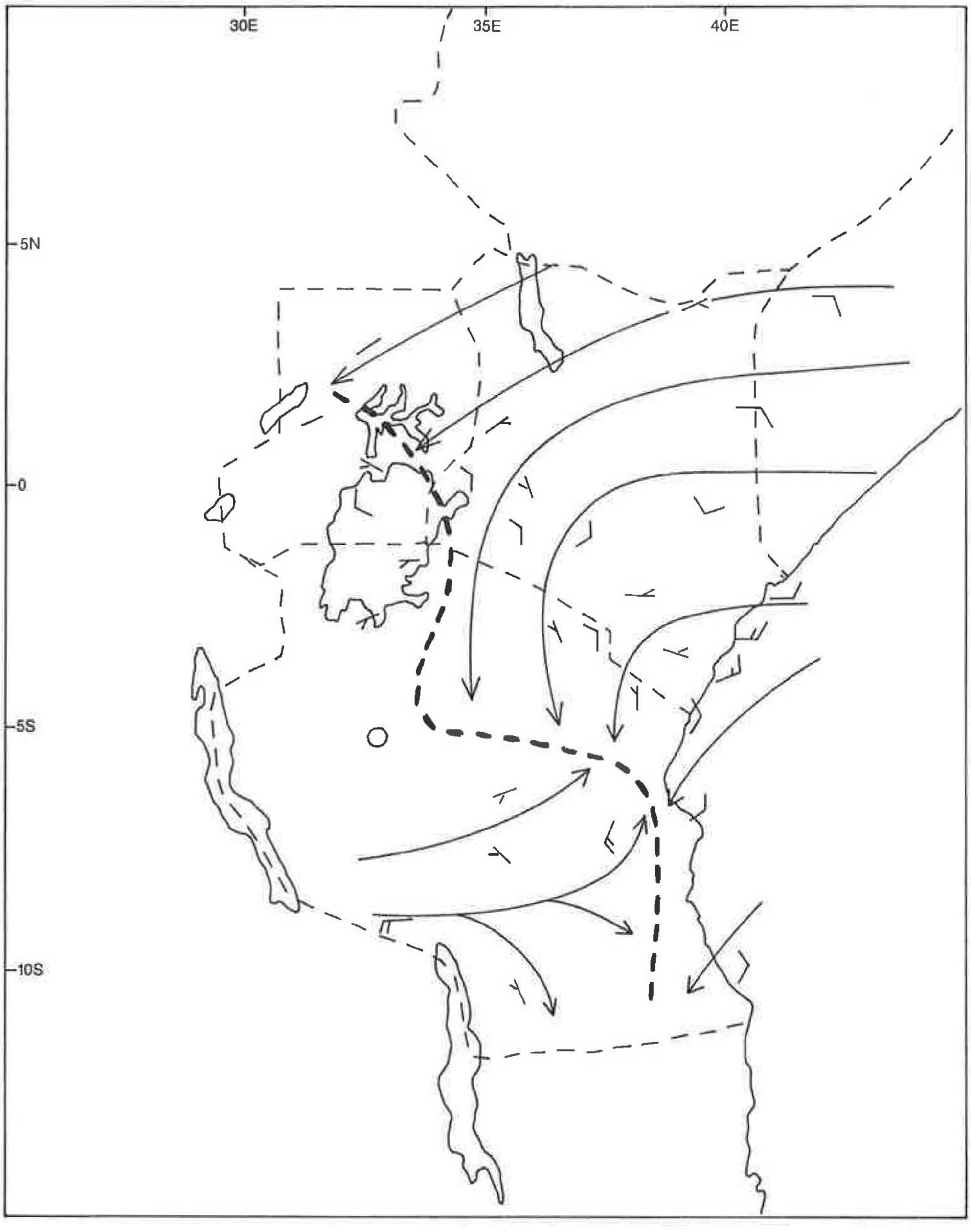

Figure 15 Surface windfield 2 January 1977

Key: Arrows are wind streamlines. Small arrows show wind directions and speeds in 2.5m/s intervals. Bold broken line is a wind convergence zone

occurrence of an outbreak near Magadi in the Kenya Rift Valley on the probable route.

In February and March, there were large outbreaks in Machakos-Kajiado districts and many small outbreaks in the north towards Mt Kenya (east-central Kenya) originating from earlier outbreaks there. These were associated with rainstorms in late January and February, separated by a dry period.

From March to April, outbreaks appeared further north in Kenya, associated with moth migration north. In May, outbreaks were reported in the south, central and east regions of Ethiopia, and in adjacent north-west Somalia. They may have resulted from moth migration on southerly winds from east-central Kenya, or from an outbreak at Lamu (Kenya coast), although migration to eastern Ethiopia and Somalia would have required at least three nights flight on low-level jet winds of about 15 m/s.

1977-78

Brief summary

A very low armyworm season with heavy early rains.

Primary outbreaks

One primary outbreak was reported in south Nyanza (west Kenya) in February (Figure 16). In areas where early season outbreaks usually occur, in Kenya south of the equator and east and central Tanzania, rainfall was above average in November and December (Table 8), and rain fell on 16 or more days in November in east-central and west Kenya. These frequent rains probably caused low rates of survival of any caterpillars present and hence led to the lack of outbreaks.

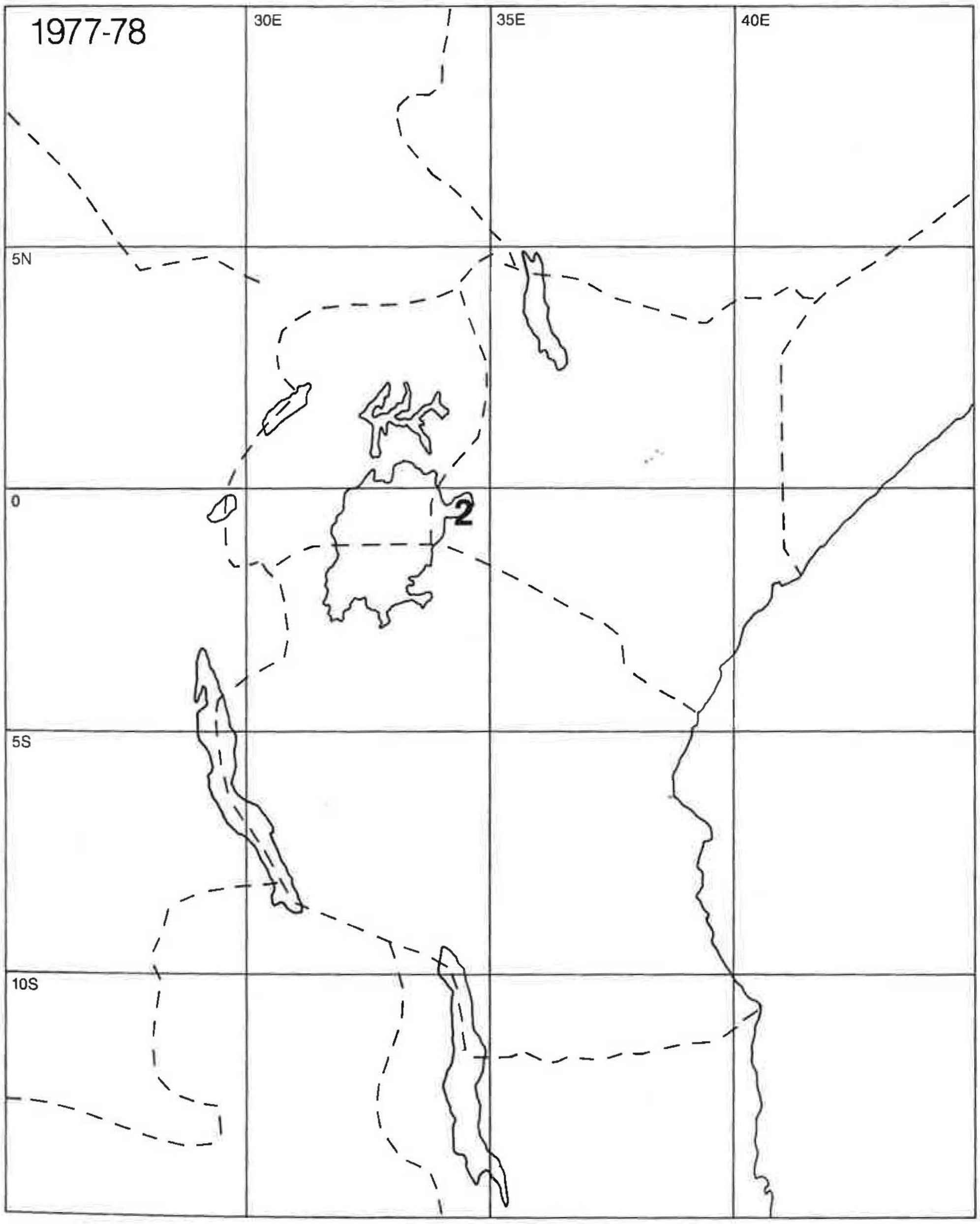

Figure 16 Summary map for 1977-78 season showing the primary outbreak

Key: See Figure 9

Table 8 Monthly rainfall October-December 1977

	October			November			December		
	Monthly mean (mm)	1977 % of mean	1977 Rain days	Monthly mean (mm)	1977 % of mean	1977 Rain days	Monthly mean (mm)	1977 % of mean	1977 Rain days
Kenya									
Mombasa	96	309		95	193		70	186	
Voi	26	181		106	148		119	175	
Makindu	28	11		172	120		115	137	
Sultan Hamud	68	6	1	211	99	16	98	141	8
Embu	157	42	10	259	151	22	54	87	9
Nairobi	38	45		134	172		74	101	
Kisumu	75	135	11	120	152	16	100	84	9
Tanzania									
Arusha	25	336		139	68		98	79	
Same	30	457		53	132		67	188	
Dar es Salaam	60	82		122	163		108	172	
Morogoro	29	172		61	74		78	215	
Kilosa	33	130		96	155		139	198	
Dodoma	4	0		20	420		107	134	
Mtwara	21	510		53	164		192	66	
Nachingwea	7	214		70	0		126	94	

Very few moths were caught in light traps, indicating that overall numbers of armyworm were very low even though the previous season had been severe in both Tanzania and Kenya.

Secondary outbreaks

There were no secondary outbreaks this season.

1978-79

Brief summary

In Kenya and Tanzania this moderate armyworm season was associated with heavy short rains. Outbreaks in mid-December in east-central Kenya may have originated from an outbreak in south Somalia, but not from the unusual September to October outbreaks in Ethiopia (Figure 17). Heavy rains continued until February in Tanzania and this may explain the lack of secondary outbreaks

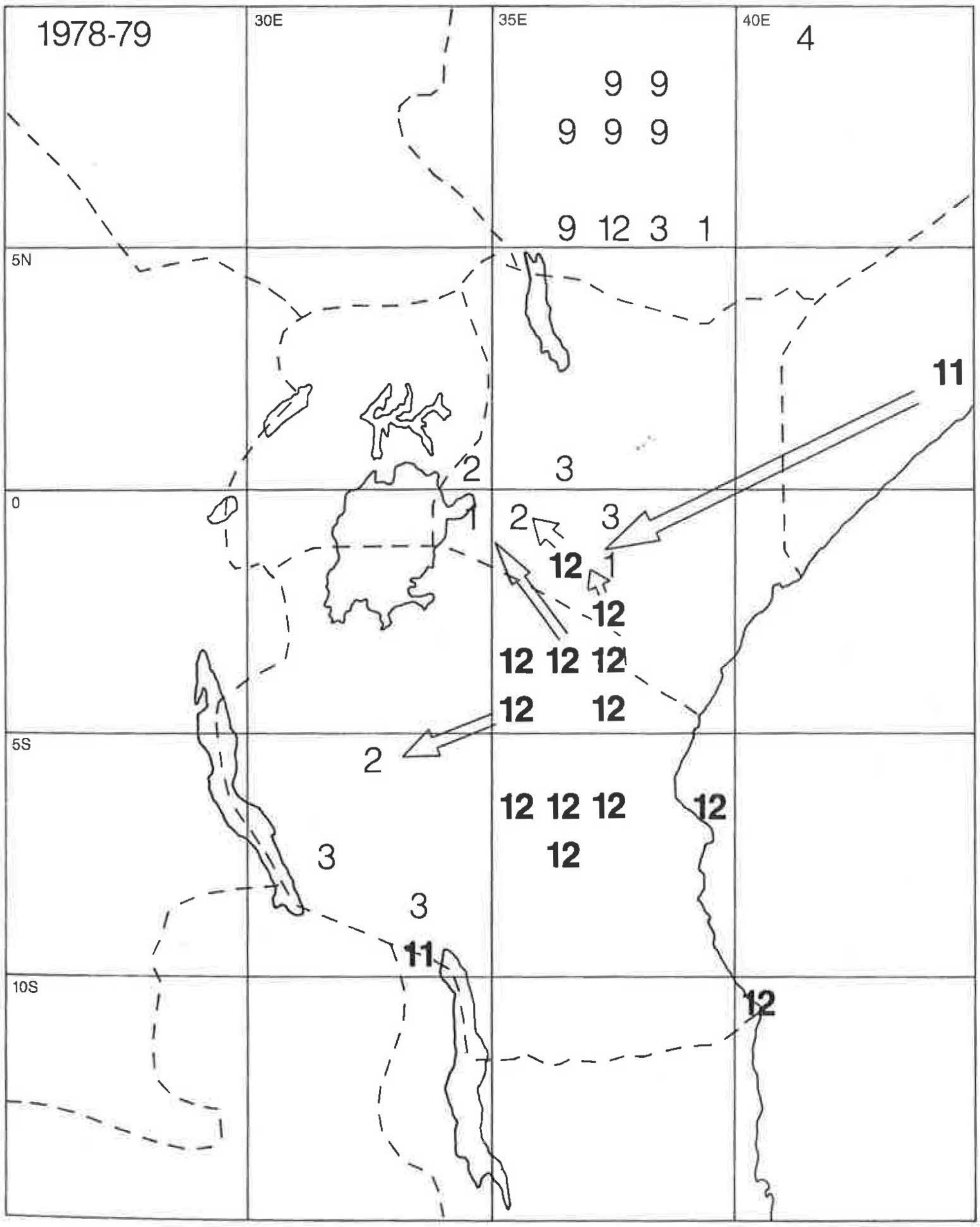

Figure 17 Summary map for 1978-79 season showing primary and secondary outbreaks

Key: See Figure 10

there. Large-scale migrations west and north-west from east-central Kenya and north-east Tanzania led to outbreaks in February in west Kenya and the Kenyan Rift Valley. The season ended early with no outbreaks in Kenya or Tanzania in April.

Unusual early outbreaks in Ethiopia

From September to October many outbreaks were reported in central Ethiopia and one in Gamo Gofa (south Ethiopia) following the end of the summer rainy season when there are usually no outbreaks. They were followed by single outbreaks in late December and early January in Gamo Gofa and Sidamo regions (south Ethiopia). The previous season had been low in Kenya and Tanzania and these outbreaks were probably derived from armyworm populations that had persisted in Ethiopia for at least one season. It is not clear whether they were primary or secondary.

Primary outbreaks

In early and mid-November, primary outbreaks occurred near Mogadishu (south Somalia) and at Mbeya (south-west Tanzania) associated with the beginning of the rains. The Somalia outbreak was large (1000 ha) but was primary because winds were north-easterly and moths could not have come from known outbreaks in Ethiopia.

Over most of Tanzania, the rains started in mid-November, after a dry October, and were heavy and persistent until mid-December with rainfall on an average of 26 days during this period (Table 9). The frequent rainstorms probably prevented outbreak formation in November. Outbreaks occurred widely in east-central, north-east and south-east Tanzania in mid-December associated with storms at the end of the rainy period, and with a subsequent mostly dry period in late December and early January.

Outbreaks occurred in Nairobi and Kajiado districts (east-central Kenya) in December, associated with scattered rainstorms at the end of the short rains and small catches of moths in Nairobi NAL pheromone trap from 10 December. No moths were trapped before December, possibly reflecting the lack of armyworm persisting from the previous very low season. Backtracks from the outbreaks indicated that moths came from the north-east (Figure 18). The timing fitted the possibility of moths migrating from the Mogadishu outbreak in four nights. The December Kenya outbreaks may have been secondary rather than primary.

Secondary outbreaks

In Tanzania very few secondary outbreaks were reported following the December primaries. There was an outbreak at Moshi (north-east Tanzania) in January, associated with a rainstorm on 25 January, and four small outbreaks in central and west Tanzania in February and March. High catches of moths at Tengeru light trap (near Moshi) from 9 January to 28 February indicated possible unreported local outbreaks. Outbreaks did occur in late January in neighbouring Taveta (south-east Kenya) which may have originated from the primary outbreaks in north-east Tanzania in December.

Outbreaks which occurred in late January in the Machakos and Kajiado districts (east-central Kenya), and further west at Magadi, in the Rift Valley, were derived from the December Kajiado and Nairobi primaries, following large-scale moth migration west towards the Rift Valley. This was confirmed by high moth catches at Muguga light trap from 24 January to 3 February. Backtracks indicated that an outbreak in south Nyanza (west Kenya) in late January originated from moths migrating from either east-central Kenya or north-east Tanzania. Similar migrations in February, indicated by wind directions and high moth catches, gave rise to a total of 26 reported outbreaks in west Kenya. Many moths also stayed within the Rift Valley, giving outbreaks at Mt Margaret and Nakuru, and in the Nairobi area where there were five small outbreaks in late February. In March

Table 9 Monthly rainfall October-December 1978

	October			November			December		
	Monthly mean (mm)	1978 % of mean	1978 Rain days	Monthly mean (mm)	1978 % of mean	1978 Rain days	Monthly mean (mm)	1978 % of mean	1978 Rain days
Kenya									
Mombasa	96	42		95	177		70	220	
Voi	26	62		106	314		119	97	
Makindu	28	625		172	120		115	201	
Nairobi (NAL)	55	195	7	135	99	14	83	159	13
Nakuru	66	153	14	68	88	12	40	165	5
Kisumu	75	139		120	119		100	129	
Tanzania									
Arusha	25	8	1	139	125	14	98	271	16
Same	30	57	2	53	400	15	67	207	13
Dar es Salaam	60			122	348	19	108	148	14
Morogoro	29	17	2	61	285	12	78	328	17
Ilonga	33			79	251	14	144	112	17
Dodoma	4	0	0	20	215	2	107	159	12
Mtwara	21	114	4	53	111	4	192	151	16

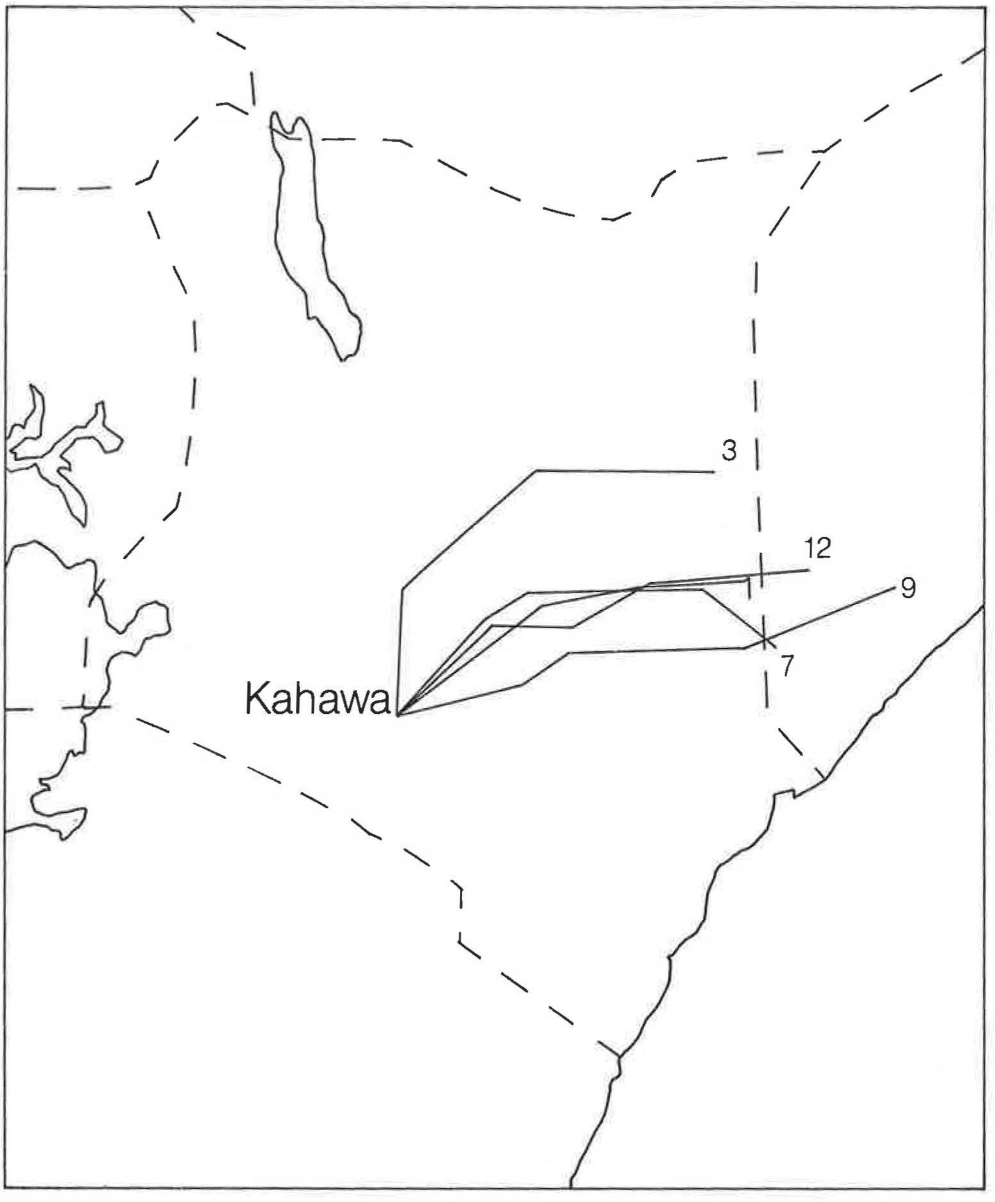

Figure 18 Backtracks from Kahawa 1-15 December 1978

there were two further outbreaks in west Kenya, and two in central Kenya (near Mt Kenya). Winds were mostly easterly although migration from the Nairobi outbreaks towards Mt Kenya may have been possible on a few nights. Winds were not suitable for taking moths to Ethiopia in March, and two outbreaks in Sidamo (south Ethiopia) in late March almost certainly came from armyworm persisting from earlier, local outbreaks. Moths leading to outbreaks in Harar in late April probably came from Sidamo outbreaks, following the seasonal windshift to south-westerly.

1979-80

Brief summary

This severe season started late, associated with a late start to the rains in Tanzania and well below average short rains in Kenya. There were widespread primary outbreaks in eastern Tanzania in December, several of which were large. Primary outbreaks in Kenya were also large but did not occur until the end of January. In Tanzania, most secondary outbreaks were in Arusha and Kilimanjaro regions, where some were severe. In Kenya, there was a sequence of secondary outbreaks, some very large, persisting until June (Figure 19). Outbreaks in east Kenya provided sources for outbreaks in south Ethiopia in April. Widespread

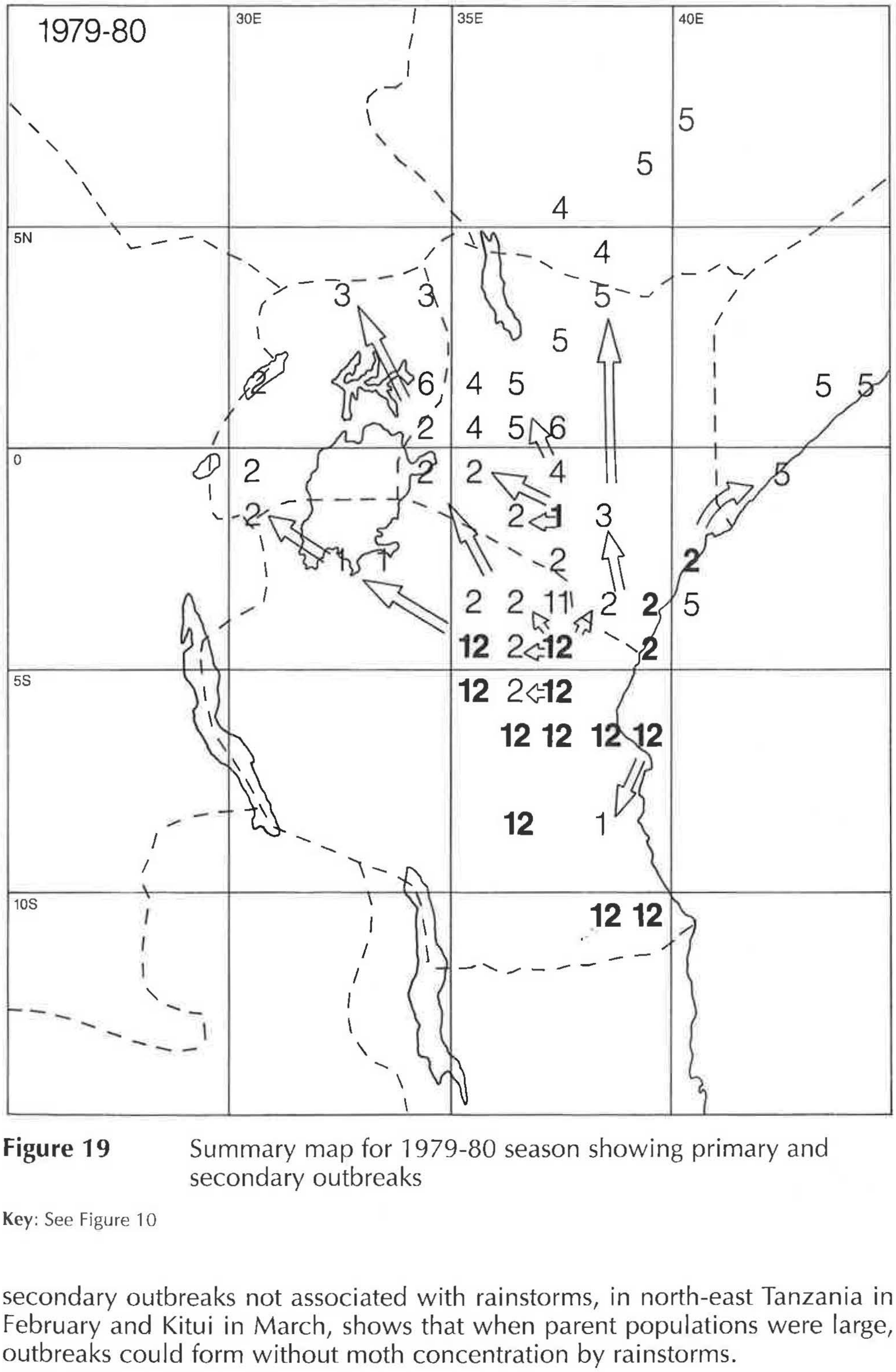

Figure 19 Summary map for 1979-80 season showing primary and secondary outbreaks

Key: See Figure 10

secondary outbreaks not associated with rainstorms, in north-east Tanzania in February and Kitui in March, shows that when parent populations were large, outbreaks could form without moth concentration by rainstorms.

Primary outbreaks

There were two unconfirmed outbreaks east of Kilimanjaro (north-east Tanzania) in November, probably associated with rainstorms recorded in nearby Taveta (south-east Kenya) in early November. October and November rains were below average in both Kenya and Tanzania (Table 10).

The beginning of the rains in Tanzania on 15 December was associated with the first confirmed outbreaks there, which were widespread in Morogoro and Dodoma regions (east-central Tanzania), at Same and Handeni (north-east Tanzania), at Bagamoyo (Tanzania coast) and at two locations in south-east Tanzania. Primary outbreaks at Bagamoyo, Handeni and Kondoa were unusually large (>1000 ha each) and caused severe damage to crops. The large number of

Table 10 Monthly rainfall October–December 1979

	October			November			December		
	Monthly mean (mm)	1979 % of mean	1979 Rain days	Monthly mean (mm)	1979 % of mean	1979 Rain days	Monthly mean (mm)	1979 % of mean	1979 Rain days
Kenya									
Mombasa	96	45		95	85		70	63	
Voi	26	88		106	75		119	185	
Makindu	28	71		172	81		115	102	
Nairobi	38	16		134	60		74	41	
Narok	26	15		63	62		71	73	
Kisumu	75	32		120	136		100	176	
Tanzania									
Arusha	25	20	1	139	1	1	98	98	10
Same	30	20	2	53	19	5	67	107	7
Dar es Salaam	60	42	2	122	34	3	108	79	8
Morogoro	29	48	3	61	66	5	78	141	11
Dodoma	4	0	0	20	35	2	107	86	10
Iringa	7	29	1	36	25	1	120	153	12
Mtwara	21	10	1	53	21	4	192	60	13

primary outbreaks and their size suggests that there were earlier unreported outbreaks, associated with isolated rainstorms in early November.

Outbreaks were not reported in Kenya until January when there were three large outbreaks on pasture in Machakos district (east-central Kenya). They covered a total area of about 6000 ha and were associated with rainstorms from 23-28 January, following four dry weeks. They were probably primary because moth sources were to the east or north-east, where there were no known earlier outbreaks.

In mid-February, there were small primary outbreaks on the Kenya coast, associated with isolated rainstorms following dry weather.

Secondary outbreaks

In January there were secondary outbreaks in Tanzania on the coast, and in Morogoro, Dodoma and Same areas, following nearby primaries; and outbreaks south of Lake Victoria (Mwanza region) following north-west moth migration.

In February approximately 50 outbreaks occurred in Arusha and Kilimanjaro regions (north-east Tanzania) probably resulting from moth migration on south-easterly winds from the Handeni primary outbreak. These outbreaks were associated with very high catches at Tengeru light trap where about 360 000 moths were caught from 9-22 February, during a period with no rainstorms. This suggests that outbreaks can form without rainstorms, when sources are large and there are other concentrating factors, such as mountain winds. Moth catches were also high in March, and moderate in April and May but no further outbreaks were reported until May when there were two.

In Kenya, February outbreaks in Taveta and south Kajiado districts were continuous with those in north-east Tanzania, while small outbreaks in west Kenya and Tororo district (east Uganda) were a result of migration from earlier outbreaks in north-east Tanzania. Isolated outbreaks in west Uganda probably came from moths migrating from Mwanza, Tanzania on south-easterly winds.

In early March there were outbreaks in Kajiado and Machakos (east-central Kenya) associated with widespread rainstorms on 1-2 March after four dry weeks. Parent moths came from the January primary outbreaks in Machakos. Later in March, there were very large outbreaks (estimated total area 50 000 ha) further east in Kitui district, which probably came from Taveta. Moth concentration occurred during three dry weeks, possibly associated with topographic winds.

There were further small outbreaks in Nyanza (west Kenya) in March and early April. In April outbreaks reappeared on the Kenya coast, at Lamu, and appeared further north in Kirinyaga (east-central Kenya), West Pokot (north-east Kenya) and in Gamo Gofa and Sidamo regions (south Ethiopia). The south Ethiopian outbreaks probably originated from moths migrating on southerly winds from outbreaks in Taveta and Kitui districts of Kenya.

In May, outbreaks were widespread in north and north-west Kenya, and large outbreaks also occurred in south Somalia, where they probably originated from outbreaks on the Kenya coast, following the onset of southerly winds. The last outbreaks of the season were in Kenya, north of the equator, with moth arrival in June.

1980-81

Brief summary

This moderate season started early, in October, in east-central Kenya. October primary outbreaks were associated with rainstorms ahead of the short rains. They were followed, in November, by many secondaries in east-central Kenya, and further primaries, mostly in south-east Kenya and north-east Tanzania (Figure 20).

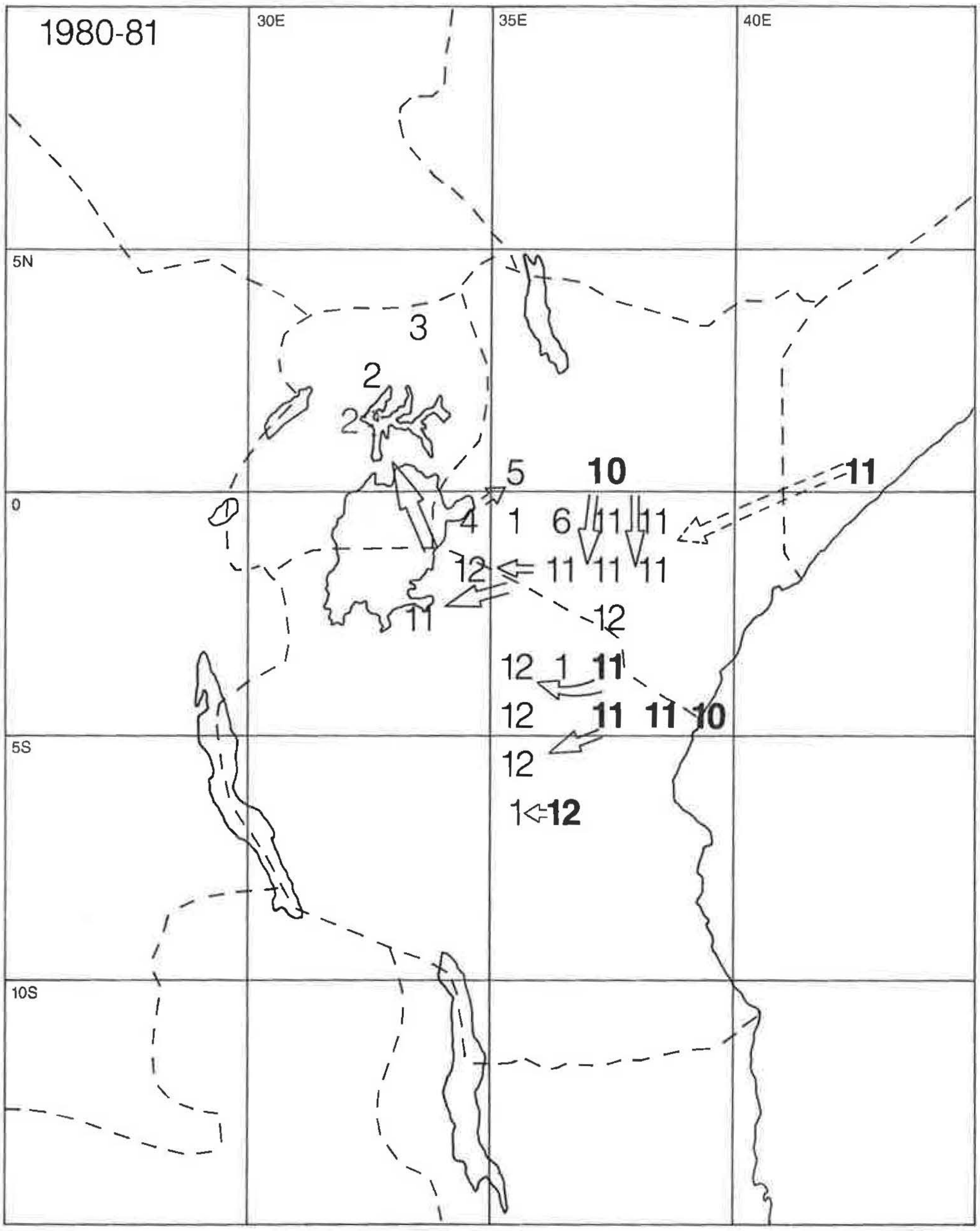

Figure 20 Summary map for 1980-81 season showing primary and secondary outbreaks

Key: See Figure 10

The season effectively ended in Kenya and Tanzania following secondaries in December, with only isolated outbreaks later in the season. The beginning of the short rains was suitable for rapid population increase in Kenya, but dry weather from mid-December to February led to an absence of outbreaks.

Primary outbreaks

Early primary outbreaks occurred at Kwale (Kenya coast) in early October (details unknown) and in Meru district (east-central Kenya) in mid-October. The latter were severe, affecting crops and grass over about 2000 ha, and were associated with rainstorms on 17-19 October, ahead of the wider onset of the short rains on 26 October.

In early November, there was a large outbreak (14 500 ha), with no known outbreak source, on maize and grass at Jamama (south Somalia). In mid-November, widespread outbreaks occurred in Taita-Taveta district (south-east

Kenya), over about 20 000 ha of maize and grasses, and at Rombo, Same and Lushoto, in adjacent Kilimanjaro and Tanga districts (north-east Tanzania). They were associated with widespread rainstorms from 12-17 November after mostly dry weather, and were too late to have been derived from the Kwale primary.

An isolated outbreak in Ilonga (east-central Tanzania) in early December was probably also primary.

Secondary outbreaks

In mid-late November, there were widespread outbreaks in Machakos, Kitui, Muranga and Embu districts (east-central Kenya). Estimated moth arrival dates coincided with rainstorms on 17 November, towards the end of the brief short rains. Moth catches at Mwea Tebere (Embu district) indicated a moth influx from 24 November to 2 December, which coincided with moth emergence from earlier outbreaks at Meru and in Somalia. Winds were north-easterly, and backtracks indicated that both sources were possible. An outbreak at Mwanza (north-central Tanzania) may also have been derived from Meru moths.

In December, there were about 40 small outbreaks in Nairobi, Kiambu and Kajiado districts (east-central Kenya). Backtracks were from the east or south-east. Most outbreaks were likely to have come from moths migrating from Taita-Taveta primaries but some later outbreaks may have come from November secondaries in east-central Kenya. December was mostly dry, but isolated rainstorms on 8 and 13 December may have concentrated the moths.

Migration west from east-central Kenya led to three outbreaks in the Narok district in late December and early January.

Outbreaks in Kondoa and Ngorongoro districts of Tanzania in December were probably derived from the November primaries in north-east Tanzania. Further west and north-west migrations from north Tanzania or west Kenya were indicated by the occurrence of heavy outbreaks in central Uganda in February and March.

In February and March, two small outbreaks in Kilimanjaro district were the last of the season in Tanzania. This abrupt end to outbreak occurrence was probably caused by very dry weather in February. There were no reported outbreaks in Kenya in these months, but armyworm persisted at low density, judging by small trap catches at Kibos (west Kenya), and outbreaks in south Nyanza (west Kenya), and Kitui district (east-central Kenya), in April. The season ended in Kenya with three small outbreaks in Nakuru and Kabarnet districts in May and June. The armyworm situation in Ethiopia was unclear from available data which mentioned caterpillar infestations but suggested that they were probably not armyworms.

1981-82

Brief summary

This severe season was associated with slightly below average early rains. In late October to November, primary outbreaks in east-central and south-east Tanzania were associated with isolated rainstorms ahead of the main rains. Outbreaks became widespread in east and central Tanzania when the rains started in December. Moth migration north-west led to outbreaks around Lake Victoria in January, and these were severe in west Kenya and south Uganda. Most of Kenya remained free of outbreaks until the end of March, when moths spread north from north Tanzania. There were primary outbreaks in south Ethiopia, and widespread secondaries, possibly with some moths migrating from outbreaks on the Kenya coast (Figure 21).

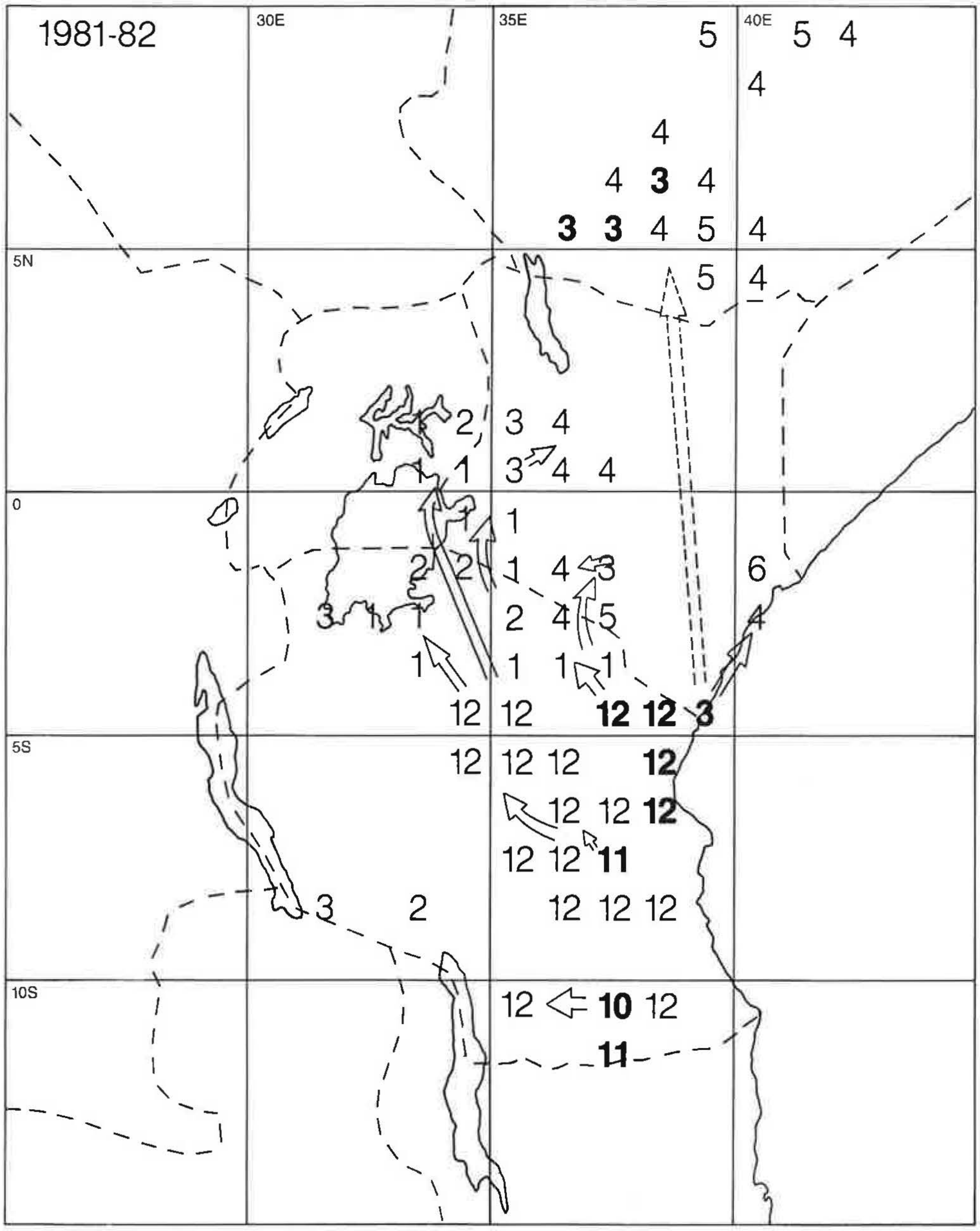

Figure 21 Summary map for 1981-82 season showing primary and secondary outbreaks

Key: See Figure 10

Primary outbreaks

In south-east Tanzania there was a small primary outbreak in Nachingwea district in late October, and a large outbreak, probably primary, on cereals in the Tunduru district in mid-November. They were both associated with isolated rainstorms ahead of the main rains. In Morogoro district (east-central Tanzania) a primary outbreak occurred in mid-November, near the Uluguru mountains, but there were no rainstorms at Morogoro, the nearest synoptic weather station. In December, during the rains, primary outbreaks occurred near Same, Korogwe and Handeni (north-east Tanzania) and at Bagamoyo (Tanzania coast).

Three outbreaks in Kwale district (Kenya coast) in late March were probably primaries because there were onshore easterly winds. They were associated with the start of the long rains on 29 March.

Widespread outbreaks in Gamo Gofa and Sidamo provinces, south Ethiopia, in mid to late March were probably primary because, although winds veered to south-easterly on 26 March, there were no known outbreak sources in east Kenya or south Somalia.

Secondary outbreaks

Over most of Tanzania the rains started late at the beginning of December. There were two outbreaks in south-east Tanzania, which may have been derived from the October primary. Outbreaks became widespread in east-central and central Tanzania downwind of, and partly derived from, the November and early December primaries at Morogoro and Same.

Moths emerging from later December primary outbreaks in north-east Tanzania, migrated towards the north-west, judging by forward trajectories (Figure 22). They probably gave rise to January outbreaks in Kilimanjaro and Arusha regions (north-east Tanzania), Taveta district (south-east Kenya) and at least some of the January outbreaks in west Kenya. Most of north-east Tanzania was very dry in January, and outbreaks occurred only in wetter areas near Kilimanjaro and in the highlands west of Arusha. In west Kenya rainstorms were less frequent than normal but outbreaks were widespread, from Busia to south Nyanza and Masai-Mara, covering an estimated total area of >30 000 ha.

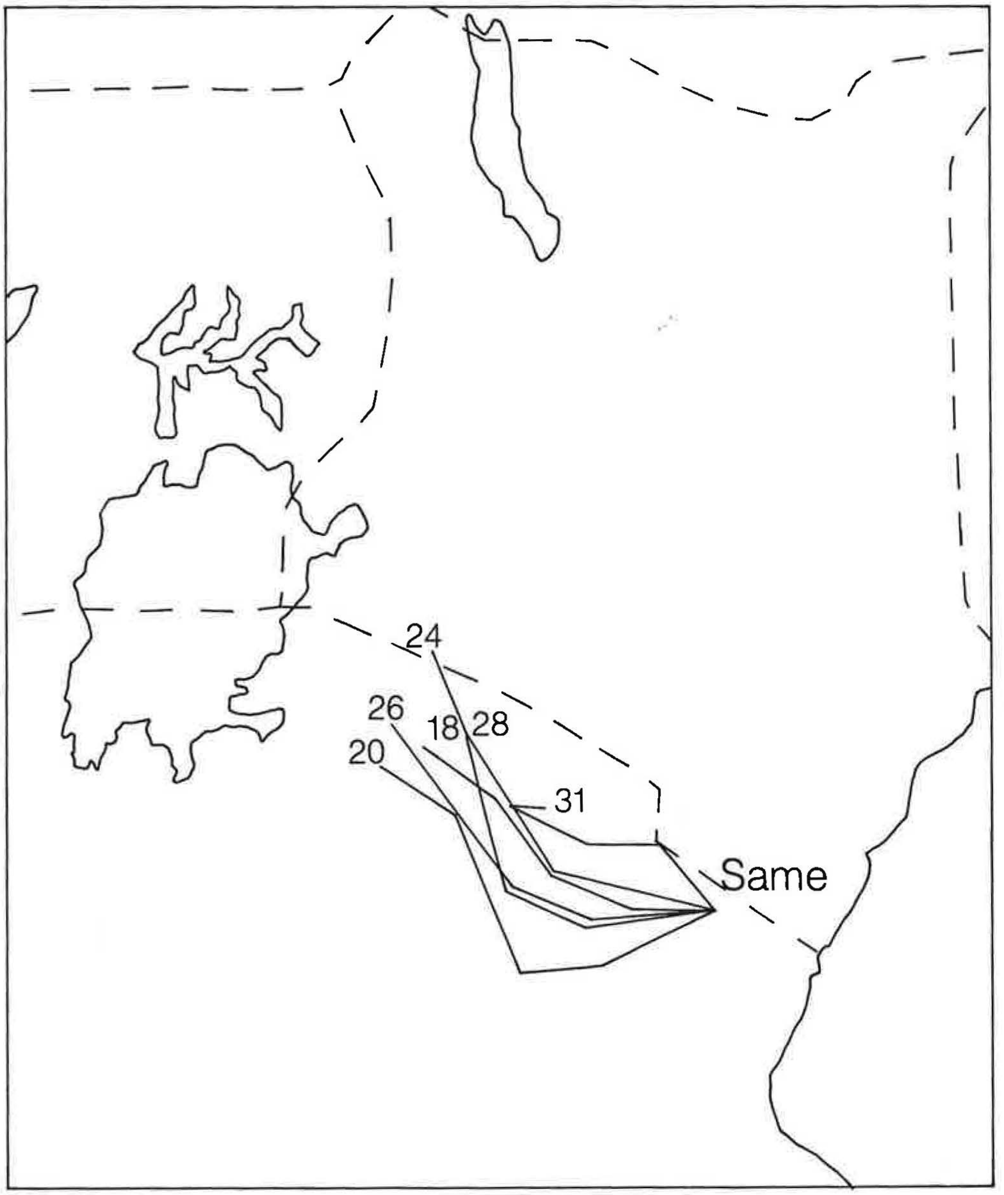

Figure 22 Forward tracks from Same, 16-31 January 1982

In January and early February, outbreaks also occurred in Mwanza and Mara districts (north-central Tanzania), including Ukerewe Island in Lake Victoria, and in south Uganda, where some were severe. Winds were south-easterly and backtracks indicated that parent moths came from outbreaks in Singida and Kondoa districts (central Tanzania) and possibly from north-east Tanzania.

In February a second generation of outbreaks occurred in Uganda and west Kenya, associated with scattered rainstorms, but there were very few outbreaks in Tanzania, probably because of dry weather.

In early and mid-March, about 10 outbreaks occurred in north-east Tanzania, associated with an increase in frequency of rainstorms, and about four occurred in west Tanzania. In Machakos district (east-central Kenya) two outbreaks occurred when moth concentration was associated with rainstorms from 28-30 March, following dry weather. These rainstorms were associated with a push of southerly winds from north Tanzania, and moths most likely migrated from outbreaks there.

A mark and capture experiment (Rose *et al.*, 1985) demonstrated that moths emerging from the Machakos outbreaks migrated west, where they gave rise to outbreaks that occurred in the Rift Valley (Kajiado and Narok districts) and Nairobi district, from late April to early May.

Further east, moths emerging from primary outbreaks at Kwale (Kenya coast) would have flown north on strong southerly winds. Some travelled along the coast to Lamu and the Tana River, where there were subsequent outbreaks. Others could have flown to south Ethiopia and contributed to the widespread outbreaks that occurred there in April and May. Ethiopian outbreaks were also derived from the March primary outbreaks in south Ethiopia.

1982-83

Brief summary

A very low armyworm season, with very heavy early rains preventing any population build-up from small early season primary outbreaks (Figure 23).

Primary outbreaks

In early October a small (2 ha) primary outbreak occurred at Voi (south-east Kenya) associated with very early short rains. There were rainstorms near Voi on most days from 24-29 September, 6-18 October and from 10 November to 5 December, with more than twice the mean rainfall reported widely in Kenya and Tanzania in October and November (Table 11). No outbreaks were derived from the Voi primary, probably because larvae were killed by heavy rains.

In north-east Tanzania, pheromone traps had small catches of armyworm moths in October, but no outbreaks were reported. In east-central Tanzania there were small (1.5 ha) primary outbreaks near Kilosa in late November and near Iringa in early December, associated with rainstorms from 27 November to 7 December. There was high larval mortality due to parasitism and heavy rainstorms.

Secondary outbreaks

In January only three very small, low density secondary outbreaks were found in east-central Tanzania all severely parasitized. No further outbreaks were reported during the season, although rainfall from January to April was below average.

Table 11 Monthly rainfall October-December 1982

	October Monthly mean (mm)	October 1982 % of mean	October 1982 Rain days	November Monthly mean (mm)	November 1982 % of mean	November 1982 Rain days	December Monthly mean (mm)	December 1982 % of mean	December 1982 Rain days
Kenya									
Mombasa	96	208	18	95	91	7	70	80	7
Voi	26	408	13	106	240	11	119	54	9
Makindu	28	529	13	172	231	18	115	137	13
Machakos	52	356	16	193	174	20	122	137	10
Embu	157	289	17	259	51	15	54	70	5
Nairobi	38	387	15	134	111	17	74	153	7
Kisumu	75	225		120	265		100	97	
Tanzania									
Arusha	25	524		139	224	13	98	101	7
Same	30	460		53	434		67	46	
Dar es Salaam	60	302		122	216		108	220	
Morogoro	29	362		61	180	9	78	336	8
Kilosa	33			96	211	11	139	165	12
Dodoma	4	175		20	330	7	107	203	12
Mtwara	21	348		53	228		192	90	

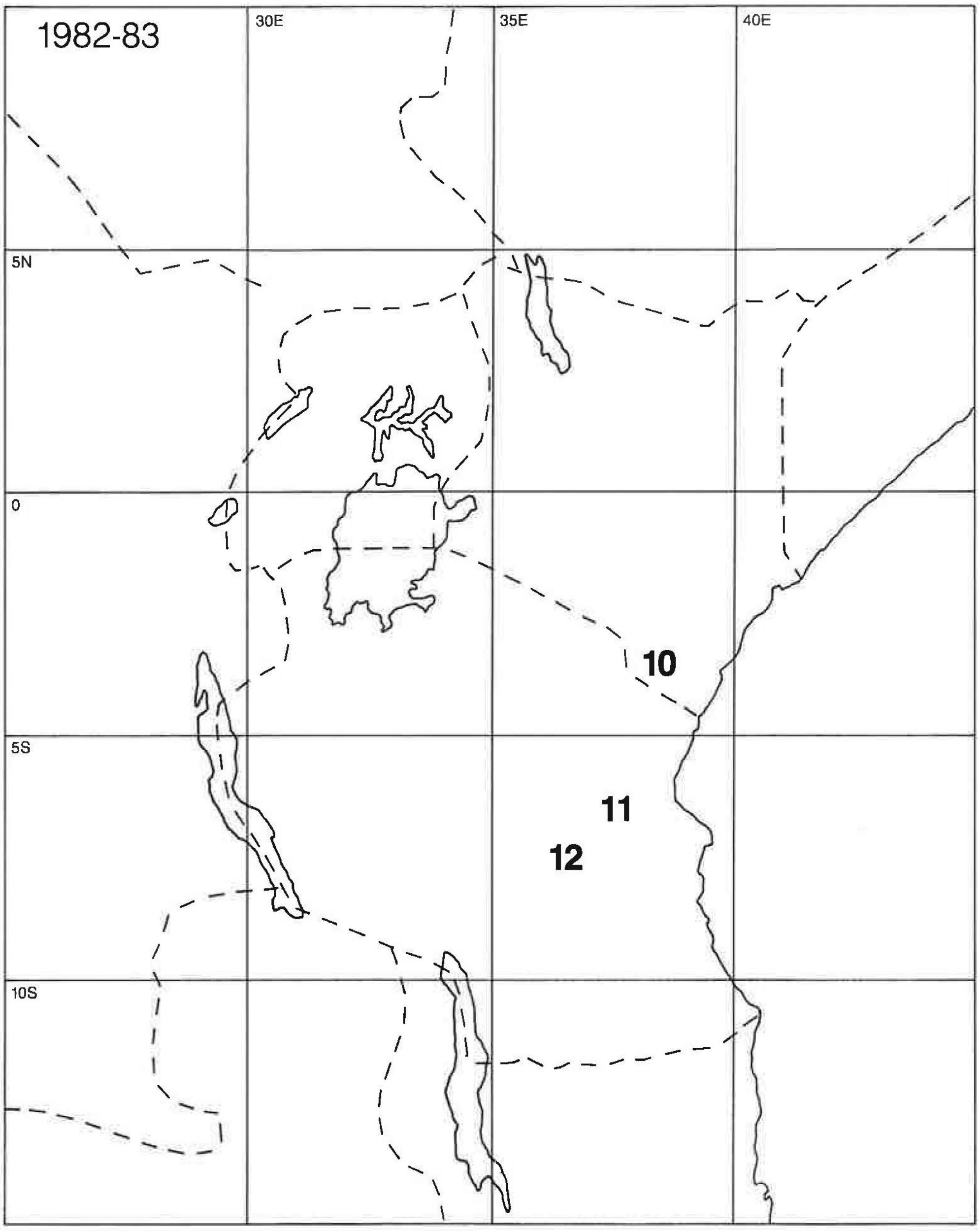

Figure 23 Summary map for 1982-83 season showing primary outbreaks

Key: See Figure 9

1983-84

Brief summary

This severe season started late, associated with a late start to the rains, except in south-east Tanzania. Primary outbreaks, in mid-December in east-central Tanzania, were small but led to many secondaries. Primaries in east-central Kenya, in late December to early January, were very large but led to very few secondaries (Figure 24). Primary outbreaks on the Kenya coast in April were associated with rainstorms following dry weather. Most of Kenya remained dry as the long rains failed, and late outbreaks were associated with migration from the coast. Late primary outbreaks occurred in south Ethiopia in April and these were complemented by moths migrating from the Kenya coast in May, leading to severe outbreaks.

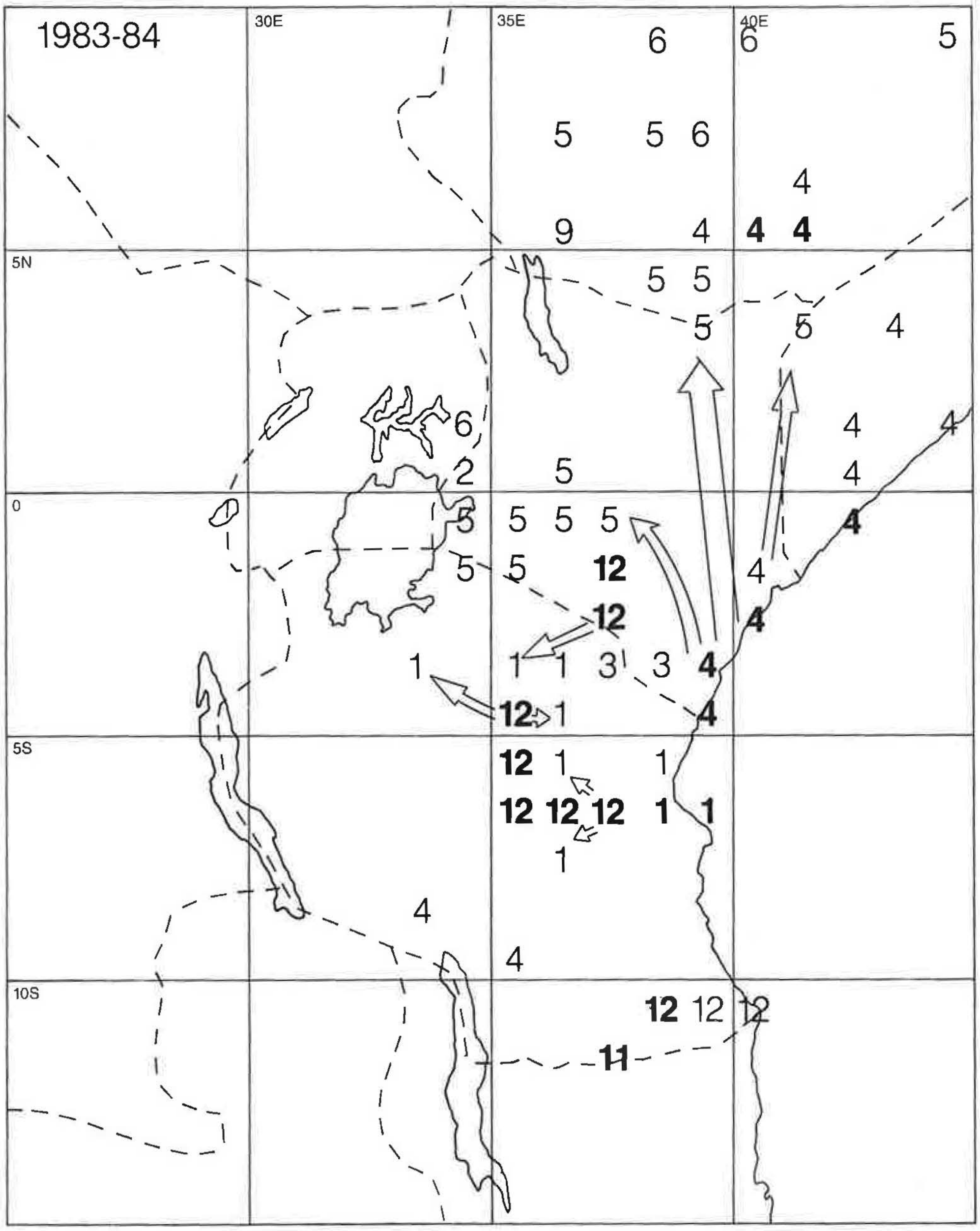

Figure 24 Summary map for 1983-84 season showing primary and secondary outbreaks

Key: See Figure 10

Primary outbreaks

In November, an outbreak occurred at Tunduru (south-east Tanzania) causing severe damage to cereals. It was associated with isolated rainstorms on 20 November. Further east, two outbreaks at Masasi in early December were also primary, and associated with the start of the main rains on 10 December.

In mid-December, small primary outbreaks occurred in Mpwapwa, Kilosa, Dodoma and Kondoa districts (east-central Tanzania) with an estimated total area of 45 ha. They were associated with moth catches from 12-17 December in light and pheromone traps, and with rainstorms following three dry weeks.

In early January, widespread outbreaks occurred near Dar es Salaam (Tanzania coast). These were probably primary as coastal winds were onshore easterlies, except for 9 January when light south-westerly winds were present and migration from east-central Tanzania was possible.

Very large outbreaks occurred over approximately 15 000 ha of pasture in Machakos and Kajiado districts (east-central Kenya), associated with widespread rainstorms from 18-25 December and an isolated rainstorm on 9 January. These were probably primary, as there were no known outbreak sources, either locally or upwind to the north-east. There may have been unreported source outbreaks associated with isolated rainstorms in Machakos district in mid-November.

Late primary outbreaks occurred on the Kenya coast near Lamu (early April), Kilifi and Kwale (mid-April) and in south Somalia (mid-April). They were associated with isolated rainstorms on 11 April and widespread rainstorms on 19 April, following very dry weather. Winds were southerly, along the coast, so it was unlikely that moths came from the only known source in Taita-Taveta district to the west. Coastal outbreaks covered an estimated area of 20 000 ha and caused serious damage to maize. Also in April, primary outbreaks occurred in Sidamo region (south Ethiopia), associated with the beginning of the rains there.

Secondary outbreaks

In mid to late December, about 15 outbreaks occurred in Mtwara and Lindi regions (south-east Tanzania). Parent moths may have come from the Tunduru primary outbreak, as the winds were westerly from 22-27 December. Young larvae were reported killed by widespread heavy rain in late December and early January. No further outbreaks were reported in south-east Tanzania.

In early January, there were about 40 outbreaks in Morogoro region (east-central Tanzania) over an estimated 1100 ha of cereals and pasture. Moth concentration was indicated by increases in the catches at Ilonga light and pheromone traps on 3 and 7 January respectively, associated with a rainstorm and westerly winds on 3 January. Variable winds meant that moths could have come from December primaries in Morogoro or Dodoma regions, but only if development was rapid (about 23 days). An earlier moth catch at Kinyasungwe on 21 December, associated with rainstorms, indicated the presence of army-worm moths not associated with known outbreaks. Outbreaks at Kondoa and Shinyanga in late January probably came from primary outbreaks in Kondoa district, following slower larval development at higher altitudes. Two outbreaks near Handeni (north-east Tanzania) in late January probably came from moths flying north-west from coastal primary outbreaks. Moths emerging from January outbreaks did not give rise to further outbreaks, partly because of high larval mortality caused by heavy rains in late January and early February.

Moths emerging from the December to January primary outbreaks in east-central Kenya, would have flown west and may have initiated two outbreaks in the Arusha region (north-east Tanzania) and one small outbreak in the Busia district (west Kenya). An absence of further outbreaks in Kenya was probably due to very dry weather and a lack of concentrating mechanisms in late January and February.

In March, three outbreaks in Taita-Taveta district (south-east Kenya) and one in Kilimanjaro region (north-east Tanzania) were probably derived from moths emerging from outbreaks in north-east Tanzania at the beginning of March during dry weather. Alternatively, they may have been primary outbreaks with moths concentrated by rainstorms from 11-16 March.

Moths emerging in May from the large primary outbreaks on the Kenya coast, would have flown north on strong southerly winds. Backtracks from Moyale (Figure 25) indicate that they could have flown to south Ethiopia, where there were many severe outbreaks in May and early June. Migration north is supported by the occurrence of outbreaks in east and north Kenya. Outbreaks on the Tana River could have originated from the earliest (Lamu) primaries, while outbreaks at Garissa, Wajir, Mandera and Moyale probably come from Kilifi outbreaks. Moths emerging from later outbreaks in Kwale district flew north-west on south-easterly winds, and caused outbreaks reported in late May in Nyeri, Kirinyaga and Muranga districts of east-central Kenya. The source of outbreaks in Nakuru and western Kenya is unknown.

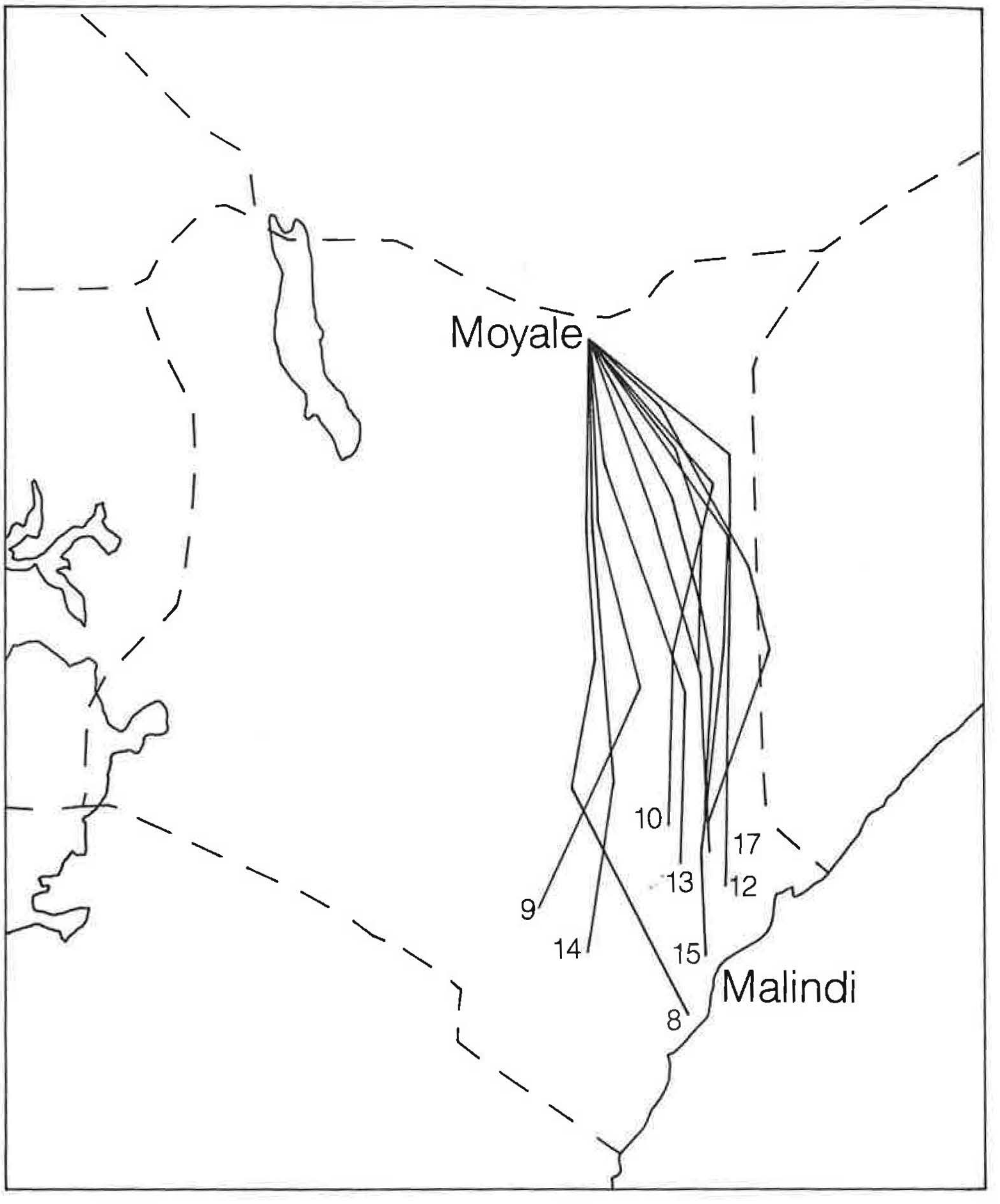

Figure 25 Backtracks from Moyale, 10-20 May 1984

1984-85

Brief summary

This extremely severe season started early, in east-central Kenya. The short rains were well above average, but dry periods, in mid-October and late-November, resulted in high armyworm survival. This led to very widespread outbreaks, estimated in November to cover six million hectares in Kenya, making it the most severe season in the period 1972-88 in Kenya. Outbreaks were widespread in north Tanzania but not in east-central or south-east Tanzania (Figure 26). The season finished early in most of Tanzania and Kenya. Outbreaks in Ethiopia developed locally, but not as a result of migration from Kenya.

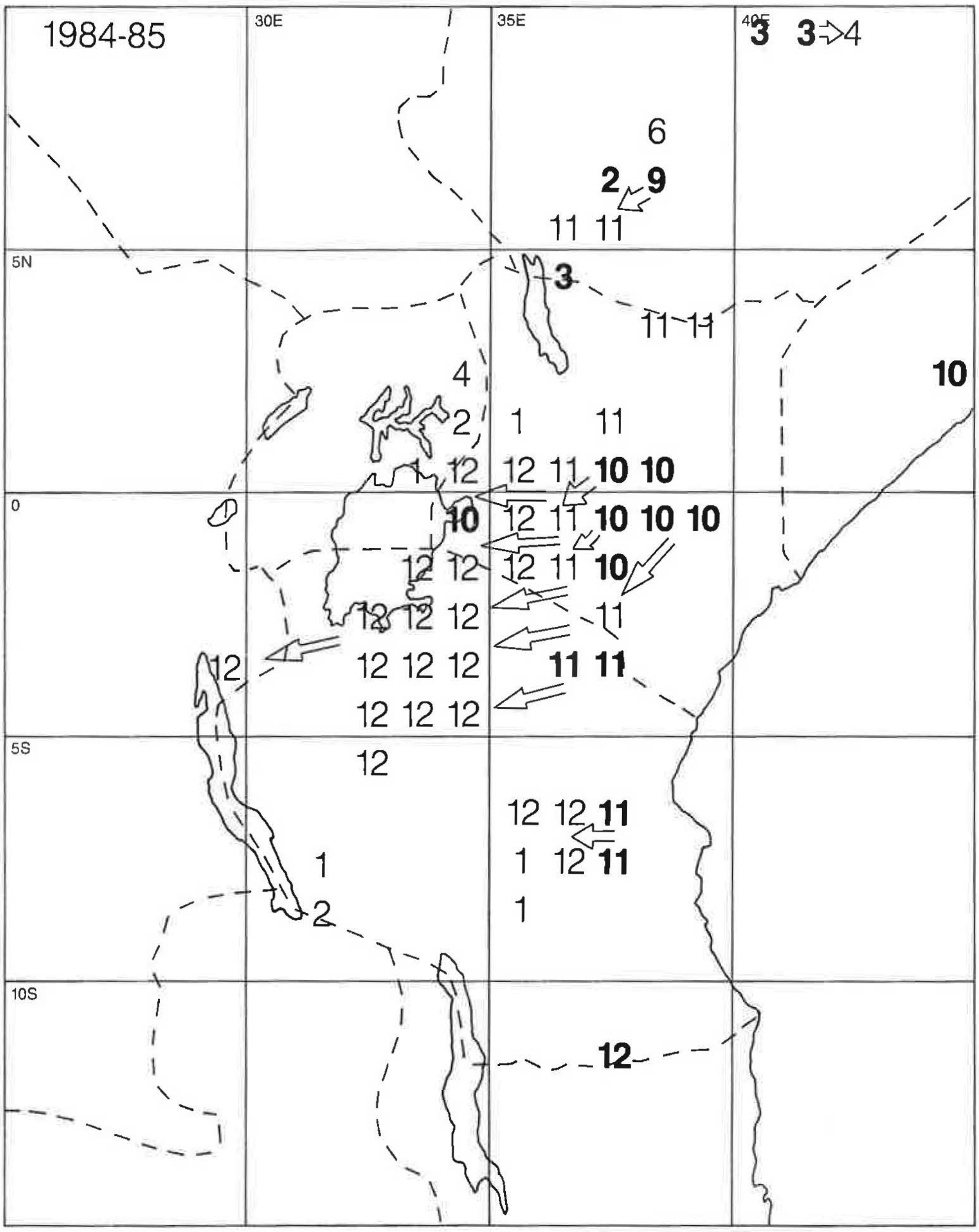

Figure 26 Summary map for 1984-85 season showing primary and secondary outbreaks

Key: See Figure 10

Primary outbreaks

Following severe outbreaks in Ethiopia from April to August 1984, an isolated outbreak occurred in Sidamo province (south Ethiopia) with estimated moth arrival in late September. This was probably primary because winds were south-easterly and the only possible parent outbreaks, in August, were in central and north-east Ethiopia.

Outbreaks occurred in Meru district (east-central Kenya) associated with the first rainstorms of the short rains, from 2-10 October. An isolated outbreak occurred in south Nyanza (western Kenya) in early October. There were further outbreaks in Isiolo, Meru, Embu, Kitui and Garissa districts (east-central and east Kenya), associated with rainstorms from 20-26 October, and also in south Somalia. These outbreaks were all primary because winds were south-easterly, so parent moths could not have come from Ethiopia.

In mid-November, outbreaks occurred in Arusha and Kilimanjaro districts (north-east Tanzania) associated with the first rainstorms of the short rains there, on 13-17 November. Winds were south-easterly, so parent moths were unlikely to have come from Kenya primaries. Small numbers of moths caught east of Kilimanjaro in October indicate the presence of a low density, potential source population.

Also in mid-November, primary outbreaks in Morogoro region (east-central Tanzania) were associated with the first rainstorms of the season, from 11-18 November. In mid-December there were primary outbreaks in Mtwara region (south-east Tanzania), associated with rainstorms from 16-21 December.

In February and March there were late primary outbreaks in Gamo Gofa and Harar provinces of south-west and east Ethiopia respectively. Winds were easterly or north-easterly so moths could not have come from Kenya secondary outbreaks (see below).

Secondary outbreaks

Moths emerging in November, from Meru primary outbreaks, migrated at least 200 km south-west on north-easterly winds. They were concentrated by rainstorms from 3-15 November and led to widespread, severe outbreaks in east-central Kenya. Moths from late October primaries in east-central Kenya, flew west during a dry spell (from 16-24 November), resulting in outbreaks at low density. Secondary outbreaks also occurred in November in south-west Ethiopia, downwind of the late September primary.

In December, moths emerging from November secondary outbreaks in Kenya, and primaries in north-east Tanzania, spread rapidly westwards, leading to outbreaks in west Kenya, north-central Tanzania, and even Burundi.

There were also further outbreaks in east-central Kenya and north-east Tanzania. Moth arrival for these outbreaks was near the end of the short rains, 10-12 December. In Morogoro region (east-central Tanzania), secondary outbreaks, derived from November primaries, were associated with rainstorms from 4-7 December.

There were a few subsequent outbreaks in Tanzania, mostly in the north-east and the west and there were many outbreaks in January in west Kenya, especially in Busia and Kakamega districts, and in neighbouring districts of east Uganda. In February, there were large outbreaks on grassland in Machakos and Kajiado districts (east-central Kenya). No outbreaks were reported there with moth arrival in January, probably because there was very little rain, but there must have been a widespread, low density population derived from December outbreaks.

In March and April there were several secondary outbreaks in west and north Kenya and one, near Baringo, was reported to be very large. In April there were widespread outbreaks in south and east Ethiopia, derived from the February and March primaries. There was no evidence for migration of moths, leading to outbreaks, from Kenya to Ethiopia.

1985-86

Brief summary

This season started in Kenya where it was severe, with most outbreaks occurring in Kenya and north Tanzania (Figure 27). The short rains started in Kenya in late October but were below average. Outbreaks were not confirmed until late November when they were widespread. Very few outbreaks were reported in late December to early January, but there were widespread outbreaks the following month in north Tanzania and west Kenya. Some later outbreaks were large, causing considerable damage to crops. There was no evidence for moth migration to Ethiopia where there were primary outbreaks in March.

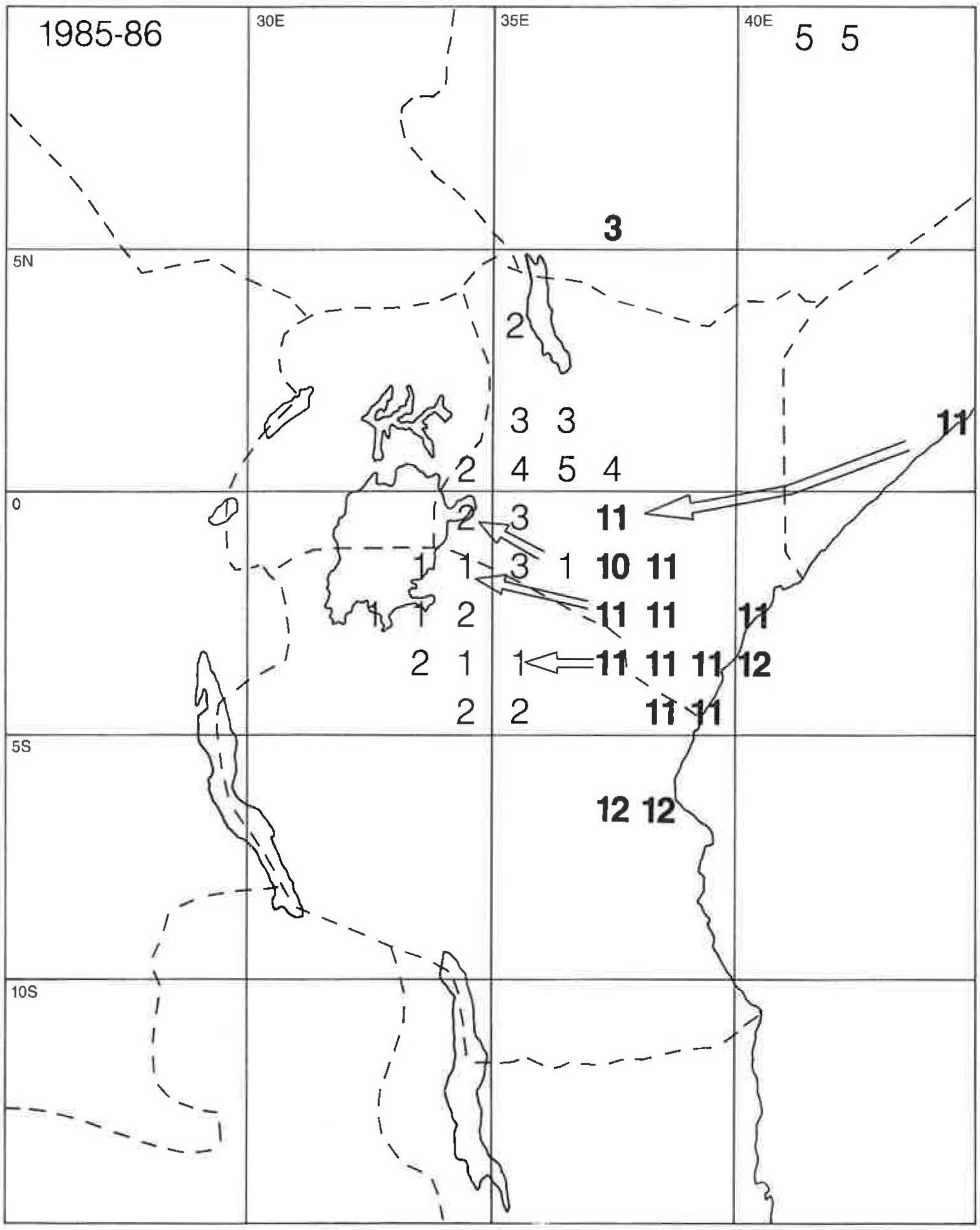

Figure 27 Summary map for 1985-86 season showing primary and secondary outbreaks

Key: See Figure 10

Primary outbreaks

There was an unconfirmed armyworm outbreak in late October, in Machakos district (east-central Kenya), followed by widespread outbreaks in November. A large (>2000 ha) primary outbreak occurred in southern Somalia, south of Mogadishu, in early November. In mid to late November primary outbreaks occurred on the Kenya coast, in Taita-Taveta district (south-east Kenya) and in neighbouring Kilimanjaro region (north-east Tanzania). In late November to early December, outbreaks occurred widely in Machakos, Embu and Muranga districts (east-central Kenya).

November outbreaks were associated with rainstorms during the short rains. In Machakos district the short rains started on 23 October, five weeks before most outbreaks, but close to the estimated moth arrival date for the unconfirmed outbreak. Armyworm populations are thought to have increased in east-central Kenya following the first rains, but may have been supplemented by immigration. Backtracks from east-central Kenya outbreaks were mostly from the east to south-east in November, giving sources towards the Kenya coast where outbreaks were too late to be sources. On 28 November and 1 December, however, winds shifted towards the north-east and migration from the south Somalian outbreak may then have contributed to some later outbreaks in east-central Kenya.

In December, primary outbreaks occurred near Dar es Salaam (Tanzania coast) and Morogoro (east-central Tanzania) associated with rainstorms.

In mid-March, two primary outbreaks occurred in neighbouring areas of Gamo Gofa and Sidamo provinces (south Ethiopia), associated with isolated rainstorms. Winds were easterly and there were no known outbreak sources.

Secondary outbreaks

Few secondary outbreaks followed the November to early December primaries. There were two outbreaks, over about 1000 ha of grassland, in Machakos district (east-central Kenya), associated with an isolated rainstorm, on 9 January, in an otherwise dry month. Another outbreak occurred near Taveta (south-east Kenya) and there was an unconfirmed report of an outbreak in Kilimanjaro district (north-east Tanzania), where rainstorms were more frequent. Moths emerging from these outbreaks would have flown west towards Lake Victoria.

From the end of January to early February there were widespread outbreaks in Nyanza and Busia districts (west Kenya), and in north-central Tanzania, from west Arusha to Lake Victoria. At Hanang (Arusha region) a serious outbreak of about 500 ha occurred on commercial wheat and barley.

From late February to early March there were further secondary outbreaks in west Kenya, with a large outbreak on wheat and grassland in west Narok and an outbreak in Machakos district (east-central Kenya). In north Tanzania, there were outbreaks in Serengeti, associated with high trap catches from 8-10 March and scattered rainstorms, and a very large (2000 ha) outbreak on the Hanang wheat scheme (Arusha region). Rainstorms from 5-7 March and 16-17 March probably concentrated moths emerging from the earlier outbreak and prevented their dispersal away from the area.

In late March and early April there were scattered outbreaks in east-central, central, west and north-west Kenya, derived either locally or from moths migrating from north Tanzania. There were no further outbreaks in Tanzania. Three outbreaks occurred in Hararghe Province (east Ethiopia) in early May, possibly derived from primaries in south Ethiopia in March.

1986-87

Brief summary

The season was severe in Tanzania, although early rains were heavy, especially in December. In Kenya outbreaks were mostly in the west and the season was only moderate. A sequence of outbreaks occurred from Morogoro region north-west towards Lake Victoria, and another from north-east Tanzania to west Kenya and east Uganda (Figure 28). In south-west Ethiopia, armyworm survived the dry season, giving rise to primary outbreaks in February and March, and later secondaries.

Primary outbreaks

In early October, primary outbreaks occurred in Busia district (west Kenya), associated with isolated rainstorms, and in Gamo Gofa province (south Ethiopia). The sources were probably local, with low density armyworm persisting from the previous season.

In late October, two small primary outbreaks occurred near Morogoro (east-central Tanzania) associated with a small catch of moths on 28 October, but no

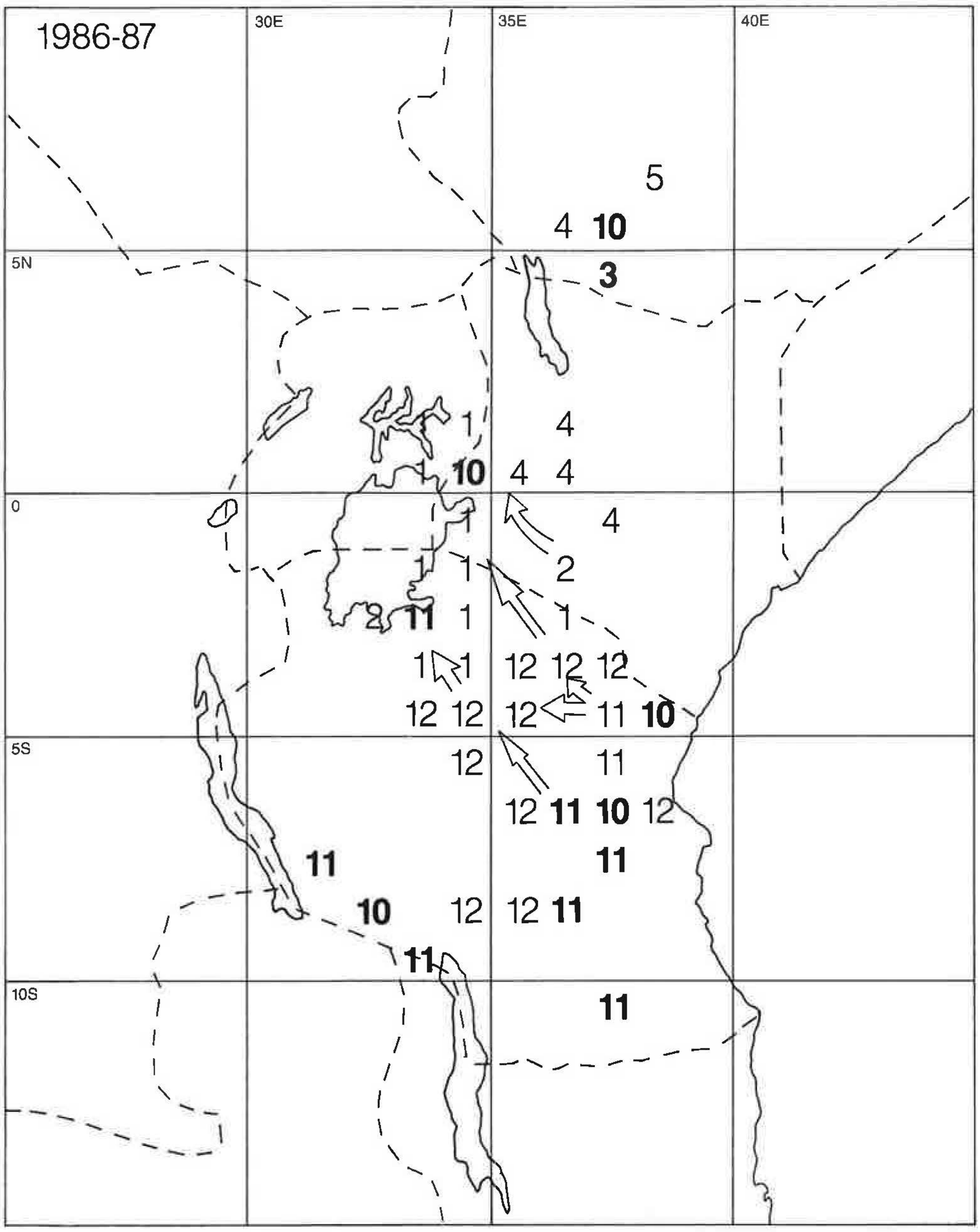

Figure 28 Summary map for 1986-87 season showing primary and secondary outbreaks

Key: See Figure 10

nearby rainstorms. Approximately 25 outbreaks occurred in November in Morogoro region, associated with large increases in moth catch at Morogoro and Ilonga pheromone traps from 14-27 November, and rainstorms from 13-26 November. Most of these outbreaks were primary, but a few later ones may have come from the October primaries. Winds were easterly, so sources were local or towards the coast where rainstorms in mid-October may have resulted in a large increase in low density populations.

Elsewhere in Tanzania, there were two primary outbreaks in Lushoto district (north-east Tanzania) associated with rainstorms from 26 October to 1 November, a primary outbreak at Mwanza (north-central Tanzania) in late November, and two small primary outbreaks in Tunduru (in the south-east) associated with the start of the rains in mid-November. In south-west Tanzania, two outbreaks occurred near Mbeya in late October and mid-November, and there were two more (one of 3200 ha) in Sumbawanga district. These outbreaks were also primary unless there were outbreak sources in Malawi (for which no data were available).

In February there was a primary outbreak in Gamo Gofa province (south Ethiopia) associated with isolated rainstorms. Small trap catches of moths indicated that armyworm at low density, had persisted from the October outbreak. Three weeks later, there were widespread outbreaks in Gamo Gofa and west Sidamo provinces, associated with rainstorms in mid-March, but probably too early to be derived from the February outbreak.

Secondary outbreaks

In late November, there were two outbreaks at Handeni and one at Same (north-east Tanzania) which probably came from moths flying west from primaries near Lushoto. In December to early January migration north-west led to further outbreaks near Arusha and Moshi (north-east Tanzania) and adjacent areas of Taveta and Kajiado districts (south-east and east-central Kenya).

During December, there were widespread outbreaks in central Tanzania, Dodoma and Singida regions and in the Hanang district of the south Arusha region. They covered a total area >80 000 ha, and parent moths came from Morogoro primaries, judging by backtracks. This indicates that control measures in Morogoro region had failed to prevent large-scale moth migration. These secondary outbreaks were associated with widespread rainstorms during December, and a well above average rainfall total. Control measures were again carried out, and heavy rain, which continued into January, was reported to have killed armyworm populations in Dodoma Region.

Three small outbreaks in Mwanza region (north-central Tanzania), in late December, were probably derived from the outbreak there the previous month.

In mid to late January about 50 outbreaks occurred on cereals in Shinyanga, Mwanza and Mara regions (north-central Tanzania) associated with below average rainfall. Most outbreaks were small and the estimated total area was about 800 ha. Backtracks were mostly from the south-east, with parent moths for Shinyanga outbreaks coming from Singida and for Mara outbreaks coming from Arusha. Outbreaks also occurred in January in Nyanza region and Masai-Mara (west Kenya), and Tororo and Mbale districts (east Uganda), with backtracks indicating sources in north-east Tanzania. Outbreaks in Kenya were larger than those in Tanzania, covering an estimated total area of 1000 ha of agricultural land and 2000 ha of wild grassland.

Further outbreaks in Tanzania occurred only in the north-east, in Arusha and Kilimanjaro regions, in March and April. In Kenya, there were outbreaks in February in the Nyanza region and Kiambu district (east-central Kenya). The Kiambu outbreaks probably came from moths flying north-west from Kajiado becoming concentrated by isolated rainstorms on 18-19 February. Subsequent outbreaks in March and April occurred in Kajiado district (east-central Kenya) and further north in Embu (east-central Kenya), Baringo and Uasin Gishu districts (north-west Kenya). Outbreaks in Gamo Gofa and Sidamo regions (south Ethiopia) in April and May probably came from earlier outbreaks there. An absence of late Ethiopian outbreaks may have been due to a lack of migration from Kenya.

1987-88

Brief summary

In this severe armyworm season the October to December rains were well below average in both Kenya and Tanzania. Widespread primary outbreaks occurred in south-east Tanzania, in early November before the onset of the rains, and in east-central Tanzania in late November, with the start of the rains. Subsequent outbreaks were in north Tanzania, following migration north-west from east-central Tanzania. An incursion of south-westerly winds in mid-March led to early moth migration into east-central Kenya (Figure 29). In April, after winds became south easterly, there was further migration north, towards north Kenya and south Ethiopia.

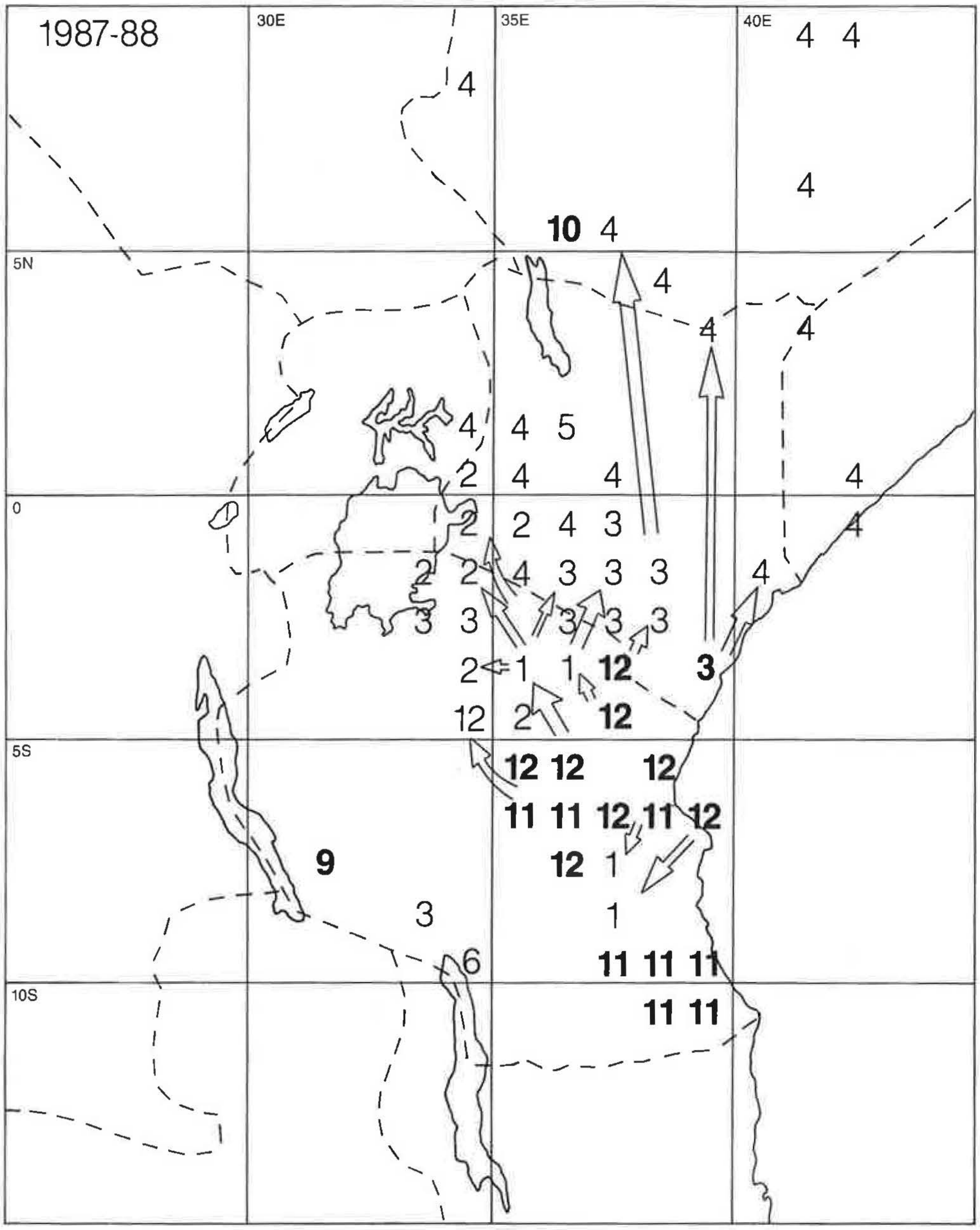

Figure 29 Summary map for 1987-88 season showing primary and secondary outbreaks

Key: See Figure 10

Primary outbreaks

In early October, a small primary outbreak occurred in Gamo Gofa (south Ethiopia) associated with isolated rainstorms.

There was a very early, unconfirmed report of an outbreak in Rukwa region (south-west Tanzania) in September. In early November, primary outbreaks were widespread in Mtwara and Lindi Regions (south-east Tanzania), associated with dry weather and isolated light falls of rain. Widespread rainstorms occurred in late November when outbreaks were already present. In early November an outbreak also occurred near Dodoma (east-central Tanzania), with moth concentration associated with isolated rain (8.6 mm) in a mainly dry period.

From late November to early December, over 40 outbreaks occurred in Dodoma and Morogoro regions (east-central Tanzania), with an estimated total area of about 3300 ha. Two early outbreaks were associated with rainstorms on 25 November and a small catch of moths at Ilonga (Table 13, Appendix 2). Most outbreaks were associated with more persistent rainstorms, and large increases in moth catch, from 9-11 December. There were also two small primary outbreaks near Dar es Salaam (Tanzania coast), associated with rainstorms on 29 November and 10 December, and one at Same (north-east Tanzania) in early December.

From late December to early January, widespread outbreaks occurred in Taveta district (south-east Kenya) and Kilimanjaro region (north-east Tanzania), associated with isolated rainstorms in a mostly dry period. These outbreaks were mostly primary, but some in Kilimanjaro region may have come from moths migrating north-west from the Same primary.

An outbreak at Kilifi (Kenya coast) in March, associated with isolated rainstorms at the start of the long rains, was probably a late primary outbreak.

Secondary outbreaks

In mid-December, there were secondary outbreaks in Lindi region (south-east Tanzania), derived from November primaries. Three outbreaks in Singida region (central Tanzania) were associated with an increase in moth catch and rainstorms from 9-15 December, after a dry period. Backtracks indicated moth migration from the early Dodoma outbreak.

In January, small outbreaks occurred in Mbulu district, south-west of Arusha (north-east Tanzania). Winds were south-easterly and backtracks indicated that parent moths probably came from primary outbreaks in east-central Tanzania. Secondary outbreaks occurred in Morogoro region (east-central Tanzania), associated with rainstorms in mid-January following dry weather.

In February, outbreaks derived from local secondaries, occurred in Singida region and Mbulu district, and also in Arusha and Kilimanjaro regions (north-east Tanzania), probably coming from the local January primary outbreaks. Outbreaks also appeared in Mara region, east of Lake Victoria (north-central Tanzania), western Kenya and Tororo district (east Uganda). Backtracks indicated that parent moths came from north-east Tanzania.

Further widespread outbreaks occurred in March in the Mara and Kilimanjaro regions of Tanzania and west Kenya. The last outbreaks in north Tanzania were in early April, in the Arusha and Kilimanjaro districts; but in south-west Tanzania, unusual outbreaks were reported from near Njombe (Iringa region) in June.

In mid to late March, there was a large-scale moth migration from north-east Tanzania to east-central Kenya, leading to about 50 outbreaks in Machakos, Kitui and Kajiado districts covering an estimated 3000 ha. A network of pheromone traps in Machakos and Kitui districts showed widespread increases in moth catch from 19-21 March, associated with rainstorms from 18-26 March (Table 13, Appendix 2) and an incursion of south-westerly winds across much of Tanzania and into south Kenya from 18-22 March (Figure 30).

From 26 March, winds veered to south-easterly or southerly over central and east Kenya. The appearance of armyworm outbreaks near Mt Kenya (east-central Kenya), Marsabit (north Kenya) and in Sidamo region (south Ethiopia) indicated widespread migration north from north-east Tanzania and east-central Kenya at the beginning of April. Further east, outbreaks at Moyale, Mandera and Wajir (north Kenya), Tana River (east Kenya) and south Somalia probably came from moths migrating from the primary outbreak at Kilifi (Kenya coast). In west Kenya, widespread outbreaks in the Trans Nzoia district in early April indicated moth migration north from March outbreaks.

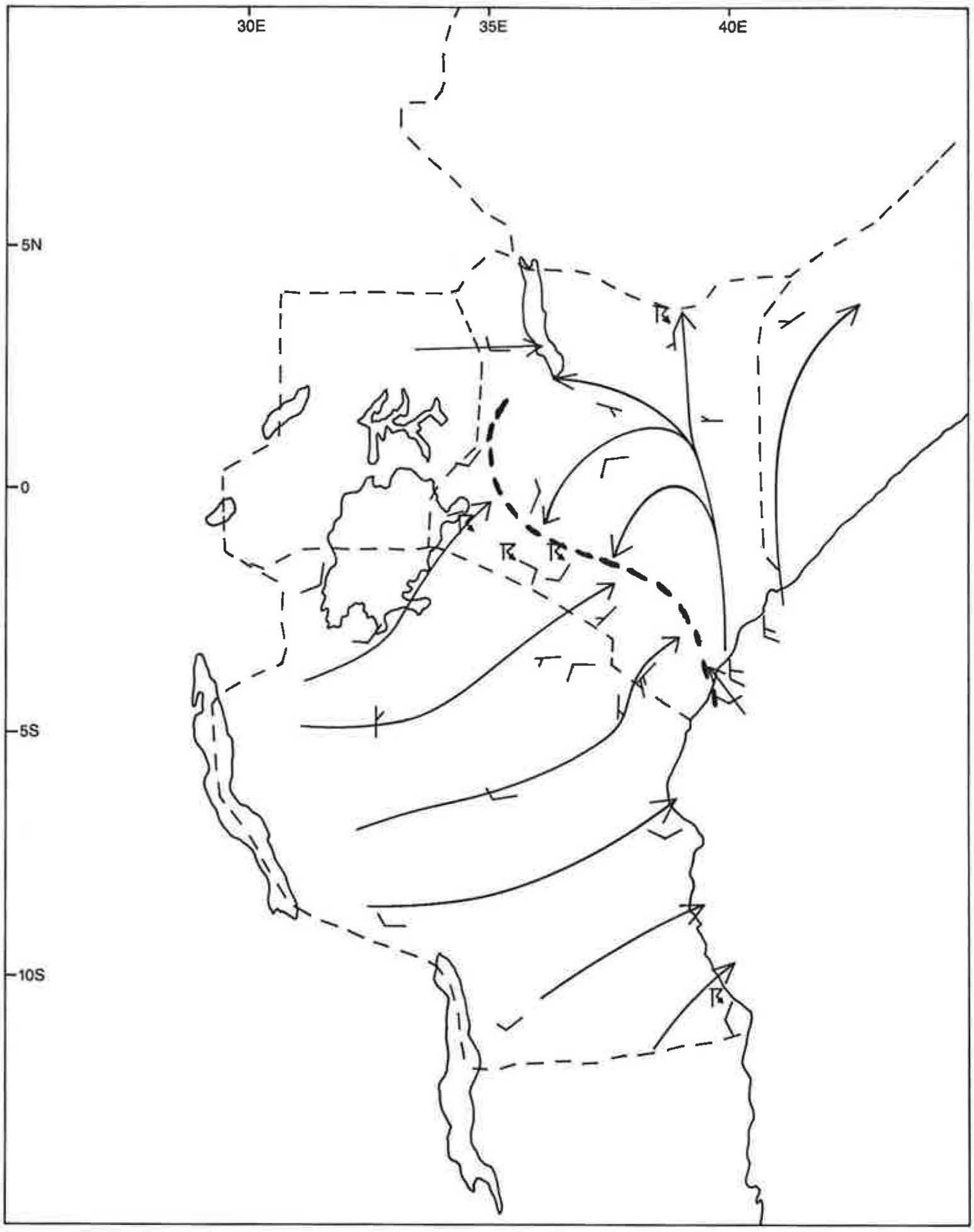

Figure 30 Surface windfield 21 March 1988

Key: Arrows are wind streamlines. Small arrows show wind directions and speeds in 2.5 m/s intervals.
Bold broken line is a wind convergence zone
ꓘ = thunderstorm

Table 12 Rainstorms associated with primary outbreaks, Morogoro area, January 1974

Outbreak location	Rainfall station														January												
		5					10					15					20					25					30
Mvomero 0620S 3725E	Mvomero										X	X															
	Berega mission																						X		X		
	Chazi										X		X	X				X	X								
	Wami prison									X	X													X	X		
	Magubika																							X			
Mikumi 0724S 3659E	Mikumi						X			X	X				X		X										
	Ulaya									X					X			X						X	X	X	
	Kisanga					X						X											X	X	X		
	Kilombero									X	X				X								X		X		X
	Kikoboga										X	X				X									X	X	
Kisaki 0728S 3736E	Kisaki										X								X			X					
Bwakira Chini 0724S 3744E	Bwikira juu										X																
	Bwikira est.										X					X				X					X	X	
	Duthumi										X				X	X				X			X		X	X	
	Singiza														X					X						X	
	Steiglers gorge										X					X				X							
Armyworm outbreaks						|—	—	—	—	—	—|																
Probable moth arrival date											M																

Notes: \|————\| Estimated moth arrival
X Rainfall >9.9 mm (rainstorm)

Table 13 Rainstorms and armyworm outbreaks in east-central Tanzania and east-central Kenya 1987-88

Rainfall station (1987)	Nov 11	Nov 13	Nov 15	Nov 20	Nov 21	Nov 25	Nov 26	Nov 28	Nov 30	Dec 5	Dec 9	Dec 10	Dec 11	Dec 12	Dec 15
East-central Tanzania															
Hombolo						X									
Dodoma						X					X				
Mpwapwa			X			X	X								
Ilonga	—	—	—	—	No data	—	—	—	→				X		
Morogoro Met				X		X						X			
Kilombero		X			X	X			X						
Ruembe		X				X			X						
Trapcatches															
Ilonga pheromone trap	No data	—	→										m	M	
Ilonga light trap						m					M	M			
Armyworm outbreaks	├	—	┤					├	—	—	—	—	┤		

(1988)	Mar 9	Mar 12	Mar 18	Mar 19	Mar 20	Mar 21	Mar 22	Mar 23	Mar 25	Mar 26	Apr 1	Apr 5	Apr 6	Apr 7	Apr 8	Apr 9	Apr 10
East-central Kenya																	
Mutomo			X					X					X			X	
Muthue			X		X		X		X				X				
Kisasi								X					X			X	
Itumba				X				X		X			X	X		X	
Ikutha				X	X			X		X			X	X			
Matinga				X		X		X	X				X	X			
											←	No data	—	—	—	—	—
Pheromone trap catches		M		M	M												
Armyworm outbreaks	├	—	—	—	—	┼	—	—	—	—	┼	—	—	—	┤		

Notes:

├──┤	Estimated moth arrival leading to outbreaks
m	Small increase in moth catch
M	Large increase in moth catch
X	Rainfall >9.9 mm (rainstorm)

The Bulletin series presents the results of research and practical scientific work carried out by the Natural Resources Institute. It covers a wide spectrum of topics relevant to development issues ranging from land use assessment, through agricultural production and protection, to storage and processing.

Each Bulletin presents a detailed synthesis of the results and conclusions within one specialized area, and will be of particular relevance to colleagues within that field and others working on sustainable resource management in developing countries.

The work reported in this Bulletin summarizes African armyworm seasons from 1972-88, and discusses the relationships between the frequency of outbreaks and weather conditions. Outbreaks are classified as primary and secondary with critical outbreaks identified as the source of subsequent infestations. The use of trajectory analysis in estimating the migration paths of windborne moths during the season is discussed together with the importance of rainstorms in concentrating the moths to cause an outbreak.

Weather and the Epidemiology of the African Armyworm (*Spodoptera exempta*) should be of interest to many working in the field of predictive techniques in migration research, and those planning control operations against this serious pest.