SPATIAL DYNAMICS OF TEAK DEFOLIATOR
(*HYBLAEA PUERA* CRAMER)
OUTBREAKS: PATTERNS AND CAUSES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY
OF THE
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY

By

T.V. SAJEEV, M.Sc.

DIVISION OF ENTOMOLOGY
KERALA FOREST RESEARCH INSTITUTE
PEECHI, 680 653, KERALA

SEPTEMBER 1999

DECLARATION

I hereby declare that this thesis entitled "Spatial dynamics of teak defoliator (*Hyblaea puera* Cramer) outbreaks: patterns and causes" has not previously formed the basis of any degree, diploma, associateship, fellowship or other similar titles or recognition.

Peechi
27th August 1999.

T.V.Sajeev

CERTIFICATE

This is to certify that the Ph.D thesis entitled "Spatial dynamics of teak defoliator (*Hyblaea puera* Cramer) outbreaks: patterns and causes" is a genuine record of the research work done by Shri. T.V.Sajeev (Reg.No. 1459) under my scientific supervision and the work has not formed the basis for the award of any degree, diploma or associateship in any University.

Thiruvananthapuram
28th August 1999

(Dr. K.S.S.Nair)
Supervising Guide

ACKNOWLEDGMENTS

I wish to place on record my deep sense of gratitude to:

Supervising guide, Dr. K.S.S.Nair, former Director, KFRI for suggesting this problem, his guidance and creative suggestions.

Dr. R.V.Varma, Scientist-in-Charge, Entomology Division, KFRI for his encouragement and kind reminders on the task at hand.

My colleagues, Dr.V.V.Sudheendrakumar and Dr. K.Mohandas, for their work on the teak defoliator which laid down the framework within which this work was possible.

Dr.P.S.Roy, Head, Forestry and Ecology Division, Indian Institute of Remote Sensing, Dehra Dun, for extending the facilities for the initial GIS anaysis.

Dr.A.R.R.Menon, Scientist, Ecology Division, KFRI, for providing aerial photographs and topographic sheets for the study.

Dr. Francois Houlier, former Director, French Institute of Pondicherry, Dr. Sonia Darraccq, and Filiduaro Limaire, Geomatics Division, French Institute of Pondicherry for extending facilities for the final GIS analysis.

Mr. Santhosh K. John, former Officer-in-Charge, KFRI Subcentre, Nilambur, for providing infrastructural facilities at Nilambur and for his keen interest in the topic.

Mr. Rajan James, Mr. A. Moosa, Mr. K. Sunny, Mr. Saji John and Mr. K. Mohammed of KFRI Subcentre, Nilambur for their painstaking efforts in assisting data collection.

Mr. Byju Hameed and Mr. K.V.Sathyakumar, Research fellows, KFRI, for their helpful participation in field trips.

Mr. K.P.Manoj, KFRI Subcentre, for his cheerful hospitality while being at Nilambur.

To my parents, and all my dears and nears who have extended moral support to see me through the completion of work.

TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

Insects are of interest to man because of two major reasons- the large diversity exhibited by the group, and man's conflict with insects for food and other resources. Insects that draw our attention because of the latter reason are called pests. In most cases, being a pest is a matter of abundance of individuals. At some times, the population density increases to cause economic damage but at other times the density remains low. This increase and decrease of population density of different species of insects has intrigued the population biologists for long. Although it is generally agreed that this fluctuation is related to the availability of food and other resources, other factors such as natural enemies and climate are also thought to regulate the size of a population.

The teak defoliator, *Hyblaea puera* Cramer (Lepidoptera, Hyblaeidae) which is recognized as a serious pest of the teak tree (*Tectona grandis* L.f..) is a typical pest that exhibits this characteristic shift in population density. Teak is a multipurpose timber species, which naturally occurs in India, Myanmar, Thailand and Laos. During the last century when the natural teak stands could not cater to the needs, plantations of teak became a necessity. The first plantations in India were established at Nilambur (Kerala) during 1842-44. Since then, the area under teak has steadily increased and plantations have been raised in several other tropical countries of the world as well. Presently, in Kerala, the teak plantations extend to an area of about 78,800 ha (Shanmuganathan, 1997). This is 46.5% of the total area under forest plantations in Kerala. The major teak growing areas in Kerala are Wayanad, Nilambur, Parambikulam, Nelliampathy, Achenkoil, Aryankavu, Konni, Ranni and Malayattoor.

Although 171 species of insects are recorded as associated with teak, only a few have attained pest status (Beeson, 1941). These are the white grubs, which attack seedling in the nurseries, the sapling borer (*Sahyadrassus malabaricus*)

(Nair, 1987), the trunk borer (*Alcterogystia cadambae*) (Mathew, 1991), the teak skeletonizer (*Eutectona macheralis*) (Beeson, 1941), and the teak defoliator (*Hyblaea puera*) (Beeson, 1941). While the white grubs are usually found restricted to the nurseries, the sapling borer to young trees; the trunk borer to specific regions; and the skeletonizer, to a period in the year when teak is about to shed its leaves, the teak defoliator occurs in almost all teak plantations during the active growing period of the tree. This characteristic makes it the most serious pest of teak. It has been estimated that damage caused by this insect in 4-8 year old plantations leads to an increment loss of 3 m^3/ha/year (Nair *et al*, 1996).

Realizing the economic loss caused by the insect, attempts were made in the past to standardize control methods, which included biological control as well as aerial spraying of chemical insecticides. Biological control using insect parasitoids did not prove successful and the environmental impact of insecticides makes them unsuitable. Biological control using a recently identified Nuclear Polyhedrosis Virus (NPV) (Sudheendrakumar *et al*, 1988) is seen as a promising alternative because it is quick acting (Nair *et al*, 1996) and is highly specific to this insect.

However, the major problem in using any control agent is the difficulty in detecting the teak defoliator outbreaks early enough to apply the control measures. The vast extent of the plantations and the hilly terrain in which the search has to be made to detect the early sites of outbreaks pose practical problems. The larval life span of the insect lasts only for about 15 days within which the entire foliage on the tree may be eaten off. To prevent damage, the early instars of the larvae have to be detected and controlled. The sudden appearance of infestations in widely separated patches during the early outbreak period, suggests that successful control of the pest could only be achieved by understanding the population dynamics of the insect.

Recent research has shown that the population trend of the teak defoliator exhibits several distinct phases (Mohanadas, 1995). The first phase which start with the onset of premonsoon showers is characterized by small patch infestations, which may appear erratically in some areas. The next phase is characterized by heavy and widespread infestations, which result in total defoliation of large extent of plantations. In the third phase, the population density declines and infestations again become erratic. Following a lull period, erratic populations appear again in August, September or October and subside. From then on, until the first phase begins again next year, the population remains very low, almost untraceable.

Based on this temporal pattern of infestations and the detection of early outbreaks in small patches, it was hypothesized that outbreaks originate, by population build up in small epicentres from where it spreads to larger and larger areas over successive generations (Nair and Mohanadas, 1996) until the population exhausts its resources and/or causes increases in the populations of natural enemies causing its decline. From a practical pest control point of view, this hypothesis is interesting because controlling the small epicentres during the phase of population build up is relatively easy. The major objective of the present investigation was to verify this hypothesis. This was sought to be accomplished by recording the spatial and temporal sequence of outbreaks in large study areas and examining whether the initial populations could cause the subsequent populations.

The opportunity was also utilized to examine whether suitable monitoring techniques could be developed to detect and predict the outbreaks, through light-trap catches of moths and/or field observation of early signs of infestation. Observations were also made on the flight, reproductive, and feeding behaviour of defoliator moths in the field to understand their influence on the population dynamics of the insect.

The study has yielded valuable information on each of the above aspects. Following a review of literature in the next Chapter, Chapter 3 describes the general methods employed in the study. Chapter 4 presents the results of a three-year study on spatial dynamics of outbreaks at one of the teak plantations of Nilambur, *viz*. Kariem Muriem and Chapter 5, the results of a similar study covering the entire plantations of Nilambur in one year. Behavioural studies on defoliator moths are given in Chapter 6. Attempts to develop monitoring techniques to detect outbreaks are presented in Chapter 7. In Chapter 8, an attempt is made to synthesize all available empirical information on the population dynamics of *Hyblaea puera* in the light of recent advances in theory. The literature referred to for this work is presented next, as per guidelines given by Anderson *et al* (1970). The algorithm used for the computation of auto correlation indices is given in Appendix A and light-trap data in relation to incidence of defoliator outbreak and local moth emergence is given in Appendix B.

CHAPTER II

REVIEW OF LITERATURE

The teak defoliator was recognized as a pest of teak in India as early as 1898 (Bourdillon, 1898). During the past 100 years, the major topics of interest were the impact, biology, ecology, natural enemies, and control strategies related to this insect.

A general description of the different life stages of teak defoliator was presented during the early part of the century (Stebbing, 1903). Two different species were described, *Hyblaea puera* Cramer and *Hyblaea constellata* Guen. along with a variety described as The Black Hyblaea- *Hyblaea puera* var. *nigra*. Descriptions of all the above said insects resembled each other except for the colouration in larvae and adults. Distribution of *H.puera* and *H.puera* var. *nigra* was continuous throughout India and Burma while *H.constellata* was recorded only from Burma. In the next year (Hole, 1904) it was reported that *H.constellata* differed from *H.puera* with respect to two characters which are (a) *H. constellata* has the outer margin of the forewing excised below the apex and excurved at the centre, whereas in *H. puera* the margin is evenly curved and not excised, and (b) in *H. constellata*, in the anal angle, on the under side of the hind wing, there is a single black spot, whereas in *H. puera* there are two such spots. He commended that it is untimely to regard *H.puera* var. *nigra* as distinct from *H.puera*. The present study does not consider the variety *nigra* as distinct from *H.puera.* All the three insects were grouped under the family Noctuidae until Zerny and Beier classified the genus *Hyblaea* Fabricius under the family Hyblaeidae in 1936 (Singh, 1955).

Early research in Burma (Mackenzie, 1921) was primarily aimed at estimating the economic impact caused by this insect and the methods to control it. Mackenzie estimated an annual financial loss of Rs.1.5 lakhs for plantations in

Burma and recommended that providing nesting boxes for birds that feed on defoliator larvae will help control the problem.

Attempts were made seventy years back by Beeson to map the outbreaks of defoliator at the same general location of the present study. Starting from August 1926, a special officer was put in charge to patrol the teak plantations at Nilambur and record the distribution and grade of defoliation (Beeson, 1928). The study showed that complete foliage loss due to the insect occurred during the months September and October. Since the observer did not confirm the presence of insect in the area, it is difficult to draw any conclusions as to the progression of outbreaks. Moreover the incidence of teak defoliator and teak skeletonizer was not distinguished while preparing the maps making it difficult to understand which insect caused damage when. This study indicated that control of the insect during the epidemic phase would be difficult and hence attempt has to be made to prevent the shift from endemic to epidemic phase. Beeson highlighted the difficulty in timely detection of outbreaks and commented that attempts to control teak defoliator requires the same alertness, as that demanded by forest fires.

In 1934, a set of silvicultural-cum-biological control measures was put forward (Beeson, 1934). They were: (a) sub-division of large blocks of pure teak (sub-division by means of pre-existing forest rather than of newly created stands or mixtures); (b) establishment of a varied flora under the teak canopy (at the outset by retention of coppice re-growth and miscellaneous seedlings rather than by artificial introduction of selected species at a later stage); (c) elimination of harmful plants (this category includes alternative food-plants of defoliator); (d) maintenance of an understorey in older stands (for its value as a shelter for beneficial animals and as obstacle to defoliators) (e) introduction of parasites and predators (after careful assessment of the defective factors of locality).

Establishment of a varied flora under the teak canopy to provide adequate breeding sites for natural enemies of the pest was tried in 1942-43 (Khan *et al.*, 1944). Two plantations nearly two miles apart with differing levels of undergrowth were compared with respect to the incidence of defoliation and presence of parasites. However, the experimental set up did not yield reliable conclusions. Eventhough the role of parasites was not empirically proved, faith in Beeson's recommendations persisted for a long period. But none of the recommendation were put to practice due to various reasons (Nair *et al.*, 1997) except for an order issued in the then Madras state prohibiting the cutting away of undergrowth in teak plantations (Kadambi, 1951).

Intensive observations were made in June 1950 at the Nilambur teak plantations to identify the causes of defoliator outbreaks (Kadambi, 1951). These observations brought out the fact that some trees escaped defoliation amidst a completely defoliated stand. Based on observation on the intensity of defoliation, it was suggested that the presence of tender foliage at the time of larval appearance was the factor that predisposed trees to defoliation. Research on how some trees escaped defoliation was also recommended.

One of the suggestions put forward by Kadambi in 1951 was to test the resistance of trees that were found escaped amidst a defoliated stand. This was attempted in a study started in 1983 in Kerala (Nair *et al.*, 1997). Trees, which escaped defoliation during one year, were observed in the next year. Many of these trees were found infested and grafting from ten trees, which had escaped defoliation under natural conditions, were readily attacked when exposed artificially to the insect. This meant that there was no genetic resistance to the pest. A comparison of resistance in the different clones at Nilambur and Arippa orchards indicated that none were resistant. Since the clones were all from Kerala, it was concluded that search for resistance may be continued using clones from other parts of India and abroad. Another study using twenty different clones (Ahmad,1987) collected from southern parts of India was done in 1987. One among the ten clones from Tamil Nadu (Top slip) showed the highest resistance to defoliator attack and another clone from Kerala (Karulai) showed the highest growth increment. The study proposed intraspecific crosses between these two clones for further improvement towards pest resistance and higher yield.

In a two-year light trap study at Jabalpur in 1978 and 1979 (Vaishampayan *et al.*,1983), collection of teak defoliator moths was restricted to July, August and September. Two explanations were put forward: migration of moths and diapause.

Although the importance of biological control agents was highly emphasized during the early period, aerial spraying of chemical pesticides was done in 1965 (Basu-Chowdhury, 1971) and 1978 (Singh *et al.*,1978). The first spraying was on an experimental basis in an area of 76 ha at Konni teak plantations in Kerala. The second spraying was done at Barnawapara plantations in Madhya Pradesh. In the second spray application, very few larvae survived in the sprayed plots as compared to the untreated controls. Although it was claimed that there was no adverse effect on wildlife including birds, the facts remain that 80 l. Malthion, 75 l. Fenitrothion and 260 kg. Carbaryl were deposited over an area of 460 ha.

Argument against aerial spraying of chemicals was put forward (Nair, 1980) based on three major reasons: (a) a realistic estimate of loss due to defoliator attack is not arrived at to calculate the cost-benefit ratio of aerial spraying, (b) environmental hazards and (c) adverse impact on natural enemies of the pest. Large-scale application of chemical pesticides against the teak defoliator has not been reported except in nurseries and private sector plantations, in recent years.

An attempt was made during the period 1979 to 1982 to answer the long-standing question of economic impact of the teak defoliator (Nair *et al.*, 1996). Experimental plots in a four year old plantation were given selective protection against one or both of the two major defoliators or left unprotected for a period of five years. Measurements of trees at the end of the experimental period showed that the annual increment loss is 3 m^3 per ha in 4-8 year old plantations at 64% stocking. Projections based on this estimate indicated that protected plantations could yield the same volume of wood in 26 years as unprotected plantations would yield in 60 years, provided other necessary inputs are given.

Evidences for migration of the defoliator moths were independently brought out by two groups of researchers during the later part of 1980's (Nair and Sudheendrakumar, 1986; Vaishampayan *et al.*, 1987). The first study based on survey of defoliation along the Western Ghats and detailed observation of infestation characteristics at Peechi and Nilambur in Kerala proposed a model for the population dynamics of teak defoliator with short-range migration of moth populations. The second study relied on eight-year light-trap data from Jabalpur and showed a close link between defoliator outbreaks and the arrival of monsoon. It suggested that Kerala situated at the extreme southwest part of the country is a centre of origin of activity of *H.puera* from where moths migrate northward along with the progression of southwest monsoon.

A synthesis of information on the population dynamics of teak defoliator appeared in 1988 (Nair, 1988). It dispelled the notion that diapause occurs some time during the life history of the insect. Instead, it placed migration as the cause of absence of defoliator activity during part of the year. In almost the same way as Kadambi suggested in 1951, it emphasized the relation between presence of tender foliage and the susceptibility to defoliator incidence. It was also brought out that defoliator incidence is not associated with stand and site conditions of teak which means that outbreaks cannot be prevented by increasing the stand vigor through silvicultural management practices.

A renewed interest in the role of biological control agents in combating the defoliator attack was seen during the past decade. Of particular importance is the nuclear polyhedrosis virus that was isolated from defoliator larvae (Sudheendrakumar *et al.*, 1988). In the same year, observations were made on the bird predators of defoliator larvae which showed that 58 species of birds were feeding on defoliator larvae during the months of March, June and July (Zacharias and Mohandas, 1990). Studies on the parasitoids of teak defoliator at Nilambur during 1983-94 and 1987-89 recorded 15 species- seven from larvae and eight from pupae (Nair *et al.*, 1995). Effectiveness of the dueteromycetous fungi, *Beuveria bassiana* (Bals.) Vuill, in causing mortality to the defoliator larvae was studied in 1993 (Rajak et at.,1993). It showed that the early larval instars were more prone to fungal infection. It is curious to note that a sixth larval instar of *H.puera* was used in this study while none of the earlier or later studies indicates the presence of the same.

In an attempt to understand the spatial distribution of defoliator outbreaks Nair and Mohanadas (1996) kept the road-side plantations at Aravallikavu, Valluvasseri, Karulai and Kariem-Muriem at Nilambur under observation during the pre-outbreak season in 1987. The study showed that the first noticeable event in the chain of events leading to wide spread outbreak of defoliator is the sudden occurrence of fairly high-density, tree-top infestations in small, discrete patches covering 0.5 to 1.5 ha. These infestations were proposed to be the transitional stage between an endemic population and an epidemic and were designated as epicentres from where wide spread outbreaks originate.

CHAPTER III

GENERAL METHODS

3.1. INTRODUCTION

This chapter summarizes the general methods used in the study; additional, specific details are described in the respective chapters. The work involved three major types of investigations- study of spatial distribution of defoliator outbreaks, monitoring of moth populations using light-trap and field observations on moth behaviour.

All investigations were carried out in teak plantations at Nilambur, in north Kerala (Fig.3.1.). Specific methods used for monitoring moth populations are described in Chapter 6, and for studying the field behaviour of moths in Chapter 7.

3.2. THE STUDY AREA

The study area is located between Latitudes 11°10' N and 11°25' N and Longitudes 76°10' E and 76°25' E, and fall within Nilambur North and Nilambur South Forest Divisions. The teak plantations cover an area of about 8516 ha spread out in a geographical area of 25,750 ha (Fig.5.1, Chapter 5).

The spatial distribution of outbreaks was studied at two spatial scales- in a continuous block of about 1000 ha of plantations at Kariem-Muriem over a three year period and in the entire teak plantations at Nilambur covering over 8500 ha., over one year.

The Kariem Muriem teak plantation is located in the Vazhikkadavu Forest Range of Nilambur North Forest Division, between latitudes 11°22.7' and 11°25.7' and longitudes 76°16.44' and 76°18.47'. This area, located 16 km from Kerala Forest Research Institute (KFRI) Subcentre at Nilambur was chosen for detailed study because of good accessibility and information based on previous studies at KFRI that it is an area prone to repeated infestations almost every year.

3.3. PREPARATION OF PLANTATION MAPS

Before the start of observations, a map of Nilambur area, showing all the teak plantations was prepared by interpreting aerial photographs in the scale 1:15,000.

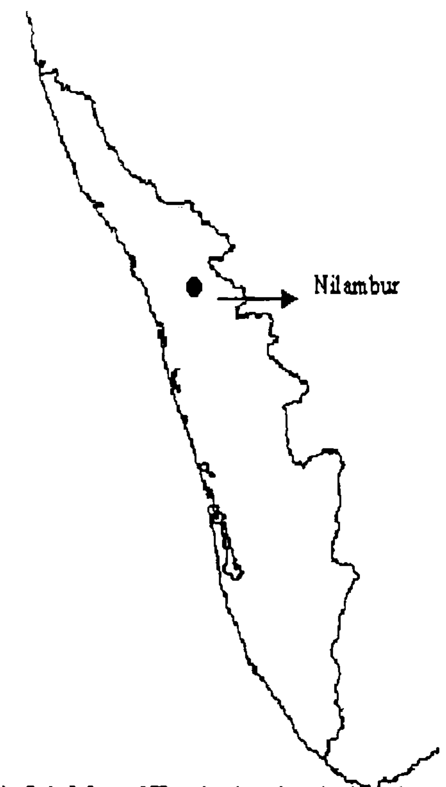

Fig.3.1. Map of Kerala showing the location of study area.

This map was brought to 1:50,000 scale and features like drainage, roads, and contours were marked by superimposing the map over Survey of India (SOI) topographic sheets. This composite map was used for plotting the defoliated sites.

3.4. OBSERVATIONS AT KARIEM MURIEM

The study area at Kariem Muriem was divided into twenty grids based on natural boundaries like streams, footpaths and roads (Fig.4.1). Each grid had an average area of 50 ha. A group of ten grids referred to above formed a block and was under observation of a single individual. Two individuals trained to identify and report defoliator outbreaks were deployed in the area to assist in the study. Each of these observers was asked to complete one round of observation within a period of 15 days.

Within each grid, the level of tender foliage and the presence or absence of defoliator outbreaks was observed by criss-cross perambulation. However, this method did not permit detection of very low populations of the insect, which required intensive search. Only populations, which caused visual defoliation of the tree, were detected.

Weekly visits were made to the plantation to verify the reports from observers. In addition, whenever the observers reported an infestation, the site was personally visited to gather information on (1) the date of egg laying and (2) the area infested. Two visits were made for this purpose, one at the beginning of the infestation to determine the date of egg laying and the other at the end of the infestation to determine the area infested. The following procedures were used.

Determination of the date of egg laying:

Larval samples were brought from each of the infested sites and were reared in the laboratory until they moulted. Based on the date of moulting, the date of egg laying was arrived at by back-calculation based on the time span needed for each previous larval instars (preoviposition period- 2 days, egg- 1 day, Instars I to V- 2,2,3,3 & 3 days respectively and pupa- 5 d).

Determination of area infested:

This was done usually when the insect was in the pupal stage because by that time the full damage to the tree would have occurred, making it easier to estimate the infested area. A sketch of the infested area was made based on landmarks like roads, streams, etc. on copies of plantation maps prepared earlier. The area was estimated using Geographic Information System (GIS) as described in Chapter 4.

3.5. OBSERVATIONS IN THE ENTIRE NILAMBUR TEAK PLANTATIONS

The study area at Nilambur was divided into 149 grids and 20 observers were employed to report defoliator incidence. The area under supervision of each of the observers was visited at least once every week to verify their observation. Whenever outbreak was reported, the date of egg laying at the site and the area under outbreak was determined as described above.

CHAPTER IV

STUDIES ON THE SPATIAL DISTRIBUTION OF OUTBREAKS IN KARIEM MURIEM TEAK PLANTATIONS AT NILAMBUR

4.1. INTRODUCTION

The teak defoliator outbreaks are characteristic in their sudden occurrence over large plantations. It has been observed that outbreaks are prevalent only during some part of the year (Beeson, 1941). Light-trap collections of defoliator moths at Jabalpur, Madhya Pradesh (Vaishampayan *et al.*, 1983) showed that a large number of moths were collected all of a sudden in July, preceded by a period of nearly 6 months when no moths were collected. This suggested that the insect is not breeding locally. Either migration or diapause was thought to be influencing the population level. A later study in Kerala (Nair and Sudheendrakumar, 1986) showed that the insect is active continuously in the teak plantations eventhough the population density fluctuated over the period - large scale outbreaks occurred during April-July and a very low population comprising overlapping generations of the insect was present during the rest of the year. In a three year study based on sample plots (Mohanadas, 1995), it was inferred that several distinct phases were recognized in the population trend of teak defoliator. The first phase during February to April is characterized by small patch infestations. This is followed by heavy and widespread infestations. It was observed that in a given large area, a second outbreak might occur before the moths of the existing generation has emerged. In the third phase, the population density declines and infestations become erratic. Following a lull period, erratic infestations occur again in August, September, or October and subside. Following this, it was observed that until the first phase begins again next year, the population remains very low, almost undetectable.

However, very little is known on the distribution of defoliator outbreaks in space. Maps of plantations showing defoliation prepared by Beeson (1928) showed that outbreaks do not occur simultaneously in all places. Based on a ground survey conducted in roadside teak plantations along the Western Ghats in Kerala and part of Karnataka, Nair and Sudheendrakumar (1986) showed that moths emerging from an outbreak site moved at least 4 km before causing another outbreak. They suggested a short-range, gypsy-type of movement of *H. puera* populations resulting in a south to north progression in the incidence of outbreaks in course of time. A later study at Nilambur (Nair and Mohanadas, 1996), showed that the first outbreaks during an year occur in a few small patches, 0.5-1.5 ha in area, which are widely separated. It was suggested that these early patches serve as epicentres where the population builds up and spread to other areas.

Except the above few studies, most studies on *H. puera* populations were concerned with temporal changes in population. Study of the spatial distribution of outbreaks is important to: (1) understand the cause–effect relationship between previous and subsequent outbreaks, and (2) examine the spatial preference of defoliator outbreaks. Detailed investigation made into the spatial distribution of outbreaks in about 1000 ha of teak plantations at Kariem - Muriem during a period of three years, are described and analyzed in this Chapter. The pattern of outbreaks and its relationship with the topography of the area was examined using Geographic Information System (GIS). It was examined whether populations of the insect noticed within the study area could cause the subsequent outbreaks in the area.

4.2. METHODS

GIS was used to map the sites of infestation and relevant site characteristics such as elevation and aspect within the study area and to make relevant analysis of data. GIS is a computer software that store, retrieve, transform, display, and analyze spatial data (Anonymous, 1995). Georeferenced data, such as insect densities, crop type, or soils can be incorporated in a GIS to produce map layers (Liebhold *et al.*, 1993). A map layer, generally composed of only one type of data, thus has a theme. The GIS serves as a tool for analyzing interactions among and within these various spatially referenced data themes. The software used was ARC/INFO in a UNIX platform. The methods used to prepare the maps and the procedure of analysis are given below.

4.2.1 Preparation of maps

4.2.1.1 Outbreak maps

Defoliator outbreaks were mapped in the scale 1:50,000 as described in Chapter 3. These maps were digitized in individual layers of the GIS database. To understand the frequency of defoliator outbreaks in different sites within the study area, all the defoliation maps of a particular year were overlaid to produce a composite map. Information on the number of times that a particular site was under outbreak was generated in the database of the composite map. This information was used to produce the outbreak frequency map.

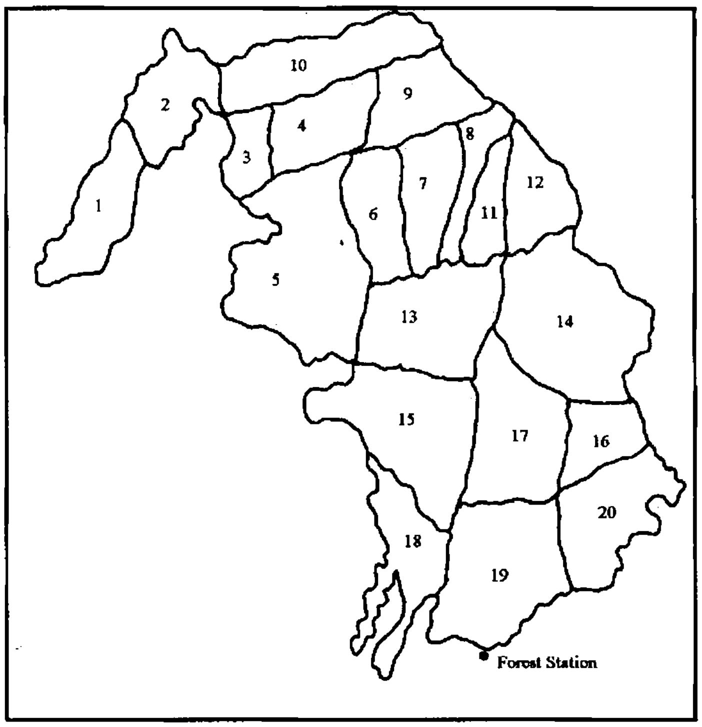

Fig.4.1. Map of Kariem Muriem showing the layout of grids.

4.2.1.2. Elevation and aspect maps

The contour lines were scanned into a separate layer. A digital elevation model (DEM) was developed using the elevation values (z values) pertaining to the contour lines. The DEM contains a closely gridded surface with a particular elevation value assigned to each grid. The aspect map was prepared from the DEM. Aspect identifies the down-slope direction of the maximum rate of change in value from each cell to its neighbours. (Aspect can be thought of as slope direction). Aspect is expressed in positive degrees from 0 to 360, measured clockwise from the north. The values of the output grid are the compass direction of the aspect. The aspect map was generated as per methods provided by ARC/INFO; the details are given in Appendix 1.

4.2.2. Spatial autocorrelation analysis

Spatial autocorrelation is a measure of the similarity of objects (outbreak patches in this case) within an area. It was used to measure the relationship of defoliation frequency values of grids and the distance between them. Two autocorrelation indices were used in the present study- Geary index and Moran index. The indices are measures of attribute similarities as a function of distance. Algorithms for the indices were provided by ARC/INFO (Anonymous, 1995) and are given in Appendix A. The interpretations of Geary and Moran indices are summed up in Table 4.1.

Table 4.1. Interpretation of Geary and Moran indices

Geary (c)	Moran (I)	Interpretation
$0<c<1$	$I>0$	Similar,regionalized,smooth and clustered
$c=1$	$I=0$	Independent,uncorrelated,random
$c>1$	$I<0$	Dissimilar,contrasting,chekerboard

4.2.3. Correlation between outbreak incidence and topographic features

The correlation between the defoliation frequency map with the topographic layers of elevation and aspect was calculated. For each pair of layers the covariance was calculated using the formula provided by ARC/INFO (Anonymous, 1995).

4.3. RESULTS

4.3.1. Outbreak pattern, 1992

The sequence of outbreaks during the year 1992 is given in Table 4.2 and Fig.1. Systematic observations at Kariem Muriem were started in June, but prior to this, in April, an outbreak was detected at a small patch. Since the area was not estimated, this outbreak was excluded from the spatial analysis. It is not known whether similar outbreaks occurred at other places before June. The first outbreak after the start of the study period occurred on 13 June at two distinct patches. An area of 1.8 ha was totally defoliated during this infestation. The subsequent outbreak on 7 July occurred at three distinct patches and extended to an area of 97.8 ha. Both the above said infestations occurred in different grids. Egg-laying was restricted to the top level of canopy in both the instances.

During the first fortnight of August, a new infestation was recorded in an area of 10.5 ha. There were two distinct patches quite close to the sites of the first outbreak. Two days later, a larger area of 111.3 ha was infested. There were two infestations in September. The first extended to an area of 35.8 ha while the second to an area of 131.8 ha. A major infestation covering an area of 169.6 ha occurred during the first fortnight of October. The last infestation during the year was on 14 October covering a total area of 21.4 ha.

Table 4.2. Sequence of defoliator outbreaks at Kariem Muriem during 1992.

Sl. No.	Date of egg-laying of the observed population	No. of outbreak patches	rea unde outbreak (ha)	Probable date of egg-laying of the resultant progeny (F1 generation)	Whether the actual date of egg-laying (Column 2) falls within the range of probable dates of egg-laying by a previous generation of moths
-	18 April	unknown	small patch	8-13 May	Unknown
1	13 June	2	1.8	3-8 July	No
2	07 July	3	97.8	27July-01 August	Yes
3	03 August	2	10.5	23-28 August	No
4	06 August	4	111.3	26 August-01 September	No
5	01 September	3	35.8	21-26 September	Yes
6	22 September	5	131.8	12-17 October	Yes
7	01 October	4	169.6	21-26 October	No
8	14 October	2	21.4	3-8 November	Yes
Total area infested (ha)			580.0	-	-

Thus, there were eight outbreaks during the year. Based on the date of egg-laying and the information on life span of the different life stages of the defoliator the probable date of start of F1 generation can be computed. It can be seen (Table 4.1.) that the date of egg-laying which caused populations 2,5,6 and 8 overlaps with the start date of F1 generation of a previous population. It is quite probable that the populations are the offsprings of earlier populations. However, it is certain that populations 1,3,4, and 7 could not be caused by the offsprings of earlier populations. The populations that could have been caused by earlier populations comprise a total area of 286.8 ha out of 580 ha infested during the year. This means that nearly 50% of the infestations during the year 1992 could have been caused by the offspring of earlier outbreaks during the year.

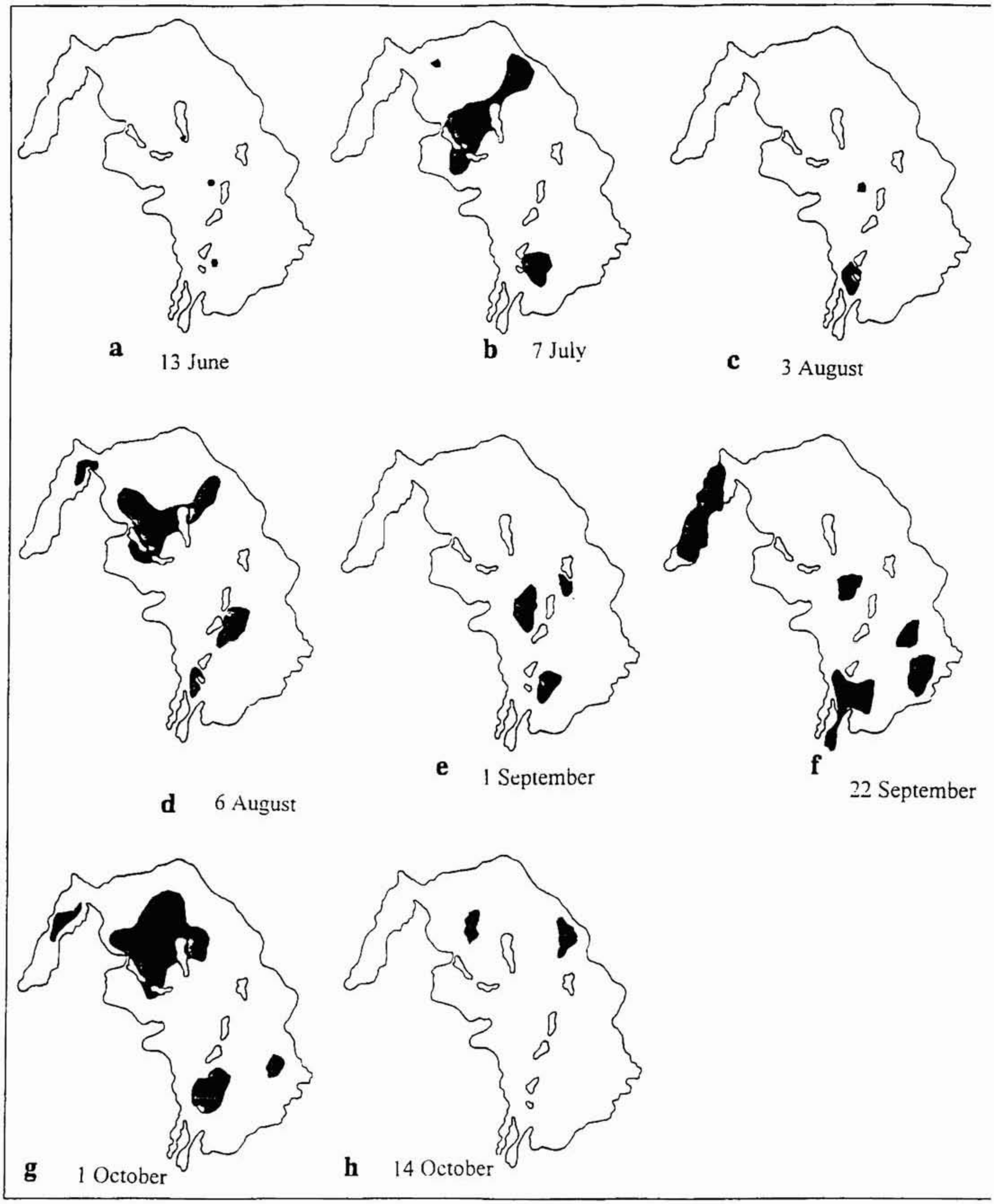

Fig.1. Sequence of defoliator outbreaks in 1992.

4.3. 2. Outbreak pattern, 1993

The sequence of outbreaks during the year 1993 is shown in Table 4.3. and Fig. 2. The first outbreak during the year 1993 occurred on 19 February at two distinct patches comprising a total area of 5.8 ha. One week later, a single patch of infestation was noticed at a different site. It was a small patch of 2.5 ha and had the typical tree top infestation. A much larger outbreak occurred on 20 March extending to the entire southern part of Kariem Muriem. The area under outbreak was 549.1 ha. The fourth outbreak, which extended to 235.8 ha started on 03 April. It was confined to the northern part of Kariem Muriem. The next outbreak occurred on 18 April in a single patch covering an area of 290.3 ha. The sixth outbreak occurred on 15 May covering an area of 720 ha. The largest outbreak during the year occurred on 10 June extending to an area of 810.2 ha. Nearly one month later, the eighth outbreak occurred in an area of 52 ha. The last two outbreaks during the year occurred on 27 August and 1 September extending to an area of 36.1ha and 35.7 ha respectively.

Table 4.3. Sequence of defoliator outbreaks at Kariem Muriem during 1993.

Sl. No.	Date of egg-laying of the observed population	No. of outbreak patches	Area under outbreak (ha)	Probable date of egg-laying of the resultant progeny (F1 generation)	Whether the actual date of egg-laying (Column 2) falls within the range of probable dates of egg-laying by a previous generation of moths
1	19 February	2	5.8	11-19 March	No
2	26 February	1	2.5	18-26 March	No
3	20 March	1	549.1	9-17 April	Yes
4	03 April	1	235.8	23 April – 01 May	No
5	18 April	1	290.3	8-16 May	No
6	15 May	1	720.0	4 - 12 June	Yes
7	10 June	1	810.2	30 June – 8 July	Yes
8	7 July	1	52.0	27 July – 4 August	Yes
9	27 August	1	36.1	19 – 30 September	No
10	1 September	1	35.7	24 Sep. – 02 Oct.	No
Total area infested (ha)			2737.5	-	-

It can be seen that outbreaks at serial No.s 3, 6, 7, and 8 could be explained as caused by progenies of earlier populations. Outbreaks caused by these populations extended to an area of 2131.3 ha (78%) out of the total area of 2737.5 ha infested during the year.

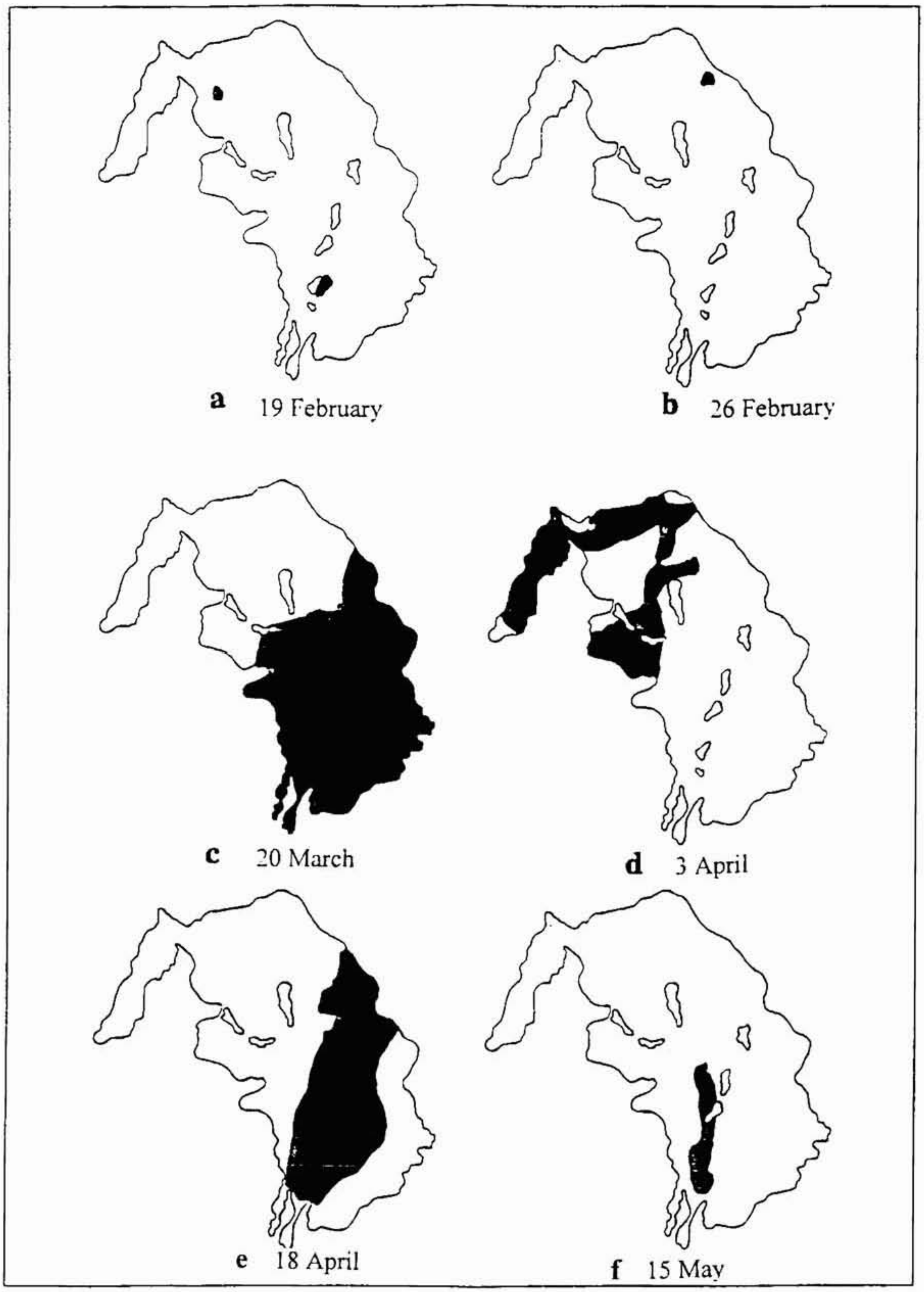

Fig.2. Sequence of defoliator outbreaks in 1993 (cont'd).

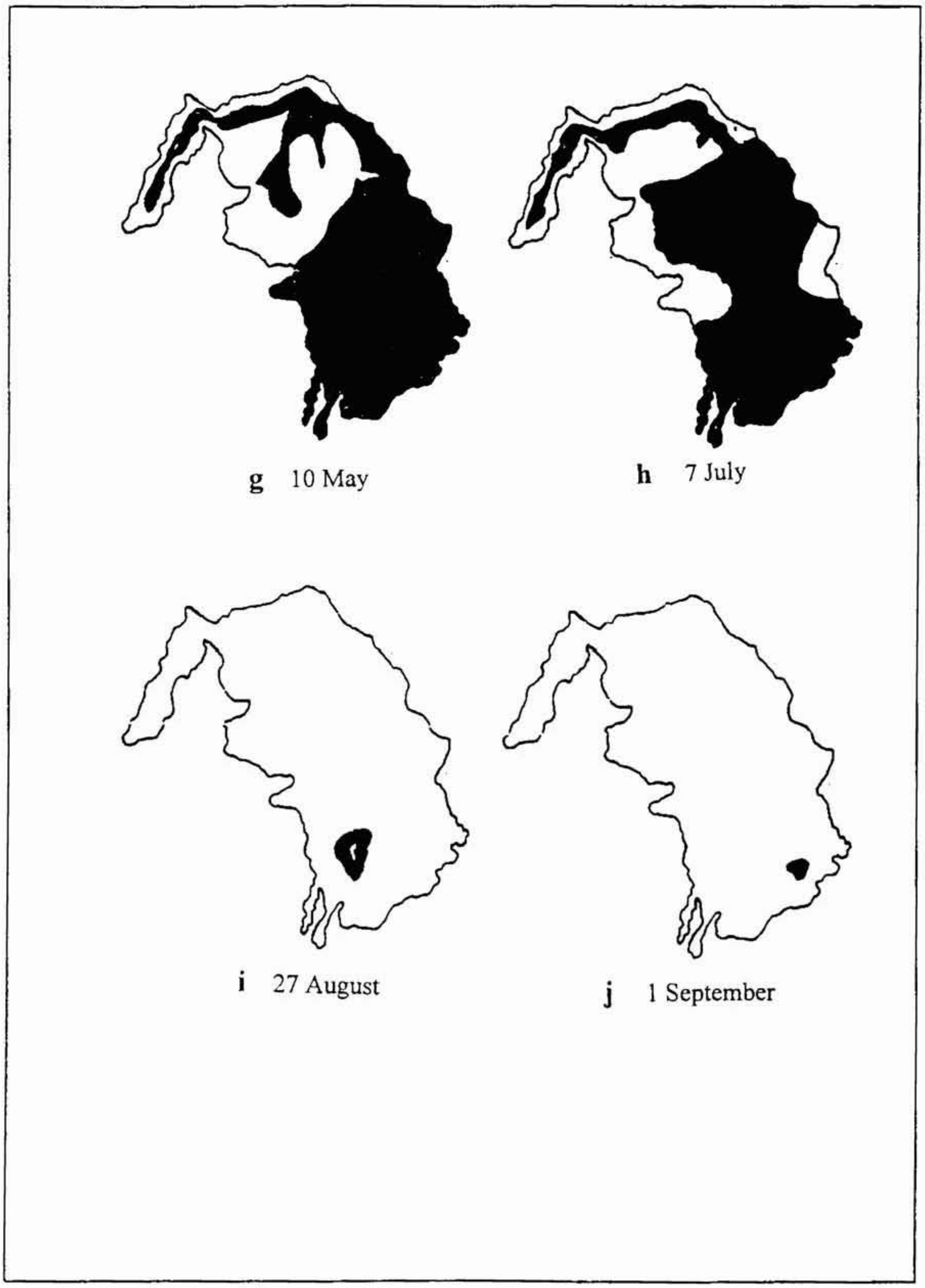

Fig.2. (cont'd) Sequence of defoliator outbreaks in 1993.

4.3.3. Outbreak pattern, 1994

Table 4.4 shows the sequence of outbreaks during the year 1994. The first outbreak was on 04 April which extended to an area of 12.2 ha (Fig.3). The second outbreak occurred at two different places on 12 May. The third outbreak was on 03 June in a single patch covering 75 ha. The last outbreak occurred about a week later on 12 June and extended to an area of 435.3 ha.

Table 4.4. Sequence of defoliator outbreaks at Kariem Muriem during 1994.

Sl.N	Date of egg-laying of the observed population	No. of outbreak patches	Area under outbreak (ha)	Probable date of egg-laying of the resultant progeny (F1 generation)	Whether the actual date of egg-laying (Column 2) fall within the range of probable dates of egg-laying by a previous generation of moths
1	04 April	1	12.2	25-30 April	No
2	12 May	2	472.5	01-06 June	No
3	03 June	1	75.0	23-28 June	Yes
4	12 June	1	435.3	01-06 July	No
Total area infested (ha)			995.0	-	-

It can be seen that only the third population could have been caused by any of the previous populations. This population extended to an area of 75 ha out of 995 ha infested during the year. Thus, the infestations that could be explained based on earlier populations comprised only 7% of the total area infested in 1994. Populations 1,2 and 3 did not cause any further outbreaks in the study area.

4.3.4. Frequency of outbreaks in space

The frequency map of defoliation was generated for each of the years (Fig. 4,5 and 6). The area under each of the frequency class is given in Table 4.5. It may be seen that the outbreak frequency was higher during 1992 and 1993 compared to that of 1994.

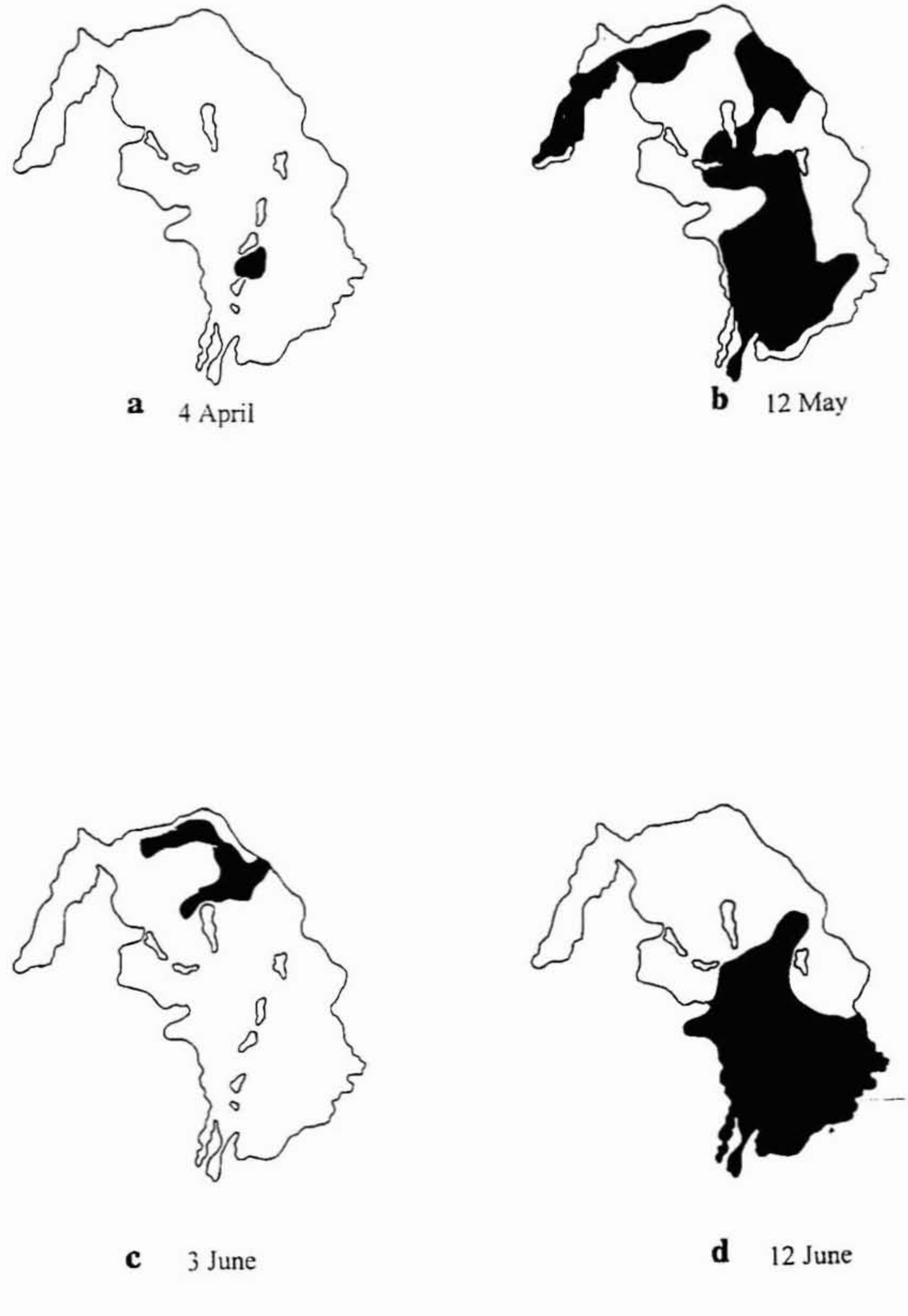

Fig.3. Sequence of teak defoliator outbreaks in 1994.

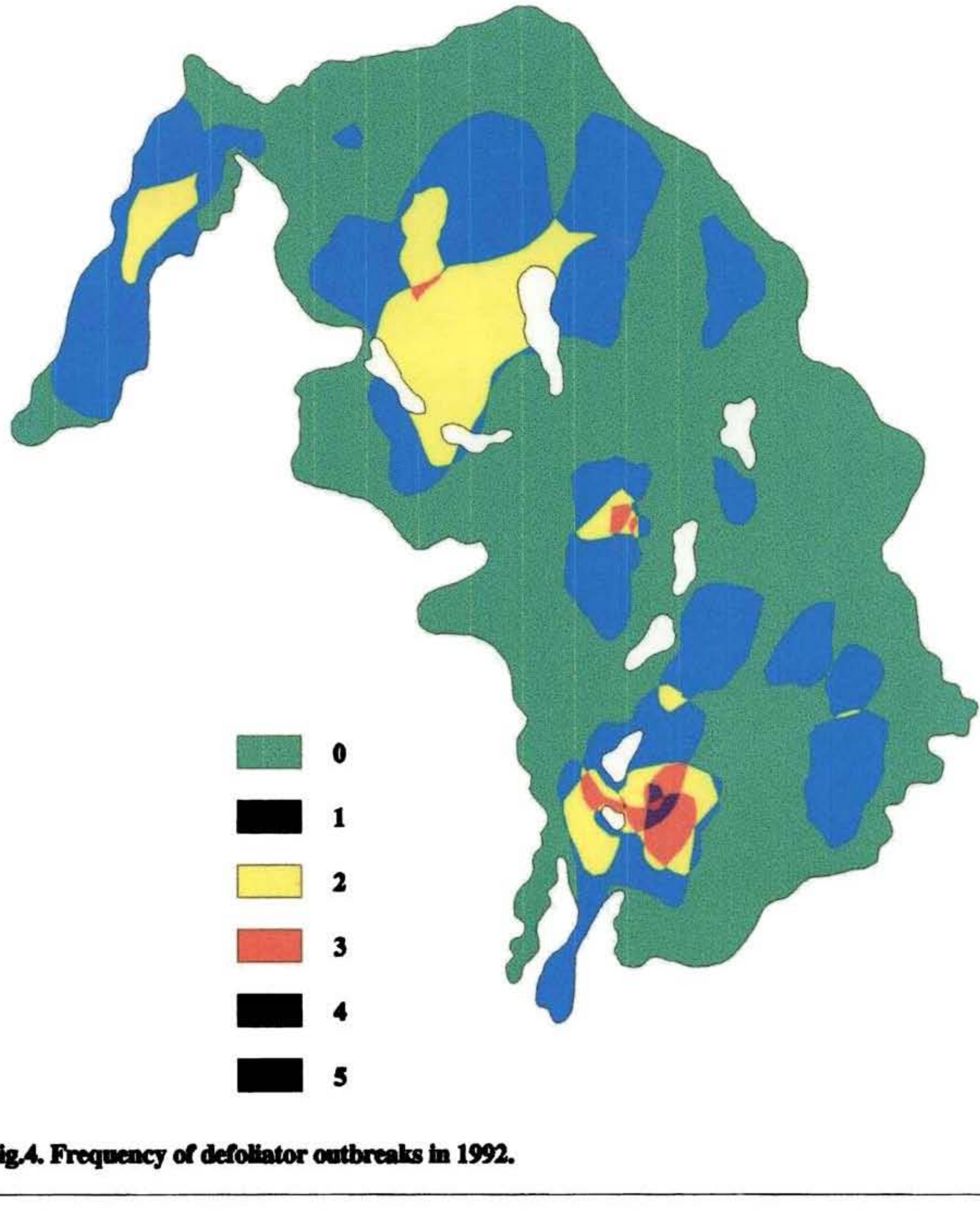

Fig.4. Frequency of defoliator outbreaks in 1992.

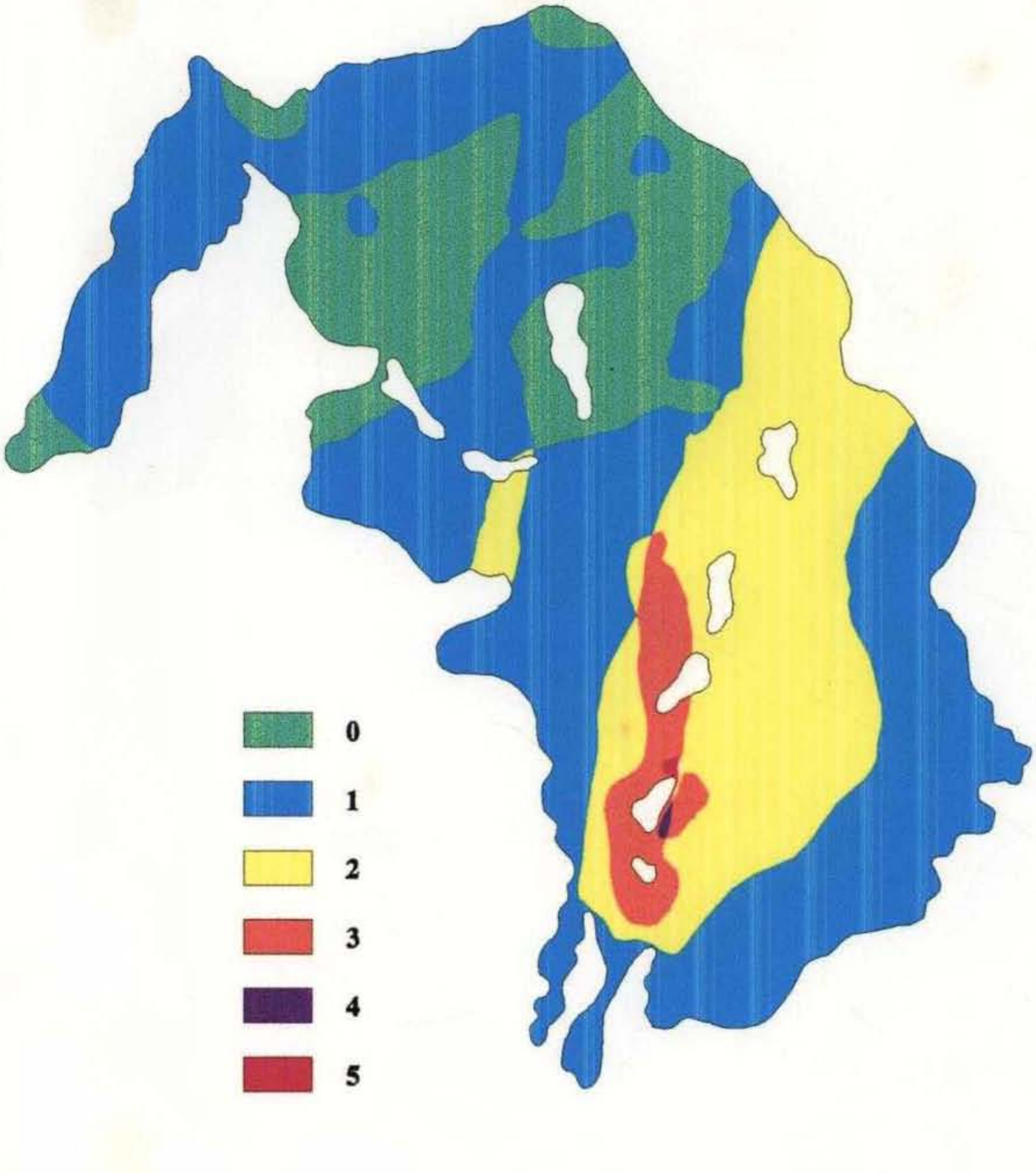

Fig.5. Frequency of defoliator outbreaks in 1993.

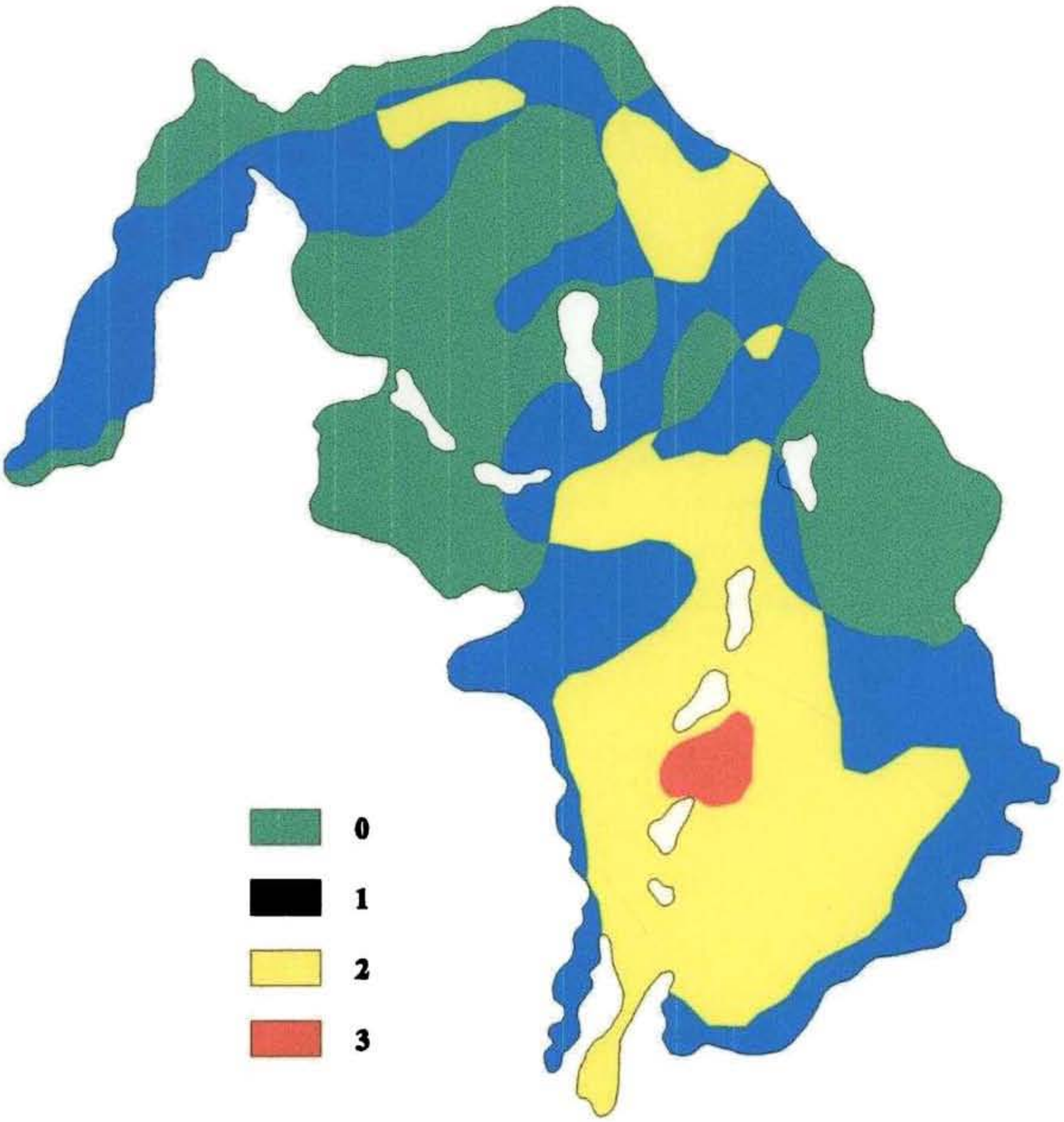

Fig.6. Frequency of defoliator outbreaks in 1994.

Table 4.5. Area under each of the outbreak frequency class during the years 1992-94.

Frequency class	Area infested (ha)		
	1992	1993	1994
0	596.6	179.1	310.8
1	286.6	523.9	359.7
2	85.4	242.0	299.4
3	11.6	35.9	12.2
4	1.7	0.7	-
5	0.2	0.5	-
Total	385.5	803.0	671.3

In 1992, the outbreaks were confined to small patches, which left more than half of the area uninfested. It can also be noticed that the sites of maximum infestation during all the three years were in close proximity to each other. Eventhough there were a large number of outbreaks in all the three years (8,6 and 4 during 1992,1993 and 1994, respectively), there were still places where no infestation occurred. The results of spatial autocorrelation analysis are given in Table 4.6.

Table 4.6. Spatial autocorrelation indices for the years 1992-94.

Year	Geary index	Moran index
1992	0.039960	0.95514
1993	0.033901	0.95600
1994	0.038924	0.95603

In all the years, the Geary index had a value between zero and one and the Moran index was greater than zero. This shows that the defoliator outbreaks are regionalized, smooth and clustered (Table 4.1). The sites with the same outbreak frequency were adjacent to each other.

4.3.5. Correlation between outbreak incidence and topographic features

The elevation of the entire study area ranged from 35.9 m to 283.4 m. (Table 4.7.).

Table 4.7. The relationship between outbreak frequency and elevation.

Outbreak frequency	Elevation (m)		
	1992	1993	1994
0	97.1±44.1	132.1±44.3	118.3±53.4
1	108.7±46.1	104.4±48.9	103.8±44.7
2	138.5±55.3	81.2±28.9	87.0±35.8
3	71.3±19.0	57.2±15.5	51.4±9.9
4	68.7±6.2	58.4±1.1	-
5	68.4±2.1	44.4±2.0	-

The elevation of sites with the highest frequency of outbreaks was between 40 to 77 metres above sea level. During 1992, a positive correlation was found between the outbreak frequency and elevation. However, in 1993 and 1994, the correlation was found to be negative. This indicates that the elevation of a site may not be determining the susceptibility of a site to defoliation. The details of aspect for the frequency classes are given in Table 4.8.

Table 4.8. The relationship between outbreak frequency and aspect.

Frequency class	Aspect (degrees)		
	1992	1993	1994
0	171.1±86.9	180.1±89.3	187.8±88.3
1	188.2±94.2	168.5±85.5	158.8±86.3
2	224.3±77.5	204.1±92.0	197.5±87.7
3	272.0±21.6	226.8±88.7	284.3±58.0
4	256.6±13.6	296.6±14.7	-
5	240.8±4.6	298.7±8.3	-

It can be seen that there is an increase in the aspect value corresponding to an increase in outbreak frequency. It is indicated that the high frequency sites face predominantly to the west while the low frequency sites face to the south. Sites that were not infested during the three years faces predominantly to the south. It was found that the aspect values were positively correlated to outbreak frequency in all the three years.

Table 4.9. shows the elevation and aspect of the first outbreaks. The first outbreaks are shown in landscape perspective in figures 17-19.

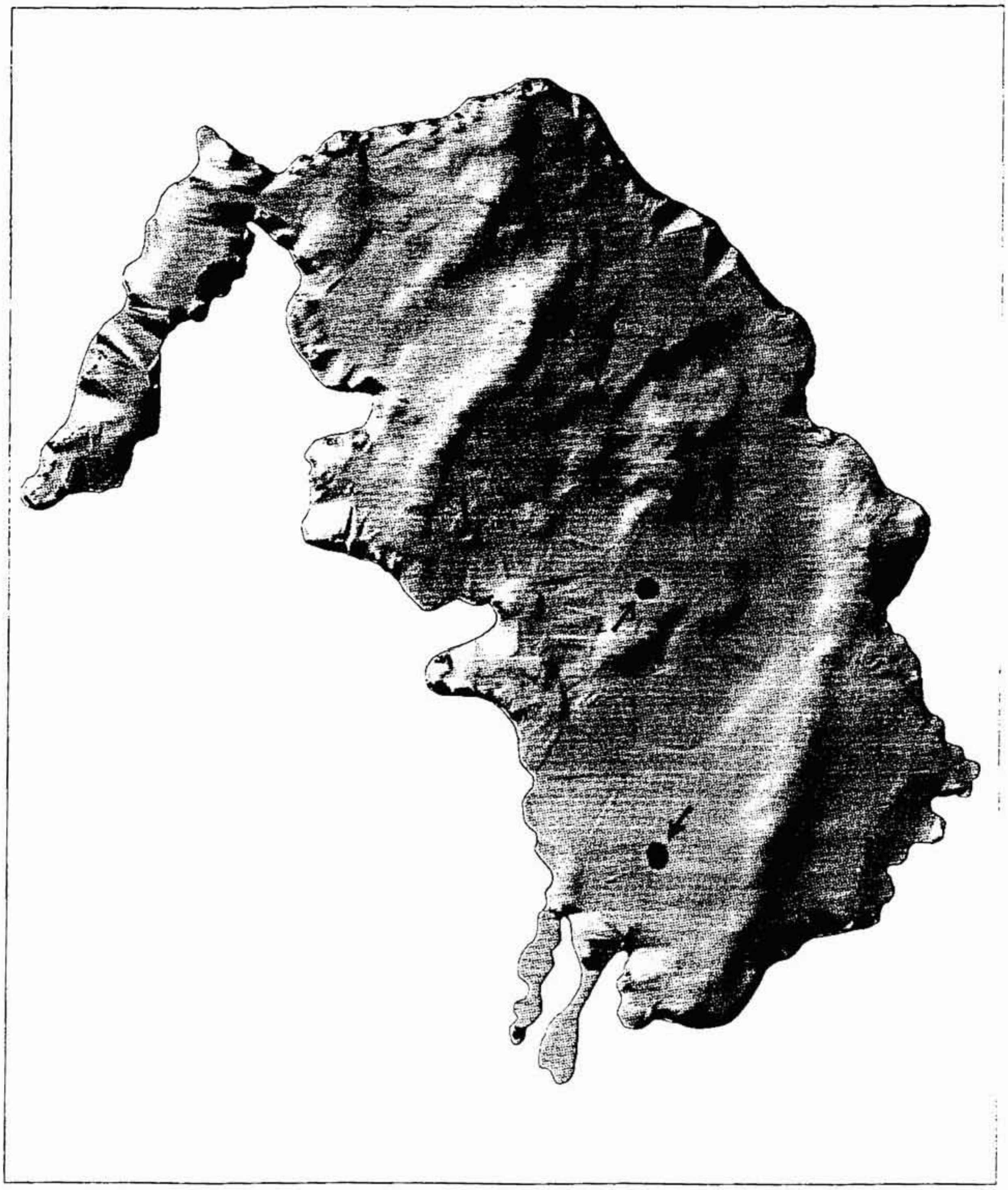

Fig. 7. Location of first outbreaks at Kariem Muriem in 1992 in landscape perspective.

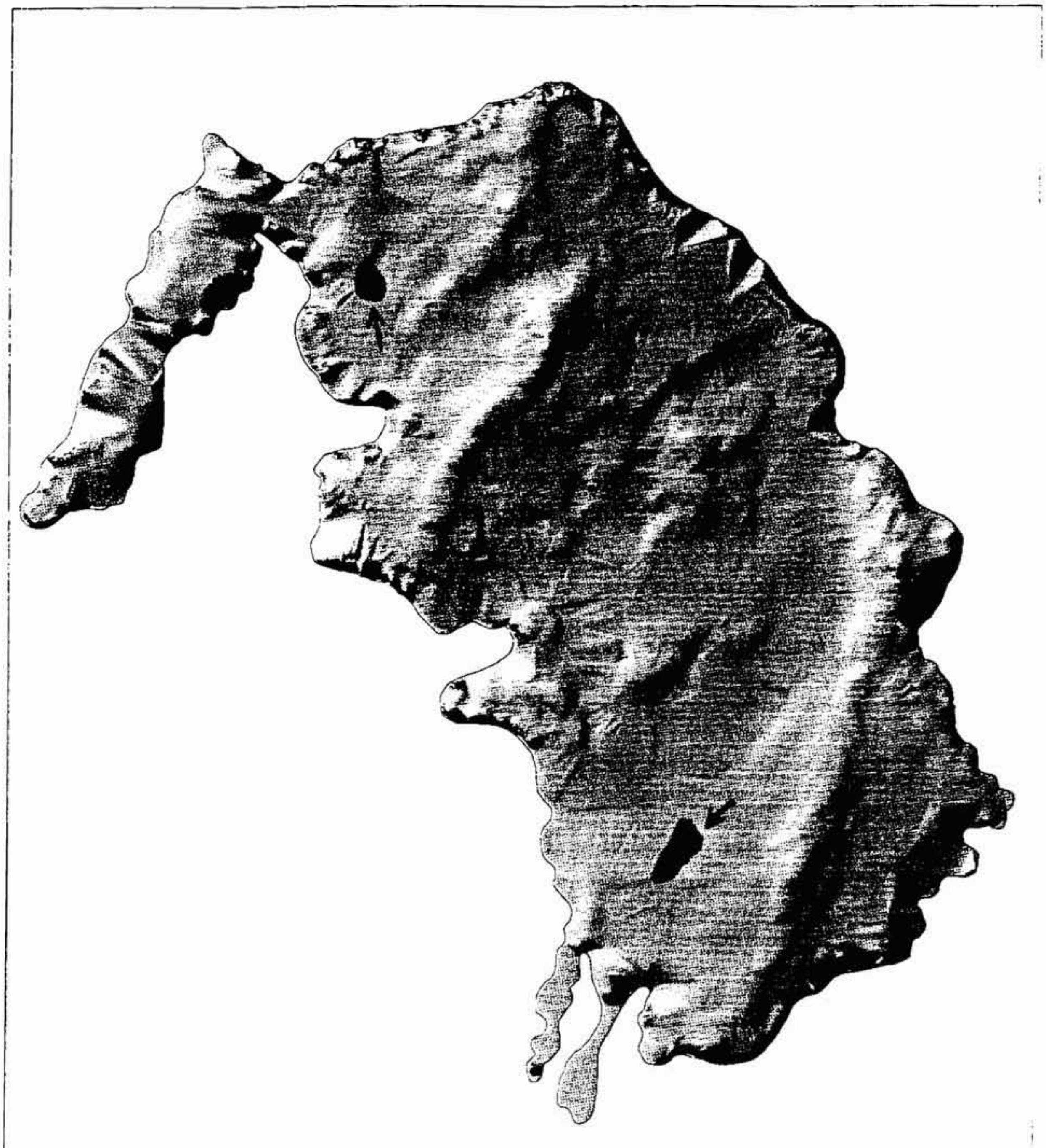

Fig. 8. Location of first outbreak at Kariem Muriem in 1993 in landscape perspective.

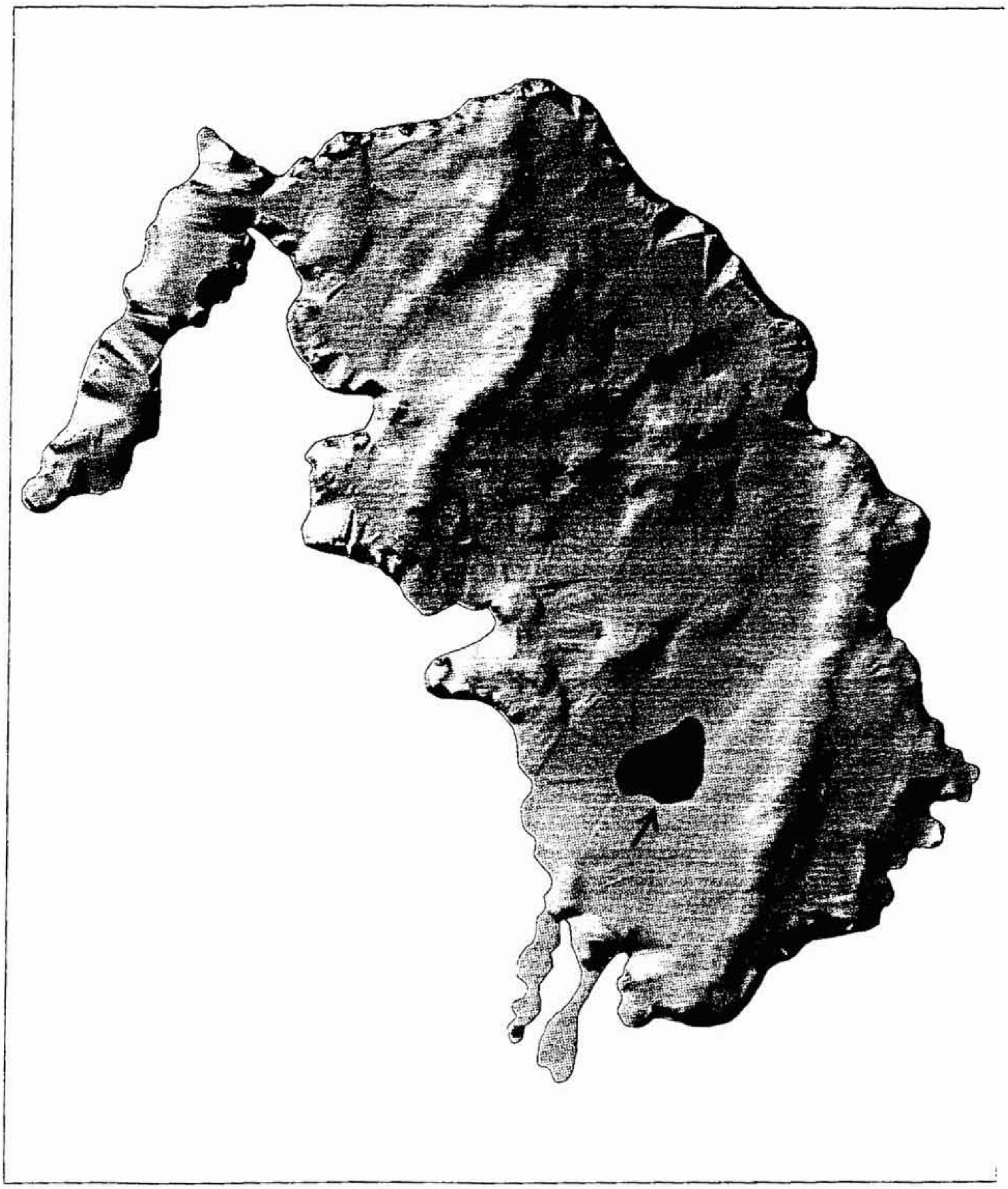

Fig. 9. Location of first outbreak at Kariem Muriem in 1994 in landscape perspective.

Table 4.9. Elevation and aspect of the first outbreak sites at Kariem Muriem in the years 1992-1994.

Year	Elevation (mts.)	Aspect (degrees)
1992	70.8 ± 3.1	284 ± 41
1993	75.7 ± 19.2	247 ± 73
1994	51.9 ± 10.1	288 ± 50

It can be seen that the site of occurrence of first outbreak in 1994 was an area that had the first outbreaks in 1992 and 1993. Small patches occurred outside this area in 1992 and 1993. Generally, these sites had a mean elevation ranging from 50-75 metres and mean aspect ranging from 247-288 degrees. If the relationship between susceptibility to defoliation and topography were known, it would greatly reduce the area to be monitored for identifying initial outbreaks. Observations at other teak growing areas are needed to generalize these findings.

4.4. DISCUSSION

The pattern of defoliator incidence in all the three years indicated that the outbreaks were not randomly distributed in space. It was observed that in all the three years, sites having the highest outbreak frequency value were surrounded by an area with the next lower frequency value. Spatial autocorrelation indices of the outbreak frequency maps indicated that the high frequency sites occur in a clustered manner. This indicates that some sites are more prone to defoliator attack. This is similar to the spatial pattern exhibited by the Gypsy moth (*Lymantria dispar* L.) defoliation (Liebhold and Elkinton, 1989).

The temporal sequence of outbreaks given in Tables 4.2, 4.3, and 4.4 shows that the outbreaks which occur during any year are not always caused by generations of the insect breeding in the same area. Out of the total of eight outbreaks in 1992, only those on 7 July, 6 August, 22 September, and 14 October could have been caused by moths emerging from the same area. The only possible cause for the other four outbreaks is the immigration of moths into the study area.

In 1993, out of the total of ten outbreaks only four (which occurred on 20 March, 15 May, 10 June, and 7 July) could have been caused by moths emerging from the same area. Immigration has occurred on 19 February, 26 February 3 and 18 April, 27 August and 1 September. In 1994, only one outbreak that occurred on 3 June could have been caused by moths emerging from one of the previous outbreak sites in the area. During the year, immigration of moths caused outbreaks on 4 April, 12 May and 12 June.

A further proof of the movement of moths is the fact that moths emerged from many of the outbreak sites did not lay eggs within the study area. In 1992, of the eight distinct outbreaks only four could have caused further outbreaks within Kariem Muriem. In 1993, only 4 out of 10 and in 1994 only 1 out of 4 could have caused similar outbreaks. The moths emerged from the other outbreaks should have emigrated from the study area.

The indication that a particular outbreak was caused by moths emerging from an earlier population in the same site is solely based on temporal correspondence. When emergence of moths from a particular population was found to coincide with the egg-laying which initiate another, it is assumed that the first population caused the second. However, if the moths that emerged move out of the study area, and a new group of moths arrived and laid eggs, they could not be distinguished. This indicates that there are chances that migration may be more frequent than can be proved as above.

The following conclusions can be drawn from the present study:

a) Occurrence of defoliation is not randomly distributed in space. The sites with higher outbreak incidence occur close together and some areas are more prone to defoliator attack than others.

b) There is no significant correlation between the frequency of outbreaks and the elevation of the site. However, there was significant relationship between aspect and outbreak frequency. The high frequency sites faced predominantly to the west while the low frequency sites faced either south or south-southwest.

c) Migration of moths plays an important role in the local population dynamics of the insect. Majority of outbreaks have been proved to be caused by moths migrating into the area.

The fact that most of the outbreaks could not be explained as caused by the progeny of earlier populations could be because the area was too small for a spatial study. Immigration of moths from a larger surrounding area may explain the origin of presently unexplainable populations. This inference was apparent from the 1992 results were only 4 out of 8 populations could be explained based on earlier populations at Kariem Muriem. Observations covering all the teak plantations at Nilambur were made in the year 1993 to understand if outbreaks occurring in a larger area could be caused entirely by progenies of earlier populations in the area; the results are presented in the next Chapter.

CHAPTER V

STUDIES ON THE SPATIAL DISTRIBUTION OF OUTBREAKS IN THE ENTIRE TEAK PLANTATIONS AT NILAMBUR

5.1. INTRODUCTION

In 1992, the outbreak pattern in the Kariem-muriem teak plantation showed that out of eight outbreaks, only four occurred when local moth populations were present. The rest of the outbreaks could only be explained by immigration of moths from elsewhere into this area. Therefore in 1993, an attempt was made to understand the dynamics of outbreaks in a larger spatial scale.

Using the same methodology adopted in 1992 for Kariem- Muriem, the entire teak plantations at Nilambur were observed for incidence of defoliation in 1993. All the outbreaks that occurred in the 8516 ha of plantation were mapped and analyzed using GIS. The objectives were to characterize the spatial and temporal pattern of defoliator outbreaks in a large plantation area, and to study the influence of scale in our understanding of the population dynamics of the insect.

5.2 METHODS

As noted in Chapter 3, the teak plantations of Nilambur extend to an area of 8516 ha spread out in a geographical area of 25,750 ha. The major continuous blocks of plantations are located at Nedumgayam, Sankarankode, Ezhuthukal, Poolakkappara, Nellikkutha, Kariem- Muriem, and Edakkode (Fig. 5.1). The area was divided into 149 grids and fortnightly observations were made in each of the grids. Trained individuals were employed to assist in identifying outbreaks. Whenever an outbreak was detected, live insects were collected to identify the developmental stage. During the pupal period of the population, the area was visited to map the outbreak area in the plantation map. The methodology adopted for data collection and analysis were similar to that described in Chapter 4.

5.3 RESULTS

The temporal sequence of defoliator outbreaks at Nilambur is given in Table 5.1. The first outbreak of the year occurred at Kariem-Muriem on 19 February (Fig 5.1). There were two distinct patches of infestation, separated by a distance of about 3 km, one covering an area of 12.8 ha and the other, 1.7 ha.

Table 5.1. Chronology of defoliator outbreaks at Nilambur in the year 1993.

Serial No.	Date of egglaying	Infested area (ha)	No. of patches	Expected egglaying period of progeny
1	19 February	14.3	2	11-19 March
2	26 February	10.0	1	18-26 March
3	17 March	38.8	1	06-14 April
4	20 March	512.0	1	09-17 April
5	21 March	1.7	1	10-18 April
6	26 March	0.12	1	18-23 April
7	03 April	254.4	3	23 April-01 May
8	07-20 April	934.4	24	27 April-18 May
9	23 April	11.9	1	13-21 May
10	25-26 April	18.1	4	15-24 May
11	28 April	1.5	2	18-26 May
12	05 May	114.7	3	25 May-02 June
13	08-30 May	2498.9	47	28 May-27 June
14	02-16 June	2531.5	67	22 June-18 July
15	28 June	4.25	1	21-30 July
16	01 July	22.4	1	24 July-2 August
17	04-11 July	208.6	16	27 July-12 August
18	14 July	2.65	1	06-15 August
19	18 July	0.5	1	10-19 August
20	27 August	40.6	1	19-30 September
21	01 September	35.7	3	24 Sept.-02 Oct.
22	03-06 September	1.3	4	26 Sept.-08 Oct.
23	08-09 September	1.6	3	01-11 October

Before this, there was no visible evidence of presence of larvae although occasionally stray larvae could be located on careful search. General observations had indicated that in most areas, leaf fall was completed by the end of January and new flushes had started. The infestation, which occurred on 19 February, was dense and concentrated on the treetops. The total area under outbreak was 14.3 ha. This outbreak could only be caused by a large number of moths. It is obvious that such a large population of moths could not have originated from the teak plantations of Nilambur all of a sudden, unless stray moths which were spread throughout the plantations got concentrated through some unexplained phenomenon.

The second outbreak occurred near one of the first outbreak patches on 26 February (Fig 5.2) covering an area of 10 ha. Since only seven days had elapsed between the first and second outbreaks, it is obvious that the second outbreak was not the progeny of the first. The 7-day gap between the two outbreaks also suggests that the second outbreak could not have been caused by the same group of moths, which caused the first outbreak because the normal egg laying period is only 5 days. In view of the above facts, the origin of the second infestation cannot be explained except in the same manner as the first.

The third outbreak occurred on 17 March in a different plantation (Fig.5.3) and covered an area of 38.8 ha. In theory, the moths which caused this infestation could be the progeny of the first population (moth population at Serial No.1, Table 5.1).

The fourth outbreak occurred on 20 March and covered an area of 512 ha in the general location of the first two outbreaks (Fig.5.4). This was the first large-scale infestation wherein over 500 ha were infested on a single day. This infestation could be attributed to the progeny of the moth population at Serial No.2; Table 5.1.

The fifth infestation was noticed on 21 March and covered an area of 1.7 ha in a different location (Fig.5.5). In theory, this could also be attributed to the progeny of population No.2 which caused the large infestation on the previous day a different location. However, the very small area of this outbreak has some similarity to the first two infestations of unexplained origin.

The sixth outbreak occurred on 26 March in a new area (Fig.5.6) and covered only 0.12 ha. In theory, this can also be attributed to the progeny of population No.2, but the very small area of infestation and the gap between the current and the previous infestation indicates that this is unlikely. As in the previous infestation, the similarity of the infestation to the first two of unexplained origin is striking.

The seventh outbreak occurred on 3 April in the same general area where the first two outbreaks occurred and covered a substantial area of about 254.4 ha (Fig.5.7). This was the second major infestation of the year in terms of area coverage. The origin of this infestation could not be attributed to any of the previous populations within Nilambur (Table 5.1).

In the following period, a very large area (934 ha) was infested from 7 to 20 April. It was not possible to distinguish the area infested on each day within this interval (Fig.5.8). There were 24 distinct patches of infestation, which included some very small patches similar to the initial infestation patches. All these infestations can be explained, in theory, as caused by the progeny of previous populations (Table 5.1).

All the subsequent infestations which occurred from 23April to 18 July (serial No. 9 to 19 in Table 5.1and Figures 5.9 – 5.19) were also attributable (in theory) to the progeny of previous populations within the area. However, the possibility of immigration or local concentration cannot be ruled out. These infestations (Serial No. 9 to 19) constitute the major part of the infestations covering an area of 5415 ha (88.42%) out of the total infested area of 7180 ha.

The last four infestations of the year from 27 August to 9 September (serial No. 20,21,22 and 23 in Table 5.1 and Figures 5.20-5.23) were not attributable to previous populations, in the same way as the first few infestations. This also indicates either immigration of moths from outside the study area or aggregation of stray moths from within the area.

Fig. 5.24 is an overlay of areas infested in all the outbreaks during 1993 ; green areas were not infested at all, each infestation frequency is indicated by a different colour. It may be seen that large areas of teak plantations were not infested during the year. At the same time, some areas were repeatedly infested, upto 5 times. It is clear that not all plantations were equally prone to defoliator outbreak. Plantations in two locations viz. Kariem Muriem, and Sankarangode - Nedumgayam - Kanjirakkadavu were the most heavily infested in 1993.

Spatial autocorrelation indices were 0.08638 (Geary) and 0.4051(Moran), which indicated that the outbreak frequency classes were regionalized, smooth, and clustered.

5.4 DISCUSSION

If we analyze the first seven outbreaks, which occurred on single days (Table 5.1), it can be seen that three of them (1^{st} 2^{nd} and 7^{th}), cannot be attributed to the progeny of pre-existing populations within the study area consisting of about 8,500 ha of teak plantations. This clearly shows either immigration of moths from other areas or aggregation of moths dispersed throughout the teak plantations in Nilambur. The 5^{th} and 6^{th} infestations, covering very small areas may also fall in this category, as indicated above.

As noted earlier, this study in a large area was made necessary because of the inability to explain all outbreaks which occurred in 1992 in a 1000 ha plantation (Kariem Muriem)as caused by progenies of earlier population during the year. During 1993, the outbreaks which occurred at Kariem Muriem plantations defoliated an area of 2737.5 ha out of which 2131.3 ha (about 78%) could be explained as caused by progenies of population which were present in the same area. Out of ten outbreaks during the year, six outbreaks (which occurred on 19 and 26 February, 3 and 18 April, 27 August and 1 September) could not be explained in this manner. When the entire teak plantation at Nilambur was studied, it was seen that the outbreak which occurred on 18 April (at an area of 290.3 ha) could be explained as caused by progenies of earlier populations in the entire Nilambur area. Thus percentage area infested by populations which could be caused by earlier populations increased to 88% when the populations in the entire Nilamur area was considered.

A comparison of temporal sequence of outbreaks which was observed at Kariem-Muriem and at all the plantations at Nilambur, including the Kariem-Muriem plantations, shows that when the larger area is considered, the sequence of outbreaks become more explainable. The percentage of outbreaks that could be attributed to local populations was computed for this purpose. Only about 33% (2 out of 6) of the outbreaks could be attributed to local populations when only Kariem-Muriem area was considered. Nevertheless, about 70% (16 out of 23) of outbreaks could be explained when all the plantations were taken together. This indicates that the chain of outbreaks that occurred during a year is more self-sustained when viewed in a larger area. Short-range migration of moths within Nilambur can explain this phenomenon. When only Kariem-Muriem is considered, the effect of emigration or immigration will lead to unexplainable outbreaks within Kariem-Muriem. However, when all the plantations at Nilambur are considered the effect of short-range movement is only spatial displacement but temporally the outbreaks remain explainable.

The salient features of the spatial and temporal pattern of outbreaks can be summarized as follows:

(a) Temporal pattern

i. The period of defoliator outbreaks at Nilambur extends from February to September.

ii. The initial outbreaks that occurred in February and March in 1993 could theoretically cause a sequence of outbreaks which comprised 78% of the total area under outbreak during the year.

iii. The outbreaks which occurred during the later part of the year (August and September in 1993) could not be caused by the initial populations which indicate that there is a break in the sequence of outbreaks.

(b) Spatial pattern

i. All the infestations occurred in discrete patches in spite of the existence of contiguous infestable plantations.

ii. Not all plantations were equally infested. While some plantations remained uninfested, some were infested up to five times during the year.

iii. Sites with high frequency of outbreaks were clustered together indicating that outbreak incidence is not a random phenomenon.

This study suggests that controlling the initial populations of the insect so as to prevent population build up leading to large scale outbreaks is a valid proposition, since it has shown that the initial populations could theoretically cause nearly 70% of the outbreaks that occur during the year. This can be confirmed by controlling the initial populations and then monitoring the entire plantations. The origin of initial populations during the year, those during the final phase of outbreaks and a single outbreak in between is still uncertain. Two possible explanations are (a) aggregation of stray moths from the same locality, and (b) long-range immigration of moths. Monitoring of defoliator outbreaks in wider geographic regions can give indication whether long-range movement of moths causes the presently unexplained outbreaks.

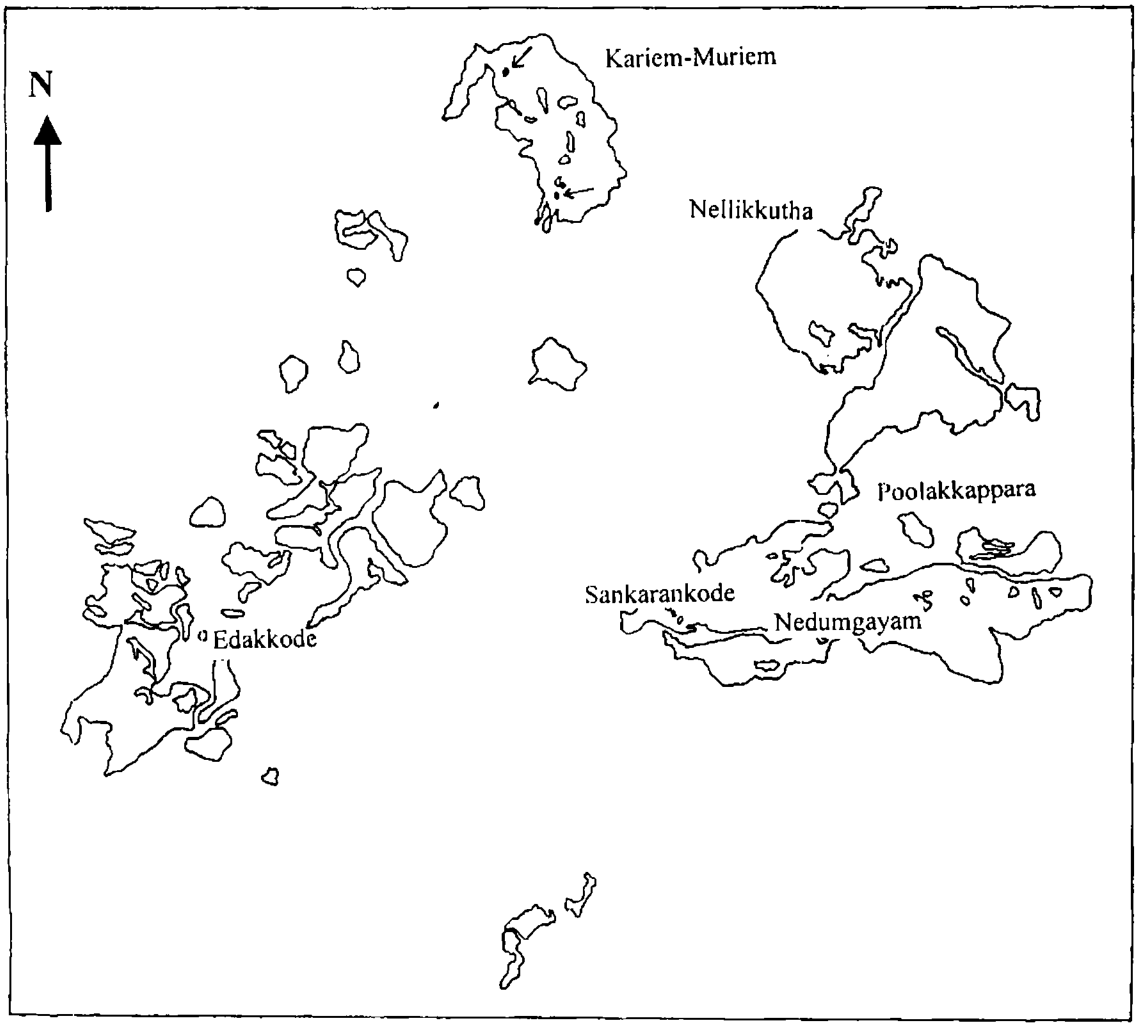

Fig.5.1. Map of Nilambur teak plantations showing the locations of the first outbreak in the year 1993 on 19 February.

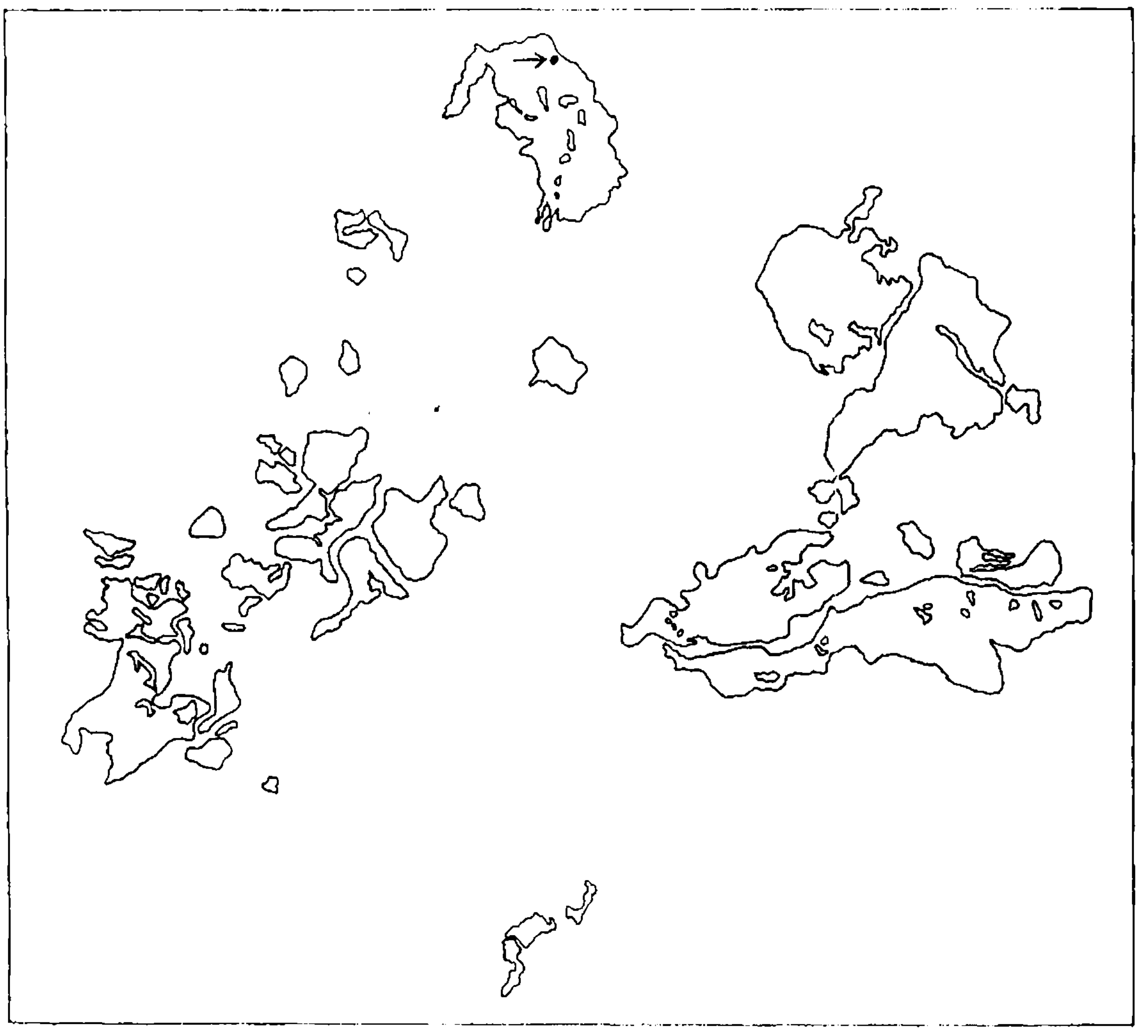

Fig.5.2. Map of Nilambur teak plantations showing the locations of the second outbreak in the year 1993 on 26 February.

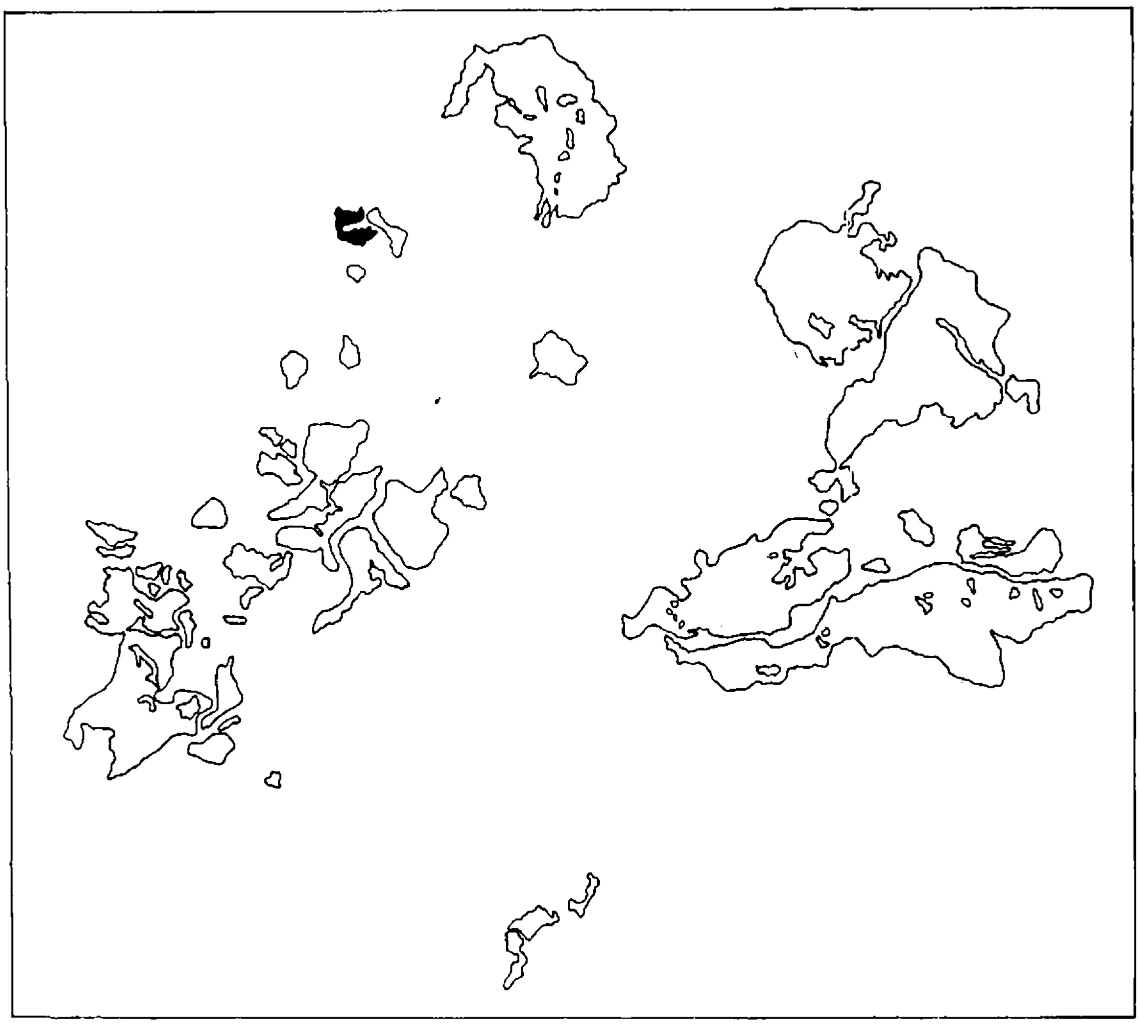

Fig.5.3. Map of Nilambur teak plantations showing the locations of the third outbreak in the year 1993 on 17 March.

Fig.5.4. Map of Nilambur teak plantations showing the locations of the fourth outbreak in the year 1993 on 20 March.

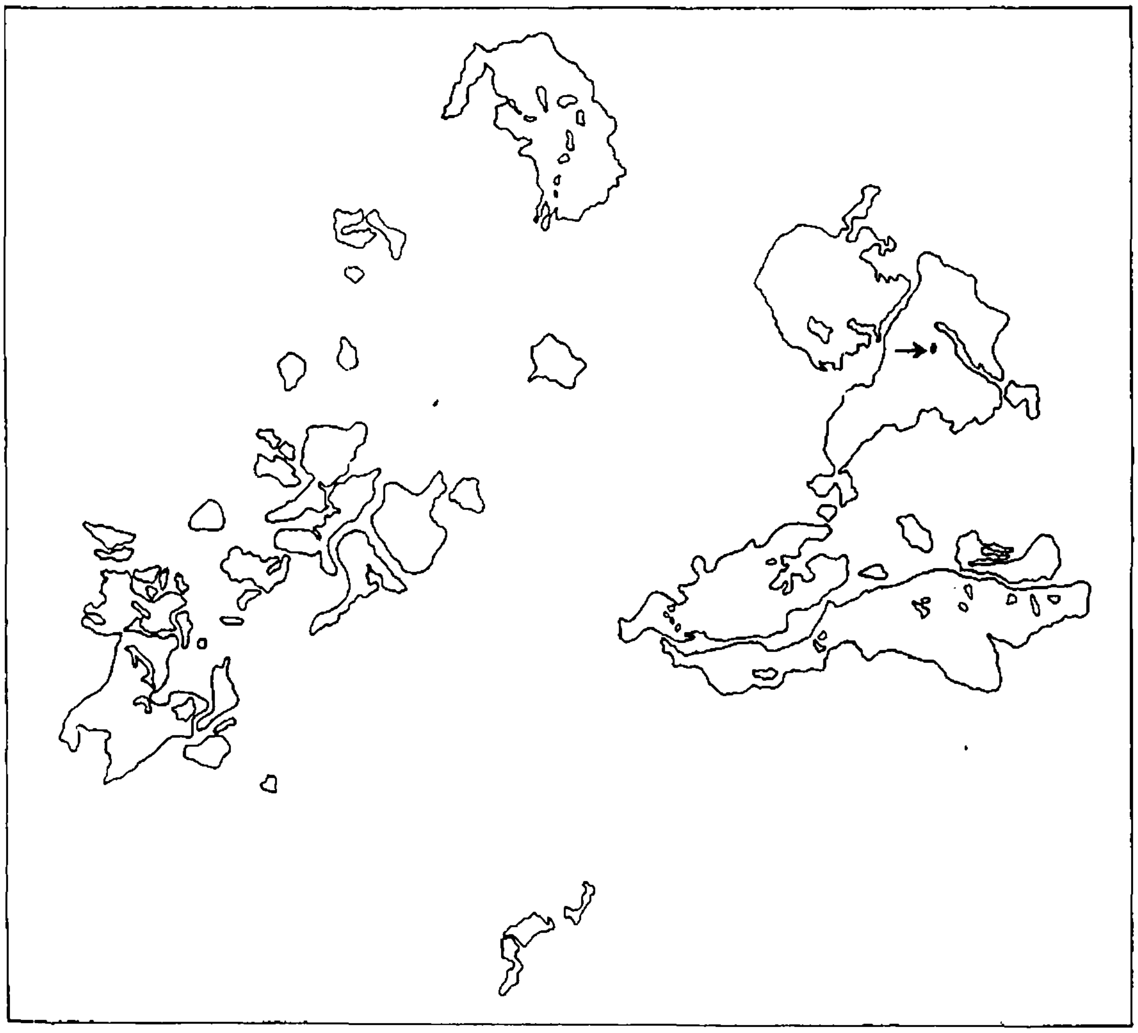

Fig.5.5. Map of Nilambur teak plantations showing the locations of the fifth outbreak in the year 1993 on 21 March.

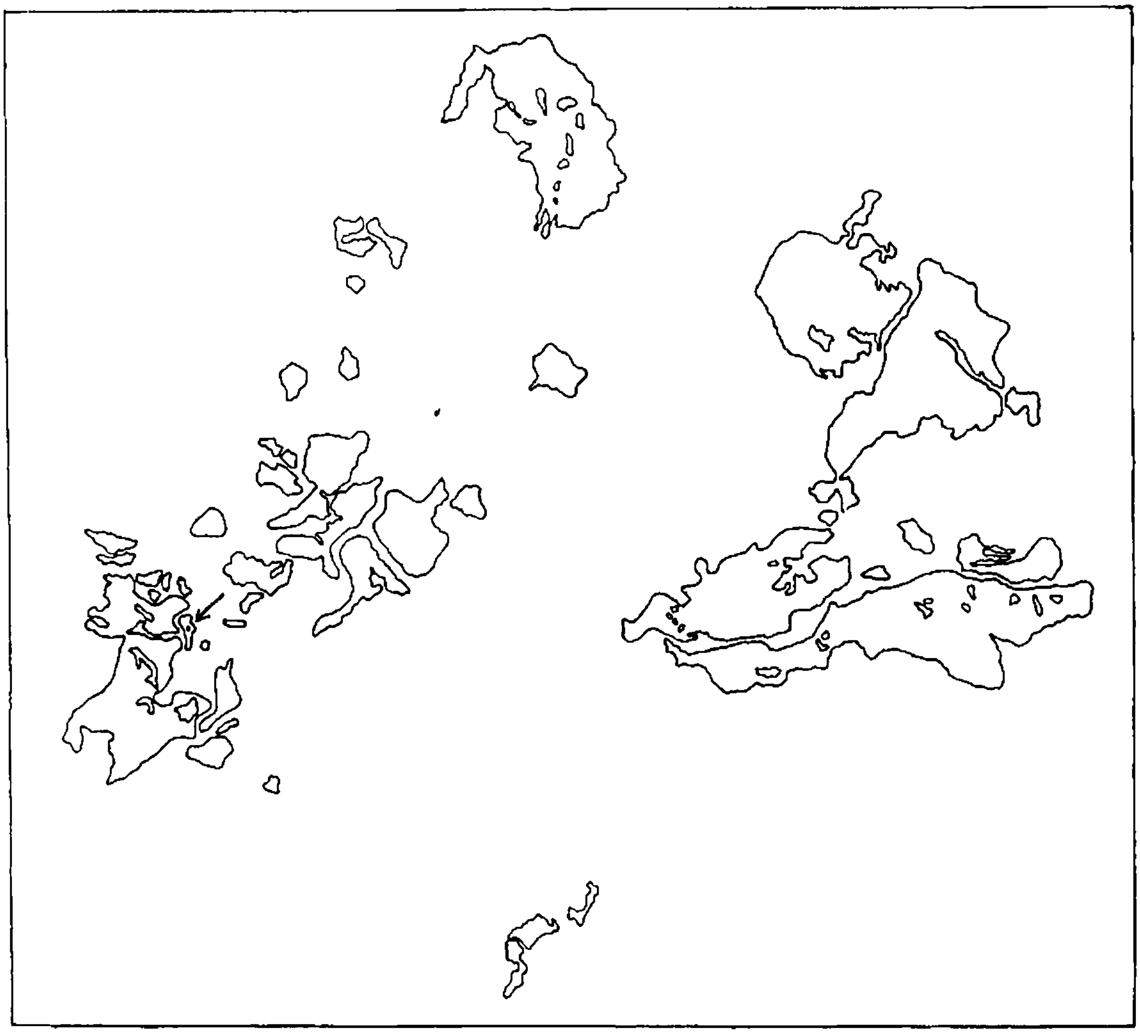

Fig.5.6. Map of Nilambur teak plantations showing the locations of the sixth outbreak in the year 1993 on 26 March.

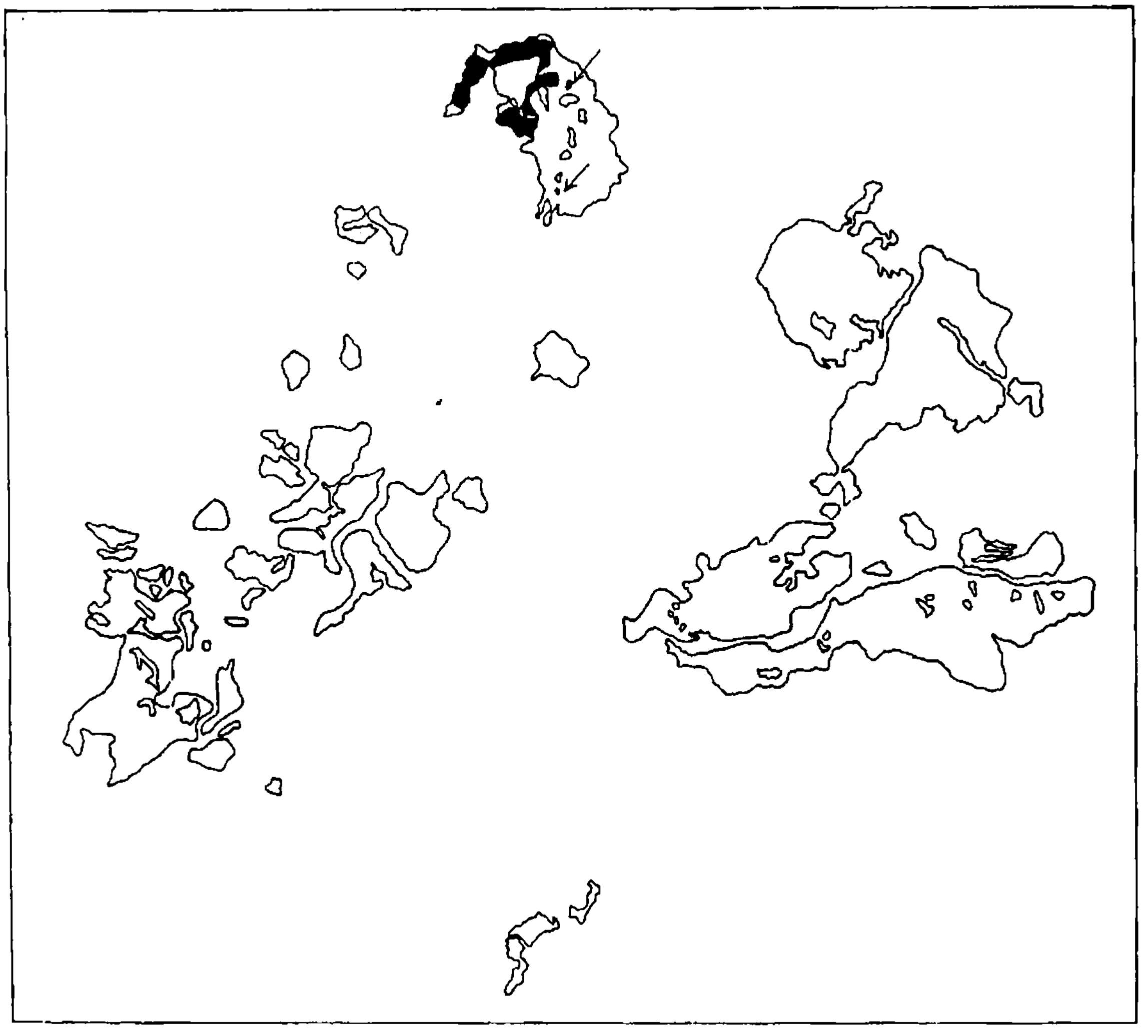

Fig.5.7. Map of Nilambur teak plantations showing the locations of the seventh outbreak in the year 1993 on 3 April.

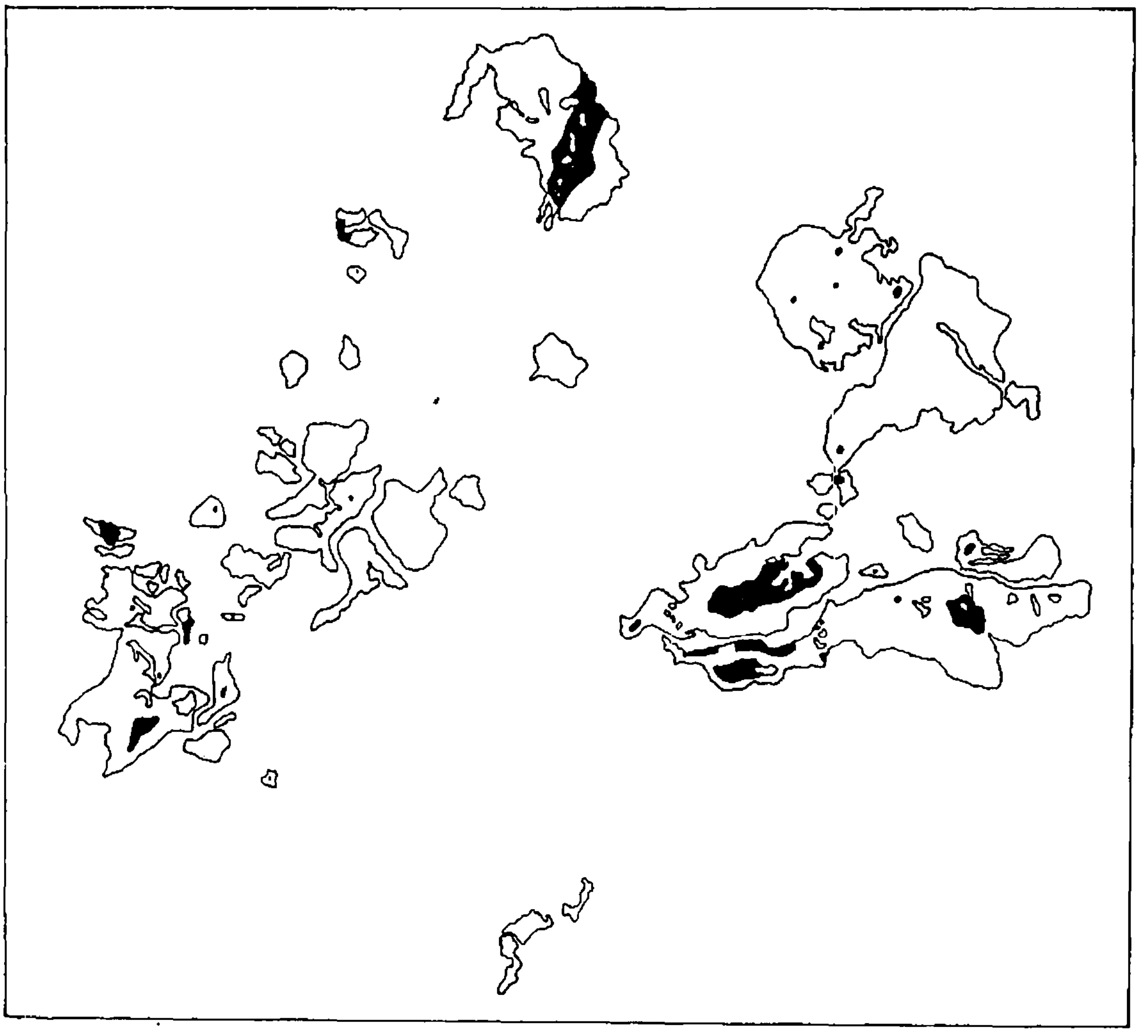

Fig.5.8. Map of Nilambur teak plantations showing the locations of the eighth outbreak in the year 1993 during 7-20 April.

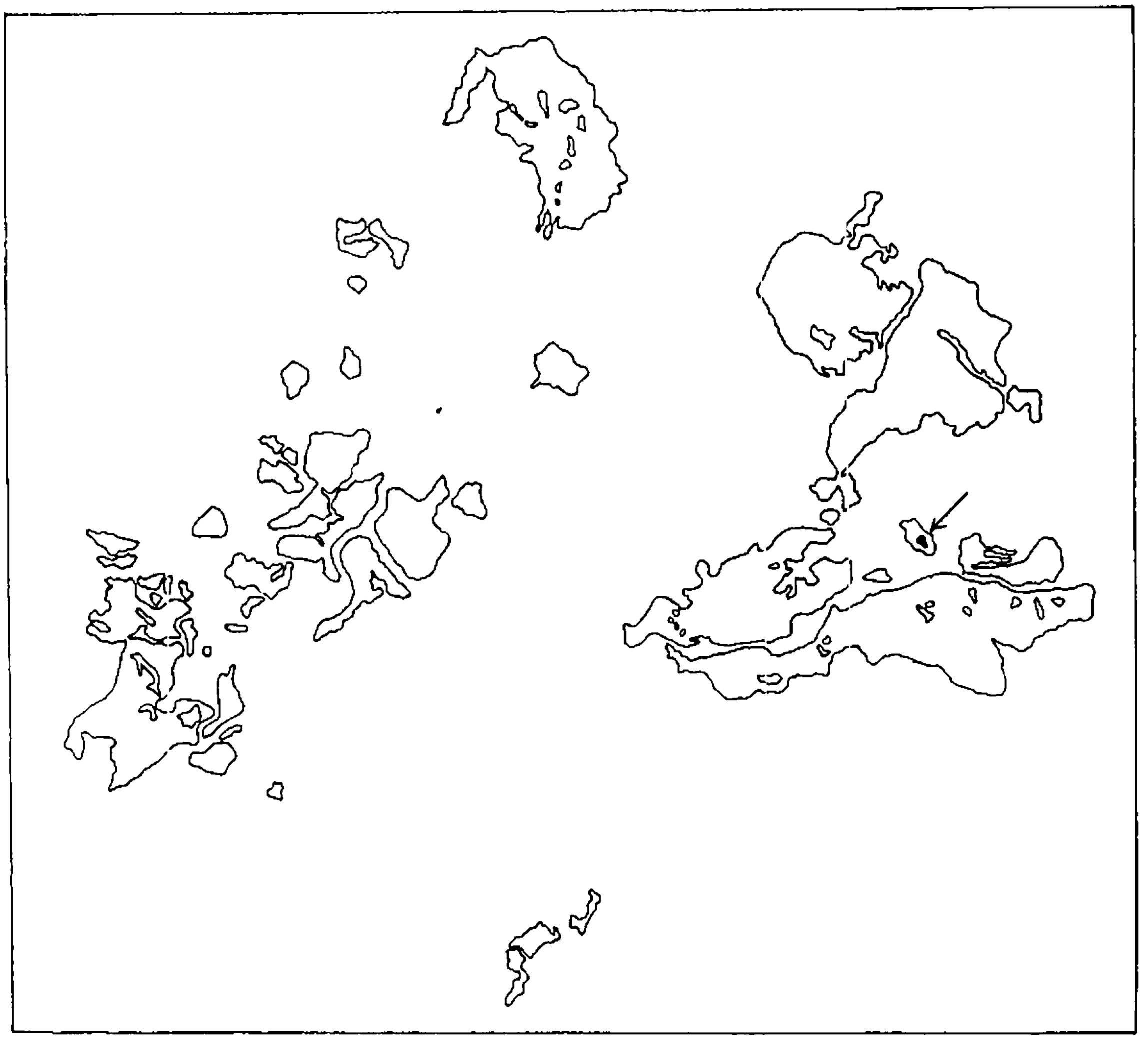

Fig.5.9. Map of Nilambur teak plantations showing the locations of the ninth outbreak in the year 1993 on 23 April.

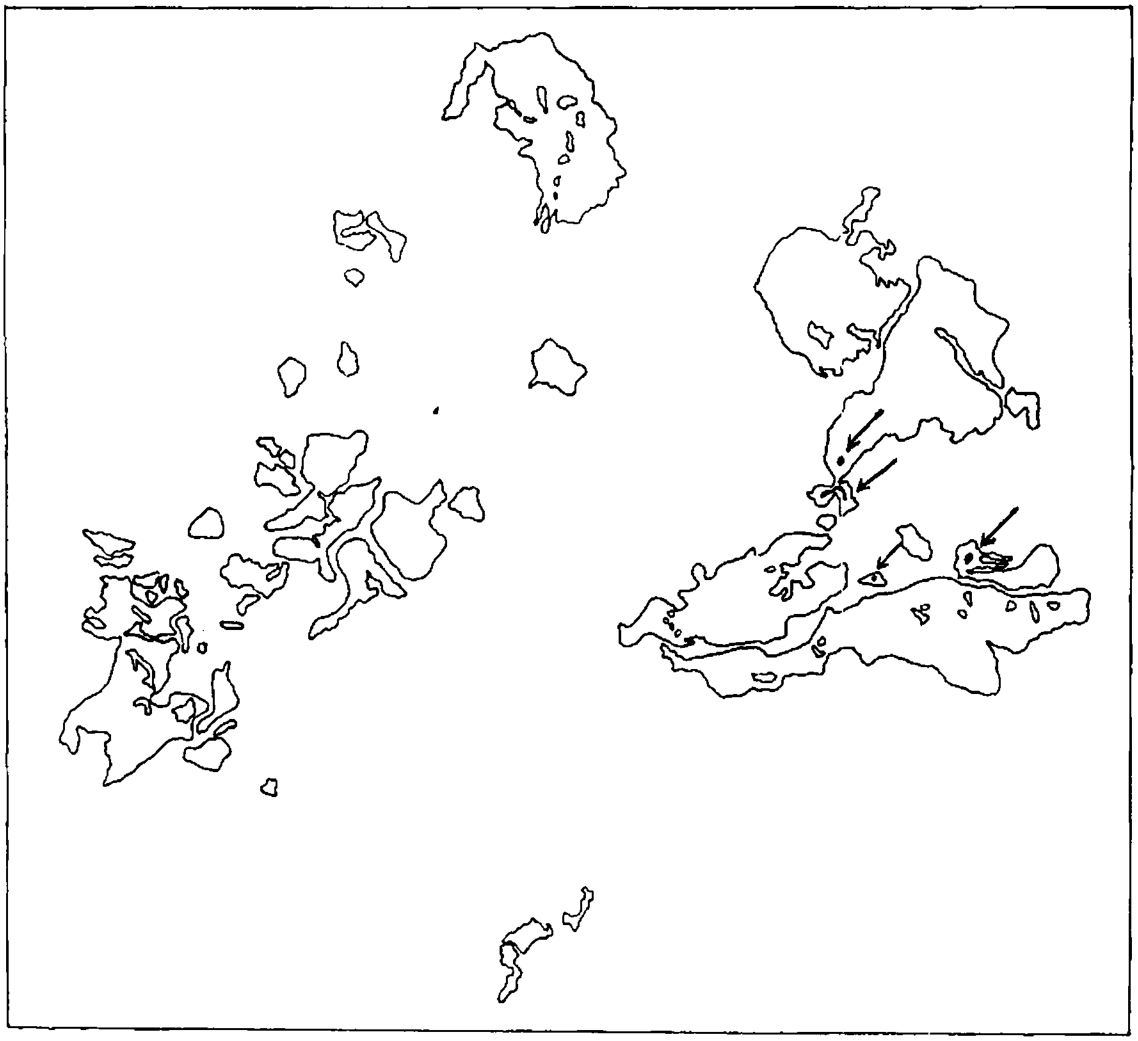

Fig.5.10. Map of Nilambur teak plantations showing the locations of the tenth outbreak in the year 1993 during 25-26 April.

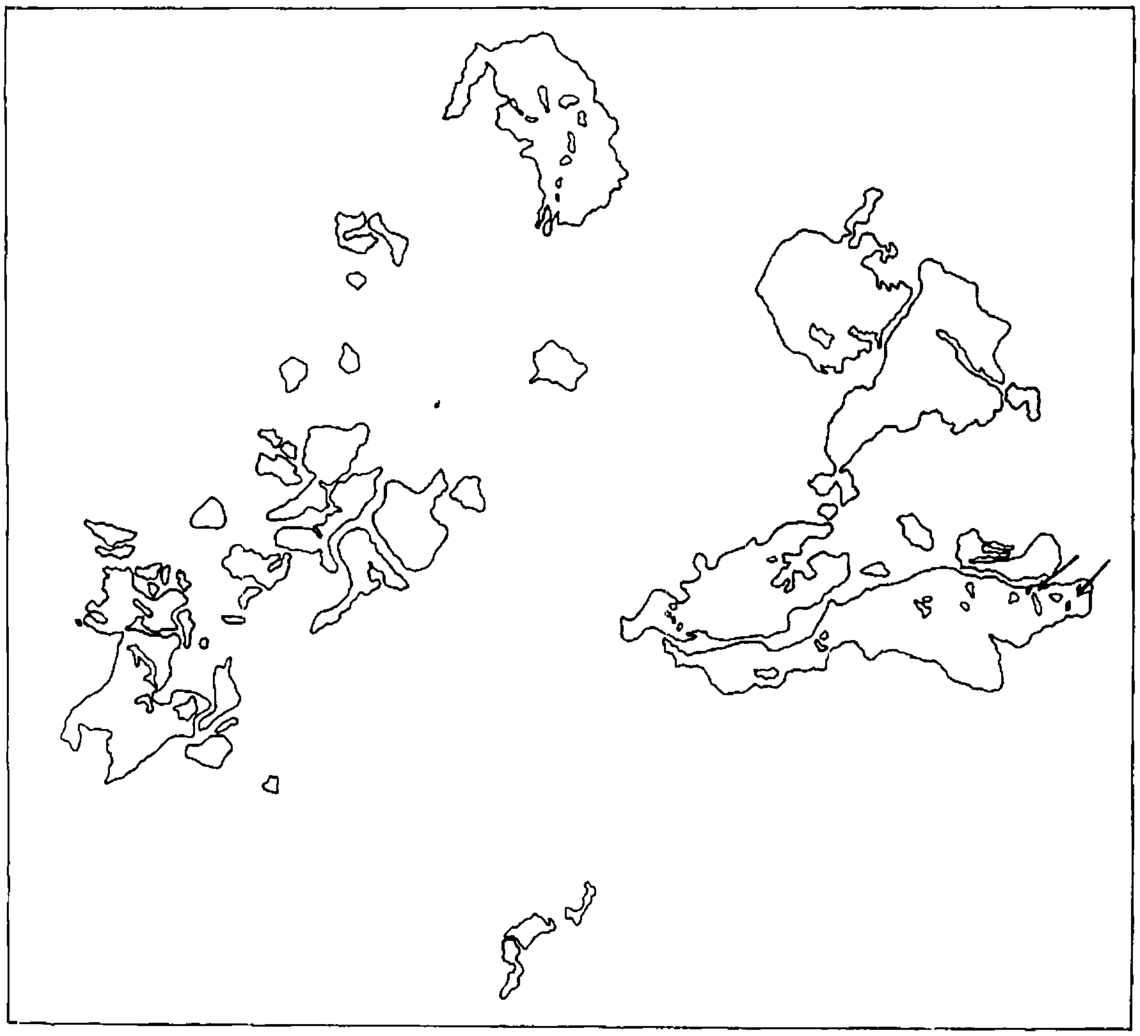

Fig.5.11. Map of Nilambur teak plantations showing the locations of the eleventh outbreak in the year 1993 on 28 April.

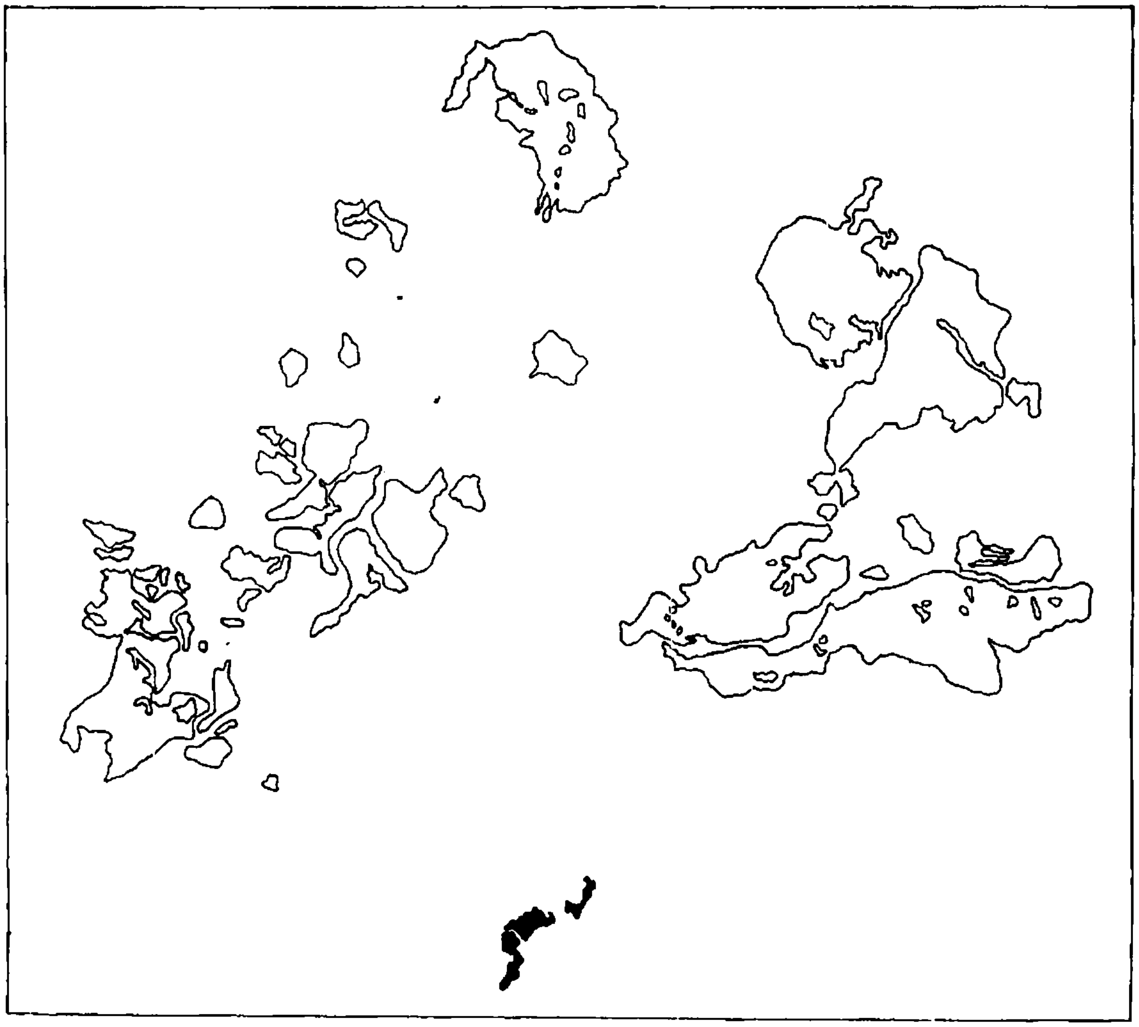

Fig.5.12. Map of Nilambur teak plantations showing the locations of the twelfth outbreak in the year 1993 on 5 May.

Fig.5.13. Map of Nilambur teak plantations showing the locations of the thirteenth outbreak in the year 1993 during 8-30 May.

Fig.5.14. Map of Nilambur teak plantations showing the locations of the forteenth outbreak in the year 1993 during 2-16 June.

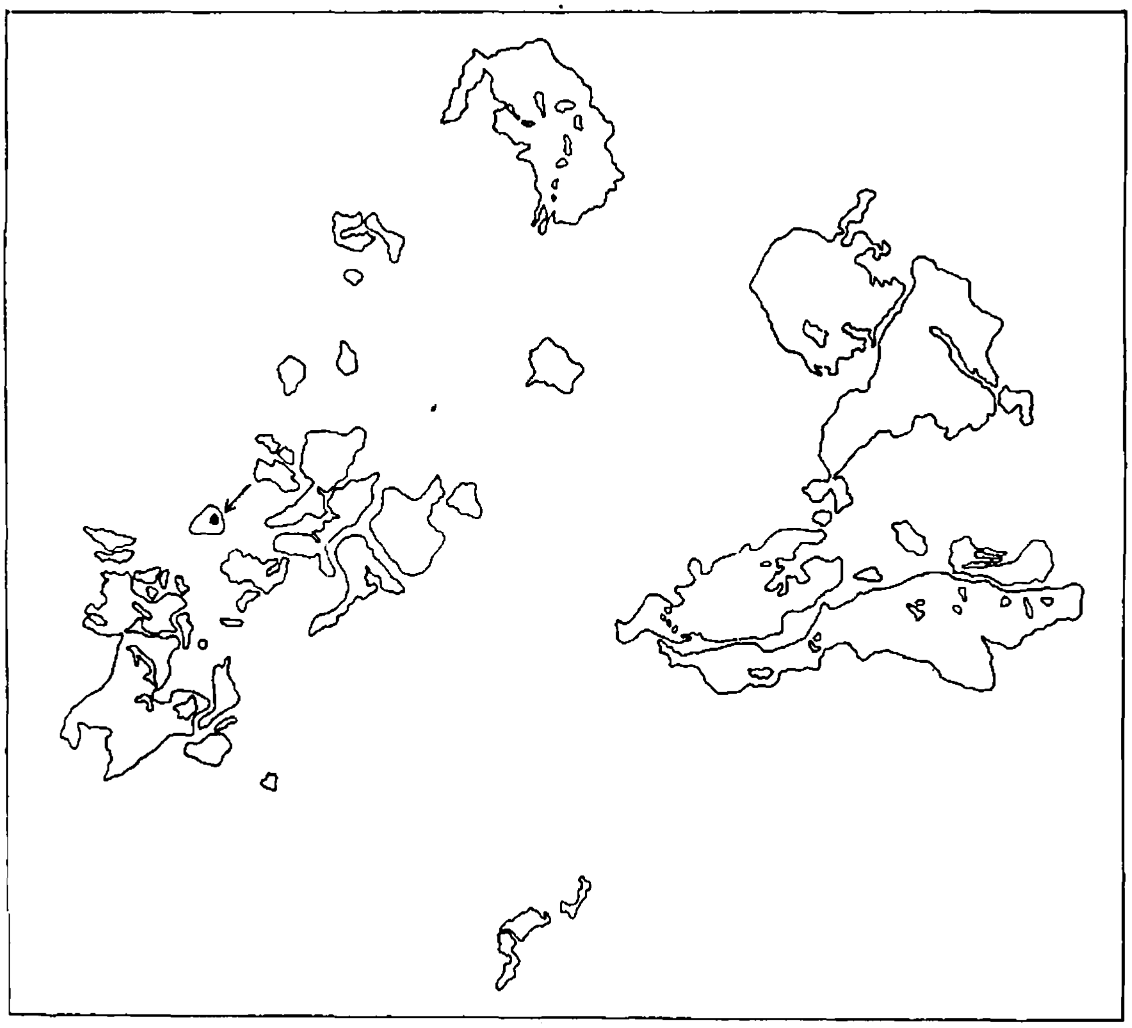

Fig.5.15. Map of Nilambur teak plantations showing the locations of the fifteenth outbreak in the year 1993 on 28 June.

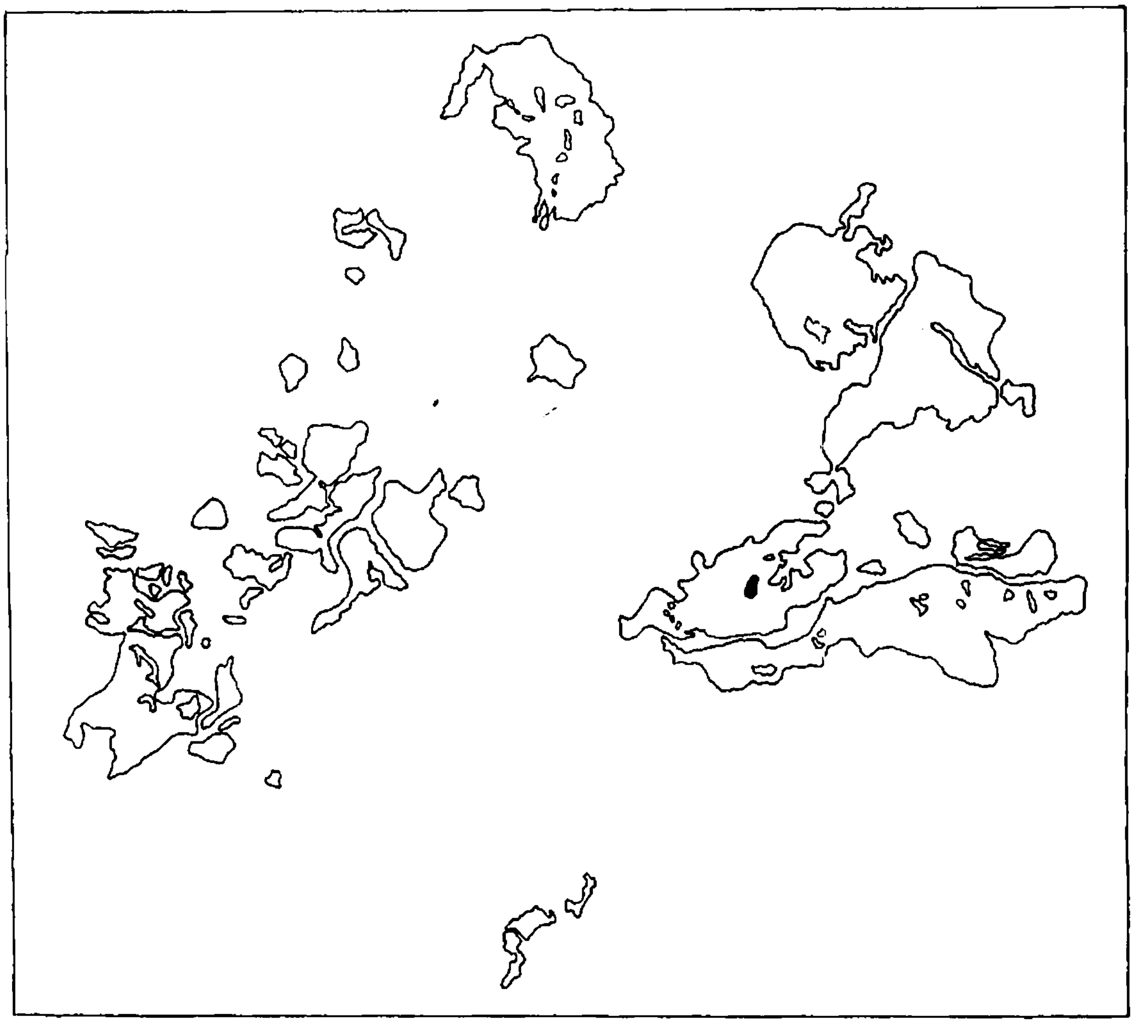

Fig.5.16. Map of Nilambur teak plantations showing the locations of the sixteenth outbreak in the year 1993 on 1 July.

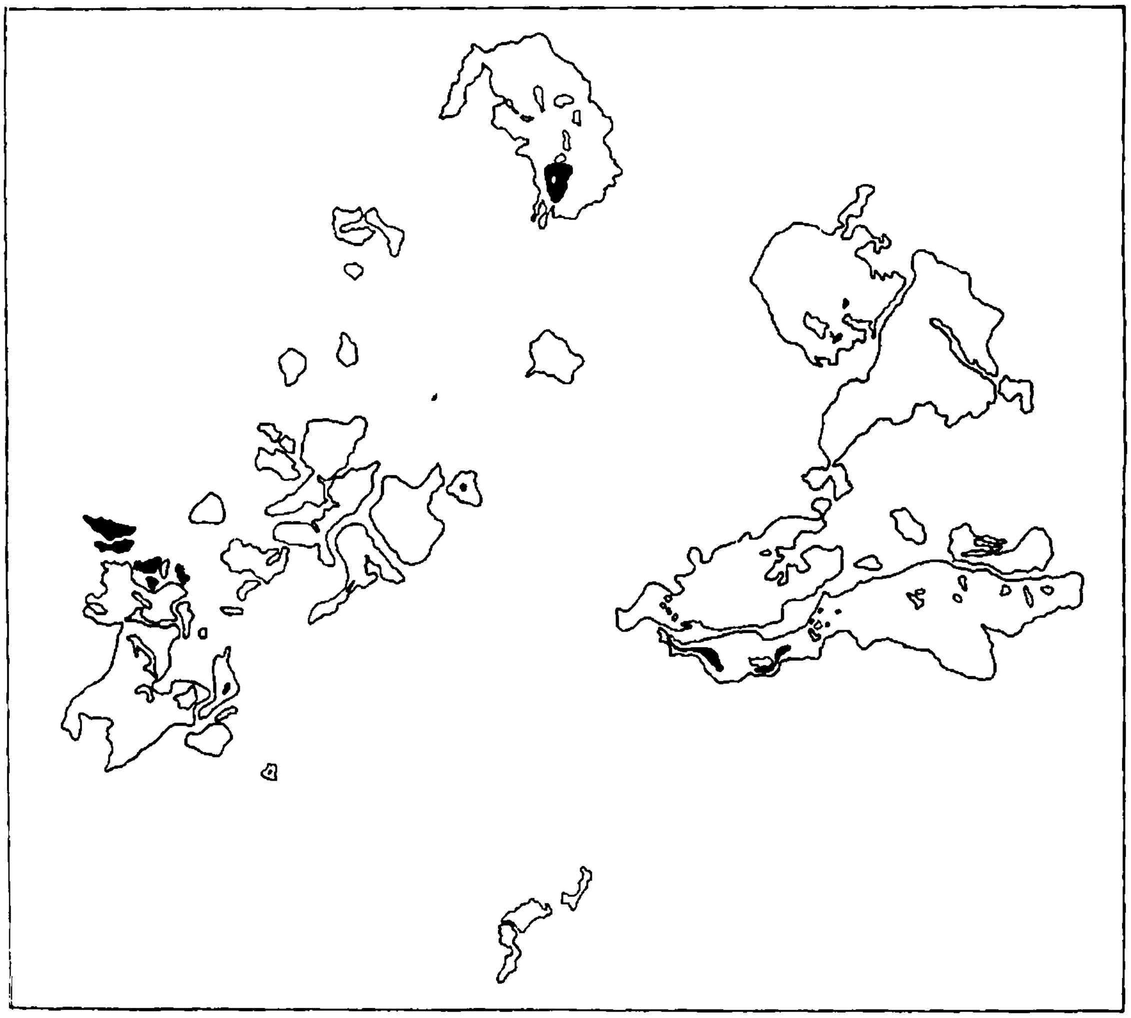

Fig.5.17. Map of Nilambur teak plantations showing the locations of the seventeenth outbreak in the year 1993 during 4-11 July.

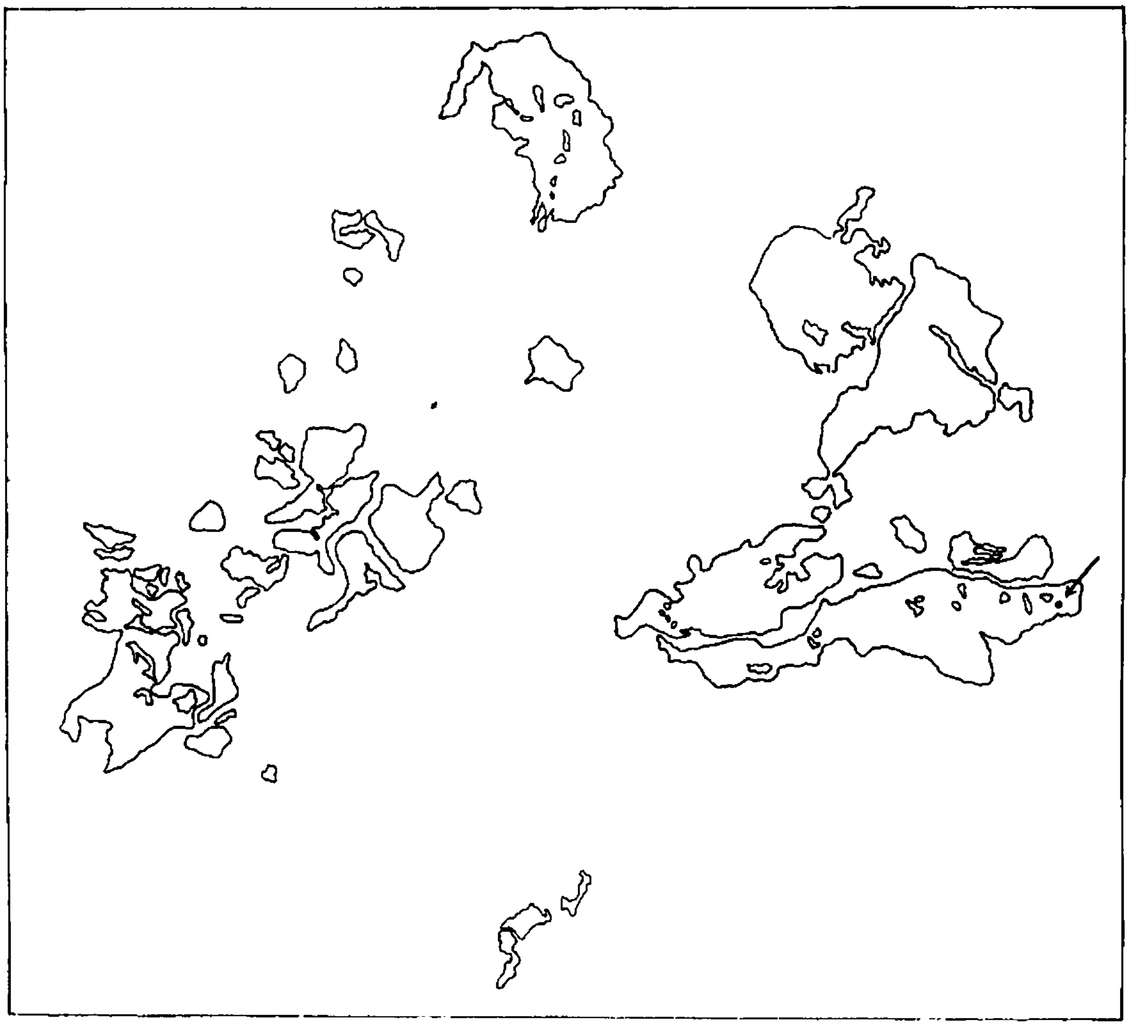

Fig.5.18. Map of Nilambur teak plantations showing the locations of the eighteenth outbreak in the year 1993 on 14 July.

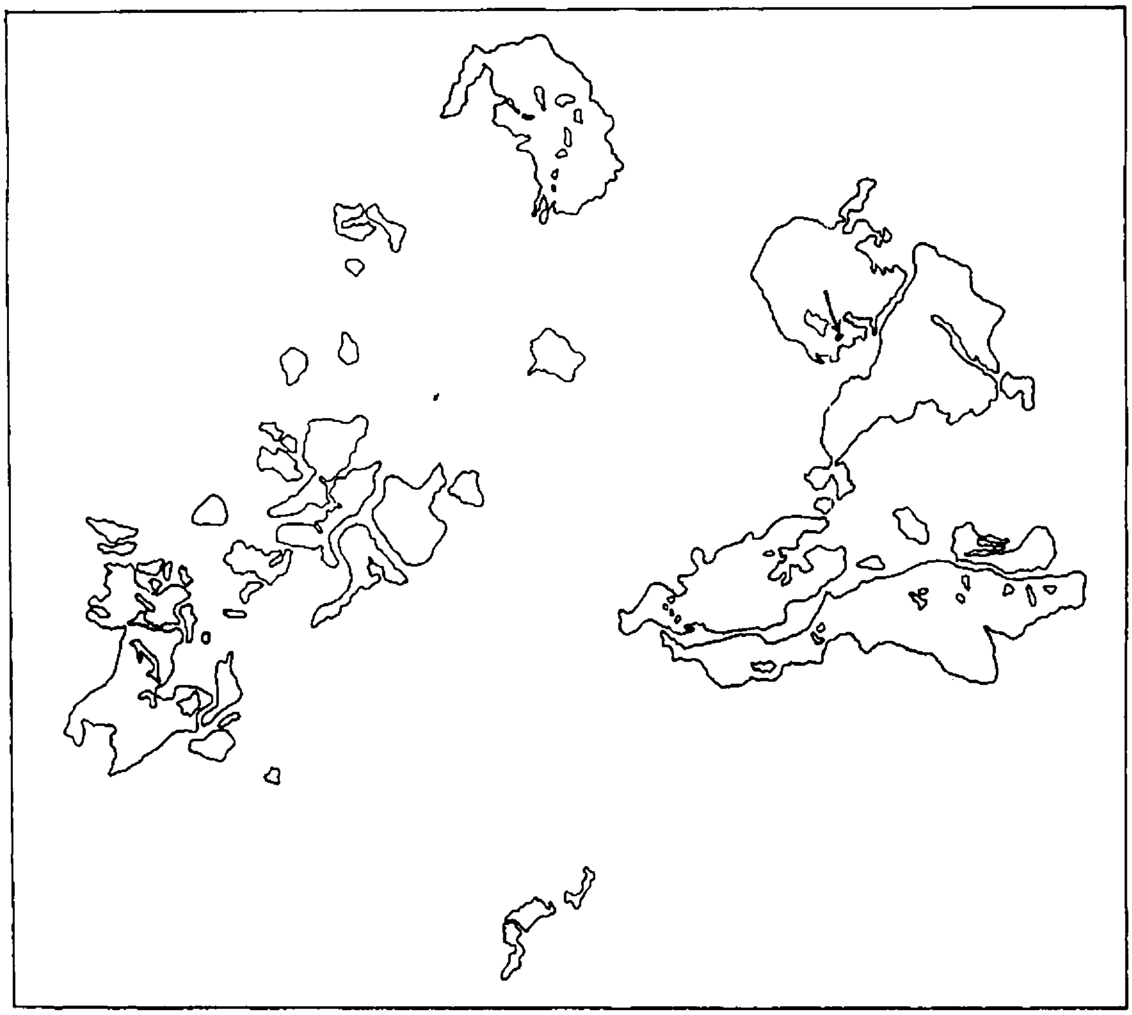

Fig.5.19. Map of Nilambur teak plantations showing the locations of the nineteenth outbreak in the year 1993 on 18 July.

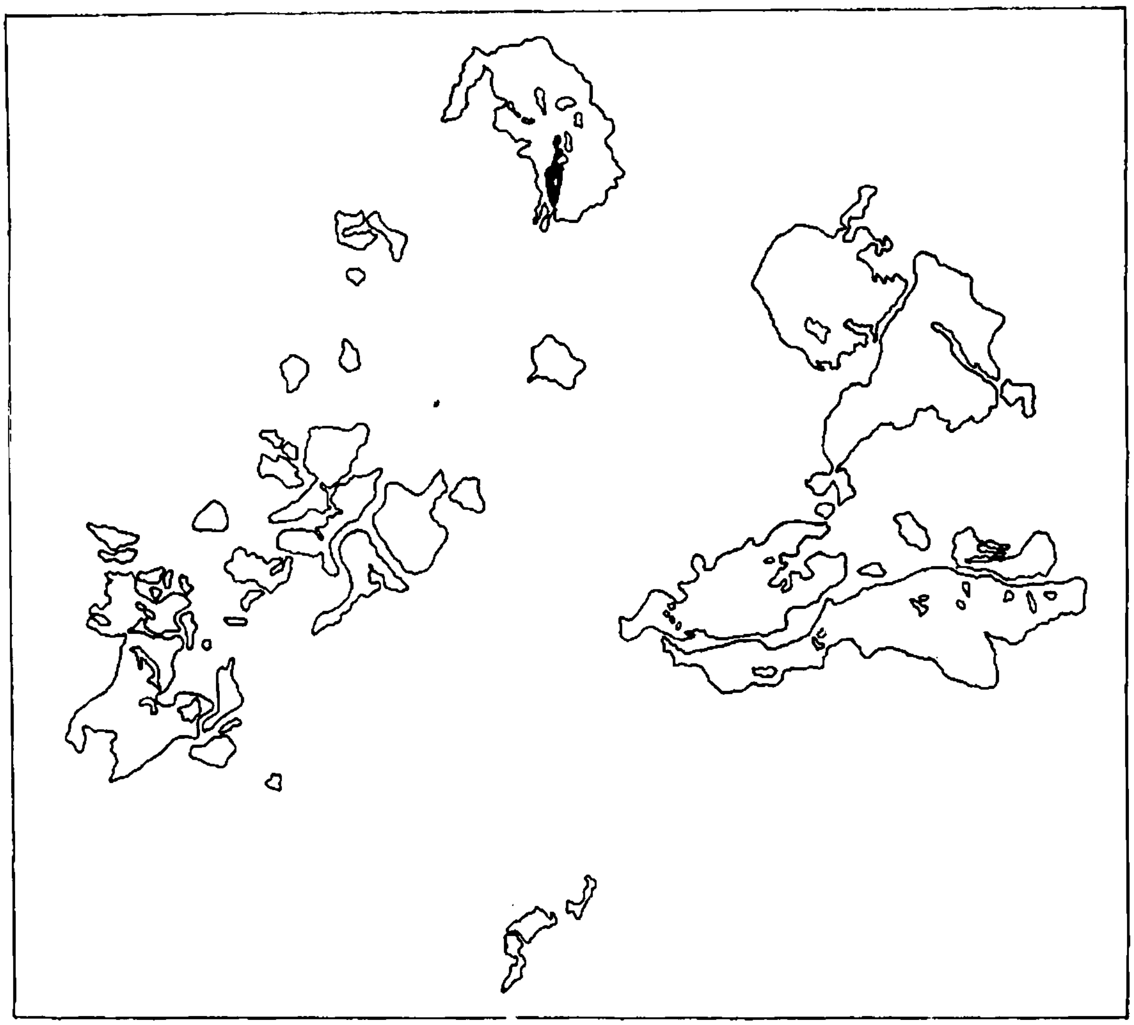

Fig.5.20. Map of Nilambur teak plantations showing the locations of the twentieth outbreak in the year 1993 on 27 August.

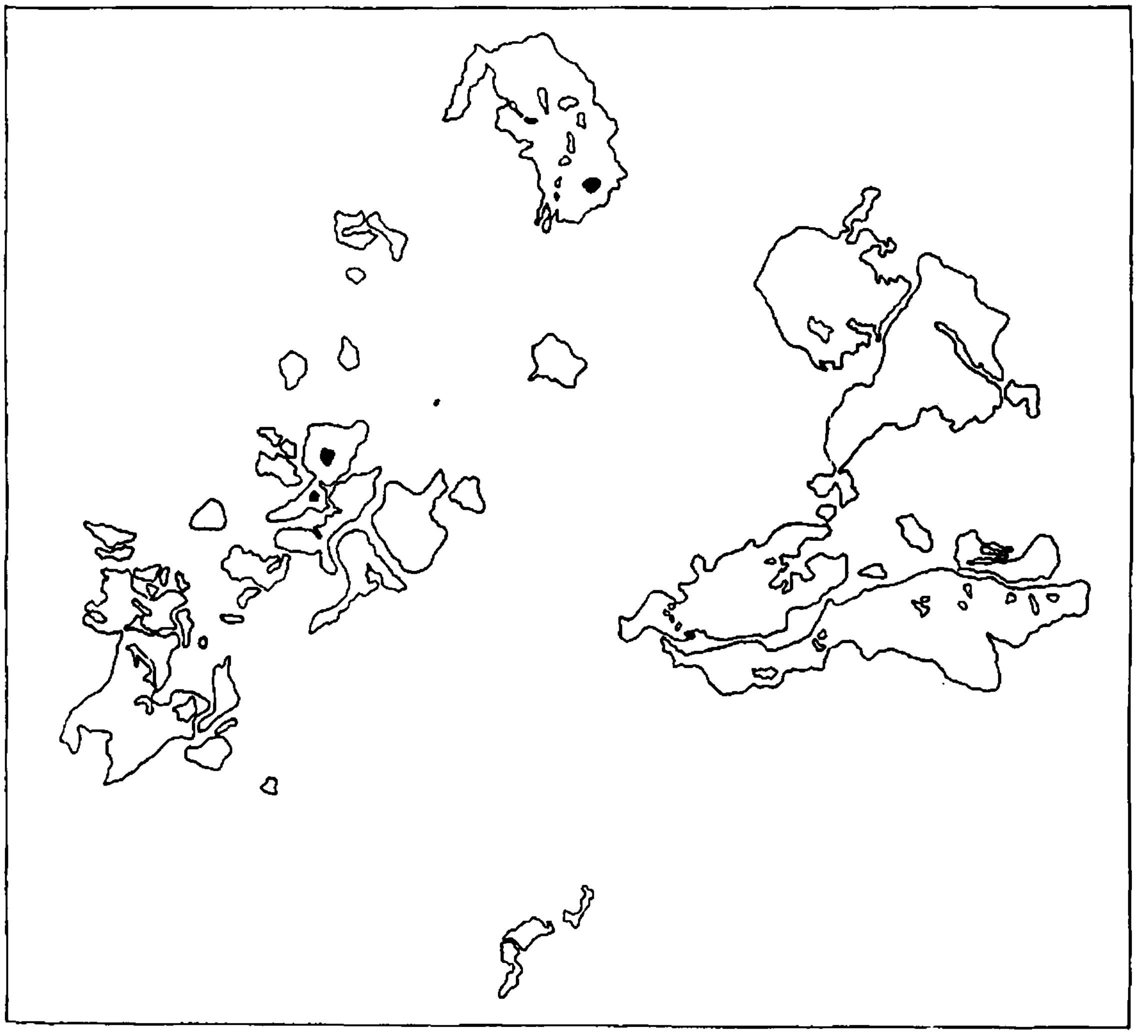

Fig.5.21. Map of Nilambur teak plantations showing the locations of the twenty-first outbreak in the year 1993 on 1 September.

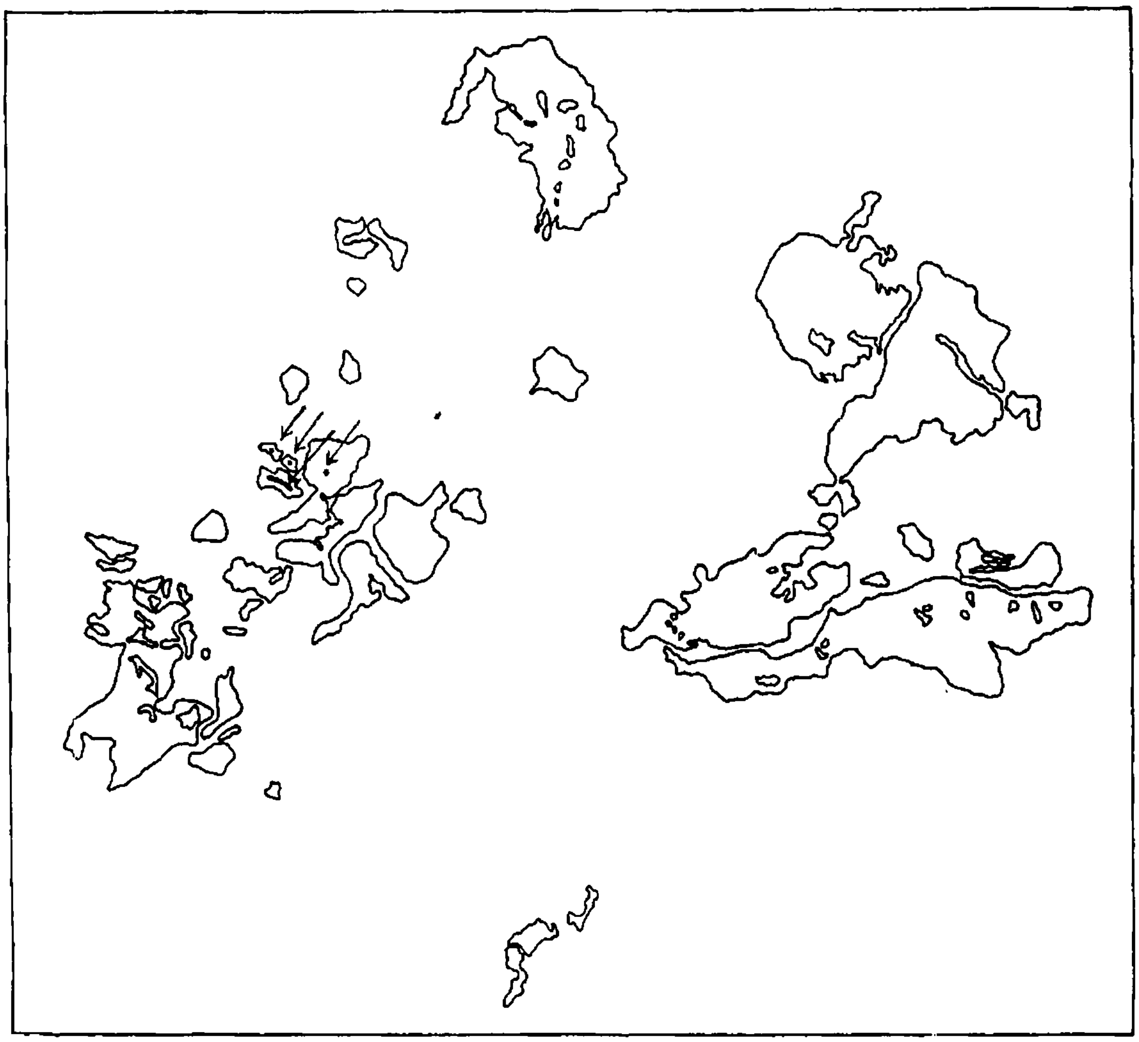

Fig.5.22. Map of Nilambur teak plantations showing the locations of the twenty-second outbreak in the year 1993 during 3-6 September.

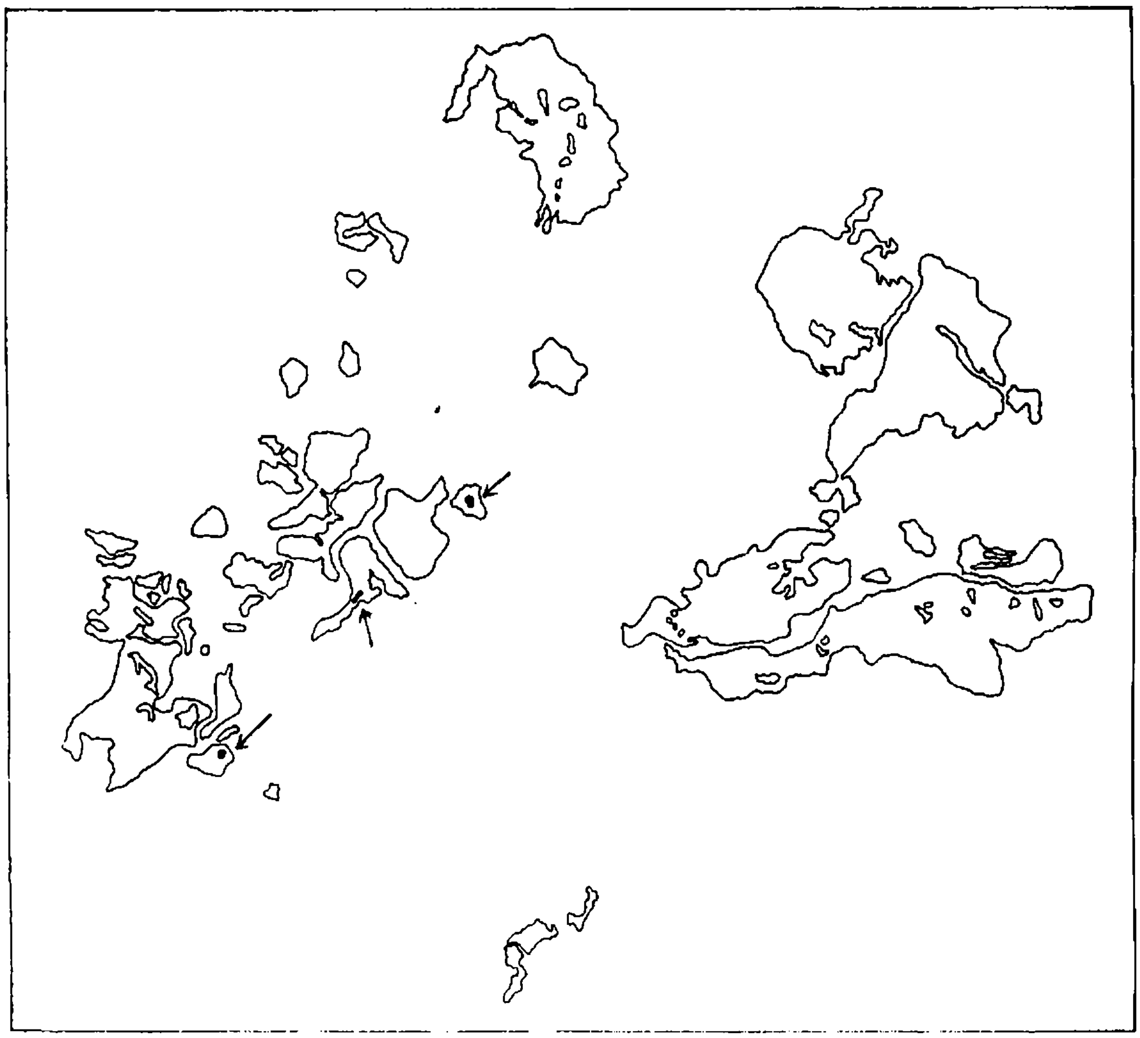

Fig.5.23. Map of Nilambur teak plantations showing the locations of the twenty-third outbreak in the year 1993 during 8-9 September.

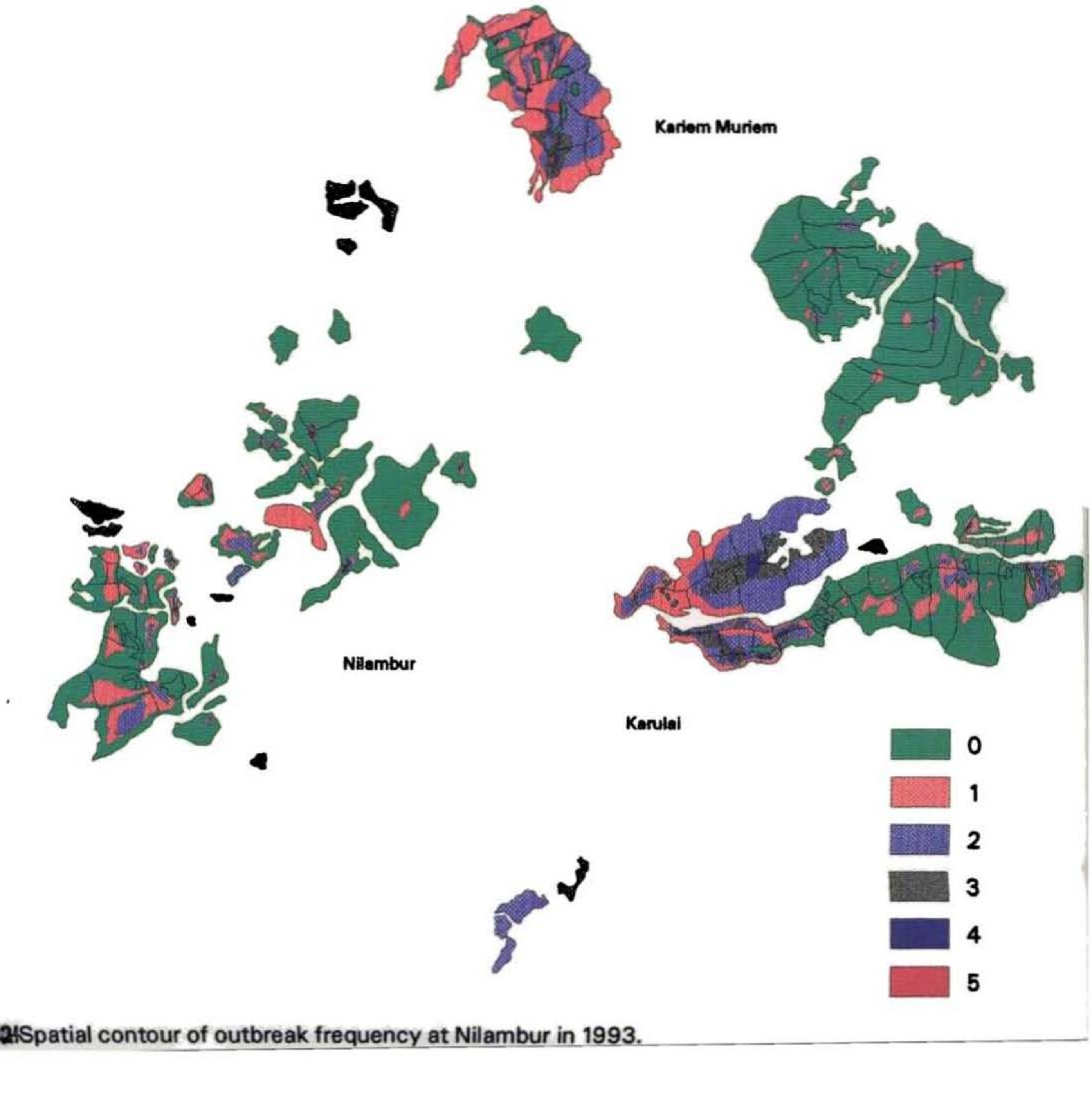

Fig.5.2: Spatial contour of outbreak frequency at Nilambur in 1993.

CHAPTER VI

FIELD OBSERVATIONS ON MOTH BEHAVIOUR

6.1. INTRODUCTION

This chapter summarizes the field observations made on aggregation, mating, oviposition, and flight behaviour of the teak defoliator moth. Laboratory studies made in the past have given information on the oviposition and reproductive behaviour (Sudheendrakumar, 1994). However, very few studies have been reported on the behaviour of moths under natural conditions.

Sudheendrakumar (1994) reported that under laboratory conditions, moths emerged from field collected pupae attained sexual maturity within 2 days while those from pupae reared in the laboratory took 3 days. Mating occurred predominantly in the second half of the scotophase, between 01.00 to 05.00 h. Duration of copulation was found to be ranging from 50-220 min. After mating, egg-laying started within 18-24 hours and continued up to a maximum period of 11 days. The fecundity ranged from 287 to 606. Egg-laying was continuous in most of the (75%) observed moths.

Relatively no information is available on the flight activity of the moth. However, short-range migration of the moths has been postulated to explain the observed spatial distribution of outbreaks (Nair and Sudheendrakumar, 1986). Aggregation of newly emerged moths has also been reported (Nair, 1988). The fact that outbreak populations of the insect consist predominantly of a single instar had suggested that during outbreaks, egg- laying occurs at a site on a single day. The admixture of two instars was attributed to the difference in the developmental time between individuals.

6.2. METHODS

In this study, post emergence behaviour of moths was studied at the site of emergence by establishing a floor-less cage within a teak plantation, when in March 1993, nearly 92 ha of teak plantations at Kariem Muriem was under infestation. A cage (3m x 2m x 2m) made of nylon net was established at a suitable site in the plantation in the first week of April when the insect population had reached the pupal stage. The ground within the cage was cleared of fallen leaves. Pupae were collected from the nearby area and were sexed. A total of 160 pupae (100 female and 60 male) were placed on the floor inside the cage along with fallen teak leaves so as to provide a relatively natural microenvironment for the pupae. Once the moths started emerging, diluted honey was provided on sponge as food. At hourly interval, observations were made on the number of moths emerged and their behaviour. During night, a dim, red light was used to make the observations. Observations were continued for a period of three days. A trained field observer was employed to take observations from the cage when simultaneous observations had to be made in the field. Some observations were also made on the behaviour of moths emerging in the field, outside the cage.

The flight behaviour of moths was observed at Kariem-Muriem during 1993. Over a period of one month period immediately following the emergence of moths from an infestation which occurred on 20th March, observations were made on the movement of moths in the field. To assess the sex ratio, collections of moths were made from aggregations that were found on ground or in flight. Since it is known that mated females start to lay eggs within two days (Sudheendrakumar, 1994), the females collected were individually reared for two days to know whether they laid eggs. Absence of egg-laying was taken as an indication of absence of mating. Whenever counts of moths in flight were taken at different sites at the same time, trained observers were deployed for the work.

Observations on the oviposition behaviour of moths under field conditions were made at Valluvassery in Nilambur in a three-year-old teak plantation. During one of the routine defoliator population monitoring exercises in 1993, a large number of moths were found hovering over the young trees at dusk. Careful observations revealed that the moths were laying eggs on the foliage. Next morning, 56 leaf pairs were marked in the plantation and the egg count was taken for each of them. Counting of eggs was repeated on the second and third day in the marked leaves.

6.3. RESULTS

6.3.1. Post-emergence behaviour

Observations made within and outside the field cage established at Kariem Muriem showed the following:

1. Freshly emerged moths were first found in the field at 18.00 h. Seven moths were collected out of which four were females. The first emergence of moths in the cage

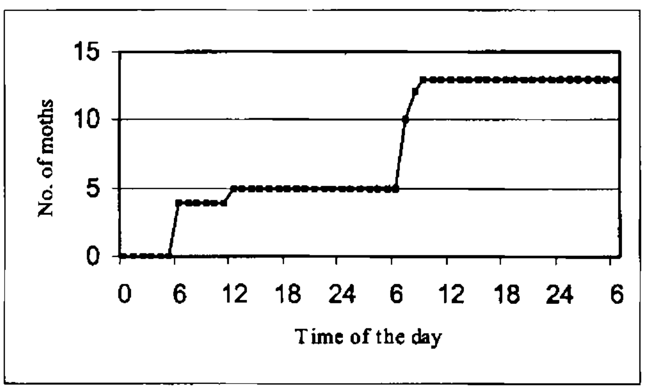

Fig.6.1. Graph showing the emergence of moths in relation to the time of the day.

was observed at around 06.15 h on the next day (Fig.6.1.). Four moths were found of which two were females. One more moth emerged at 12.00 h. No emergence was noticed until 07.00 hrs on the next day. Ten moths were found emerged at 07.00 h. At 09.00 h, 13 moths had emerged. No further emergence was noticed during the next day.

2. The moths that emerged in the cage spent nearly 1 hour before they were able to fly.

3. Feeding commenced after about 5 hours from the time of emergence.

4. A single pair of moths was found to start mating behaviour at 01.40 h. The duration of copulation was found to be 200min.

5. Before mating, the females exhibited characteristic calling behaviour (lifting of wings, curving of abdomen and protrusion and retraction of terminal abdominal segments).

6.Observations outside the cage revealed that during the time of emergence of moths from a densely populated site, birds flock in and feed on the newly emerged moths while they are unable to move by flight.

6.3.2. Aggregation

Finding moth aggregations depended on chance. Since systematic observations are difficult, only limited data could be generated. The first aggregation of moths was found on 16 April 1993 on the top of a hillock at Thannikkadavu in Kariem Muriem. This area was under outbreak; egg-laying had occurred during the period 9-11 April. The moths were found on the undergrowth and moved only when disturbed. The group consisted of both freshly emerged and old moths of both the sexes. This indicates that moths emerged on different days can be present in a single aggregation.

On the next day (17 April 1993), search was made for moth aggregations within the Kariem Muriem area. Aggregation was found on top of two hillocks-Ambalakkunnu- in the middle of the Kariem Muriem and Enpathukunnu-about 1 km north of Ambalakkunnu. Collections of moths were made both in the morning (4 males and 4 females) and evening (10 females and 3 males) from an area of 25 sq m at Ambalakkunnu. At both the places, fresh and old moths were found together. The females collected in the morning and evening laid eggs during night on the same day. No aggregations could be detected on the low-lying areas within the plantation.

6.3.3. Flight behaviour and dispersal

6.3.3.1. Movement of moths outside the teak plantation

Directional flight by a group of defoliator moths was observed on 5 April 1993 at Kariem Muriem. Moths were found to cross a paddy field and move into the teak plantation bordering it. The flight was at a height less than 5 m above ground level. A steady stream of moths was found moving in the same direction. This movement was detected at 15.45 h. Three hundred moths could be counted from a single observation point until the movement ceased at 16.40 h. It was observed that the movement of moths occurred in a wide area. Next day, moths were observed to move as on the previous day but towards the opposite direction (towards south) during the period 16.00 -19.30 h. Observations revealed that the flight path was nearly 200 m. wide. On the third day, movement of moths was detected at dusk towards south and away from the plantation. A total of 650 moths were counted from two observation points.

Two moths (one male and one female) were collected when in flight on 6 April 1993. The female laid eggs on 8 April. Moths collected when in flight on 7 April were predominantly females (28 females and 1 male). The females laid eggs on 8 April.

6.3.3.2. Movement of moths within teak plantations

The number of moths found in flight and the direction of their movement as recorded in observations made between 18.45 hr and 19.30 hr over a period of five days from 16 to 20 April are shown in Fig.6.2.

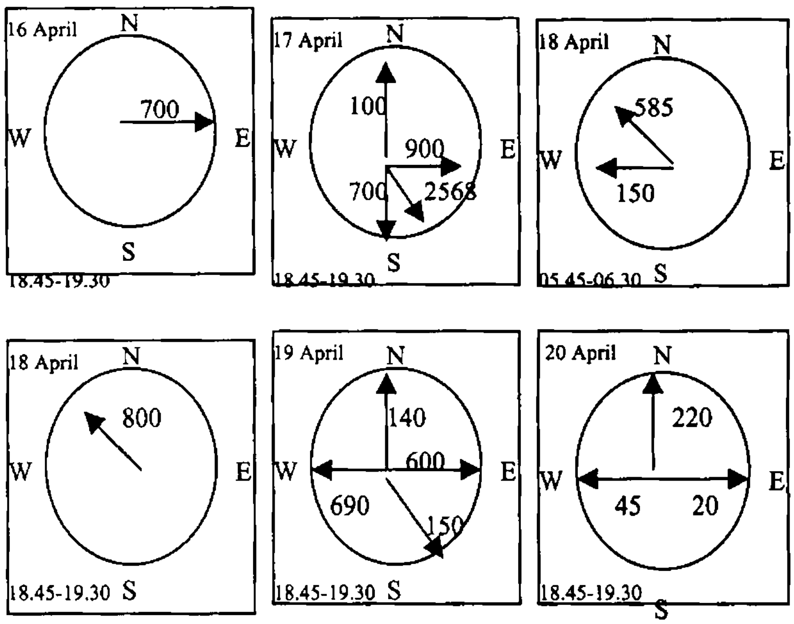

Fig.6.2. Number and direction of moths found in flight at Ambalakkunnu, Kariem Muriem.

On one of the days, observations were also made between 05.45 hr and 06.30 hr. An average of 1400 moths were observed in flight on each evening. Uni-directional flight was observed on two occasssions –16th dusk and 18th dawn. On other days, the movement was to different directions indicating diffusion of moths in the plantation.

6.3.4. Oviposition

Egg-laying was found to start at dusk (6.55 p.m. to 7.10 p.m.) on all the three days observed. The females hover over the shoot for a while and settle on the leaves. Eventhough some moths settled on the older leaves, they moved on to the lower surface of nearby tender foliage. The female moth walks on the leaf with the tip of the abdomen touching the leaf surface. The moth lays a single egg at a time close to the veins of the leaf. Moths were found to oviposit on leaves which was oviposited earlier.

On the first day of observation, there were 372 eggs in the 56 leaf pairs tagged. On the second day, the number of eggs increased to 619. On the third day, a total of 750 eggs and 93 first instar larvae were found. There were no further additions on subsequent days. It can be seen that the maximum number of eggs was laid on the first day. On the second and third days, the numbers of eggs laid were almost equal- 269 and 268 respectively. Observations on 56 leaf pairs concluded that egg-laying can happen on the same leaf for at least three consecutive days. The population of moths that laid eggs on all the three days can either be the same group of moths arriving each day from a place of aggregation or different groups of moths.

6.4. DISCUSSION

Cage observations confirmed the earlier known information on pre-mating period. The characteristic calling behaviour of the moths could be observed in the cage, which could not be seen in the earlier laboratory studies. Observations made outside the cage gave new information on one of the most mortality prone life stage of the insect- the time immediately following adult emergence from the pupa. Attraction of birds to the emergence site suggests that they are responding to some cue, possibly scent emanating during adult eclosion.

Aggregations of the moths were predominantly found on hillocks at Thannikkadavu and Ambalakkunnu during the daytime. "Hilltoping" is a phenomenon exhibited by many species of lepidopterans to aggregate from a wide area (Brown and Alcock, 1990; Pinheiro, 1990). It has been argued that this behaviour facilitates the insects from a wide area to reach the top of one or other hillock. Aggregation of moths within the hilltop can be mediated through chemical means. Thus "hilltoping" can help the formation of a moth aggregation. The aggregations, which were observed, consisted of moths emerged on different days as indicated by the simultaneous presence of fresh and old moths.

Observations on the dispersal of adult defoliator moths indicated two distinct types of movement. The first was the unidirectional movement observed outside the plantation and the second was the dispersal type of movement found within the plantation. While the first type of movement was noticed during daytime, the second type of movement was found only during dawn and dusk.

Even though only a small number of moths could be collected during flight, it indicates that during unidirectional flight, the group consists predominantly of mated females. It can be inferred that mating occurs before the mass movement of the moths. However, males are not absent from the migrating group. The aggregations that were detected were also predominantly consisting of females. There is high chance of mortality during mass movements. Therefore, mating before the movement reduces the risk of not finding enough number of males at the destination to mate with the surviving females.

In this study, egg-laying has been found to occur for three continuous days in the same plantation. In the earlier studies (Mohanadas, 1995) it had been noted that at any given time during the larval period of the insect, any one among the five instars will be dominating even though simultaneous presence of at least three instars were noticed. This observation had led to the conclusion that the insect lays eggs only on a single day and the presence of instars other than the dominating one was due to the difference in developmental time of the insect. The present study shows that egg-laying on different days can also lead to the presence of more than one instar. This oviposition behaviour need not necessarily be typical as the present observations were made during the month of July in a young plantation. More observations are needed on the oviposition behaviour of the immigrant moths during the early outbreak period.

Based on the results of this study, the sequence of events from the emergence of moths to the start of the next outbreak can be described as follows:

The newly emerged moths after a period of about one hour move by active flight to form an aggregation. Moths that have emerged from different stands and/or those emerged on different days form part of the same aggregation. After mating, the aggregation moves to a new habitat. Post migratory aggregation can also bring in moths from different stands or those emerged on different days. Both males and females will be part of this group but females are predominant. It seems that the aggregation remains until the completion of egg-laying.

The behaviour of the defoliator moths proposed above can explain many of the characteristics of *H. puera* population dynamics. Incidence of outbreaks in different patches at the same time can be caused by short-range movement of a group of moths during the period of egg-laying. Similarly, the simultaneous occurrence of more than one stage of the insect at any particular stand can be explained by the fact that the insect lays eggs on the same stand more than once. It is not certain whether the eggs laid on a single stand on different days is by the same group of moths or by different groups. Long-range movement of large group of moths outside teak plantations observed in this study could cause sudden outbreaks in plantations.

CHAPTER VII

DEVELOPMENT OF OUTBREAK MONITORING METHODS

7.1. INTRODUCTION

Early detection of defoliator population is necessary to adopt timely measures to prevent damage. The eggs of the defoliator are quite small which can only be detected on careful observation. The first instar larvae, which emerge from the eggs, are also small and they feed by scraping the foliage and therefore neither the larva or the damage caused is visible from ground. The damage can be detected visually only when the second instar larvae cut the leaf and make folds out of it. By this time at least three days would have elapsed from the start of the outbreak. Since egg-laying is the first step in the initiation of an outbreak, the best indicator of a forthcoming infestation is the presence of moths. It is known that *H .puera* moths can be monitored by light traps (Vaishampayan and Bahadur, 1983). However, a major limitation in the use of light traps is the necessity to have electricity at the site of operation. This is often difficult, particularly in teak plantations. To surmount this difficulty, attempts have been made to use car batteries as the source of electricity. However, the need to recharge the batteries at frequent intervals, which is either cumbersome or not practicable under some situations, is a serious handicap. In addition, the light intensity of battery operated lamps will vary depending on the battery charge. Incandescent (tungsten filament) bulbs of 100 to 200 watts are generally used in light traps. The Pennsylvanian trap uses a fluorescent tube. An increase in the intensity of light usually results in increased trap catches. Use of ultraviolet light also increases the trap catches, particularly of moths (Southwood, 1976). "Black-light" tubes emitting portions of the ultraviolet spectra, not harmful to the human eye, have recently been developed and are now commercially available. Since they are much more attractive than incandescent lamps, tubes of lower wattage can be used. In this study, a solar-powered light trap was developed for operating in plantations and the correspondence of outbreaks and light trap catches was tested.

Since it was found that the correspondence between light trap catch and outbreaks was not adequate, attempts were made to develop an outbreak monitoring method by combining light trap and visual observations.

7.2 METHODS

The light trap was developed using a black-light tube, powered by a battery. The battery is charged during the daytime, using sunlight, through a photovoltaic system. The light trap system consisted of three sub-units: (1) the trap, (2) the collection cage, and (3) the Solar photovoltaic (SPV) system.

Details of the trap system are given below (see Fig.7.1).

(1) The trap

The basic trap unit is similar in design to the Pennsylvanian trap. It consists of a framework made of two flat iron rings, 30 cm in diameter, with cross arms in the middle, and connected together with 4 iron rods. A tube holder is fixed at the centre of the cross arms of each ring, to hold a fluorescent tube. Aluminium channels fixed in the cross arms serve to hold 4 baffles, 60 cm tall and 12 cm wide, made of 4 mm thick transparent perspex. The baffles can be removed to replace the tube. A funnel, 30 cm diameter at top, made of 20 gauge smooth aluminium sheet, is fixed to the bottom ring of the framework. The tail of the funnel extends into a collection cage. Alternatively, the tail of the funnel passes through a hole cut in the centre of a stainless steel bottle cap to which a collection bottle can be screwed. The top ring supports a conical aluminium hood 45 cm in diameter at bottom, to protect the trap from rain. Insects are attracted by light emitted by a 20 W black-light fluorescent tube, 60 cm long. It works on single phase AC electric supply of 230 V, 50 Hz and emits light rays of low frequency (Wavelength 300 to 400 nm), not harmful to human beings.

(2) The Collection Cage

The Collection cage is a walk-in-cage, 180 x 180 x 210cm, made of angle iron frame and covered with nylon netting fixed with nuts and bolts. The cage is placed on a basement plastered with cement.

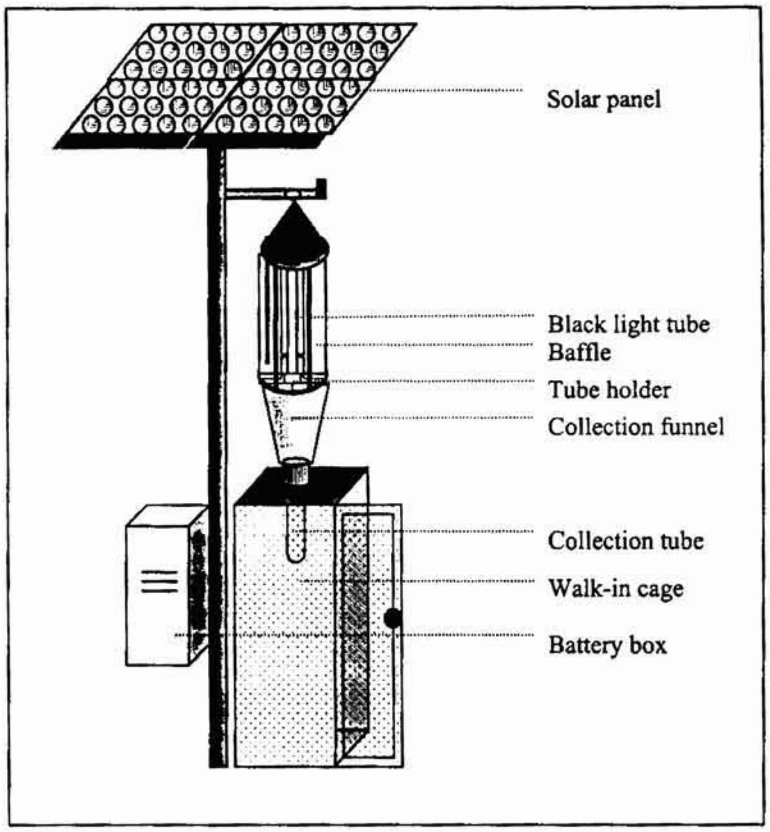

Fig.7.1. Diagram showing the prototype of the light-trap.

(3) The Solar Photo-voltaic System

The Solar photo-voltaic system (SPV) system was developed with the help of ANERT (Agency for Non-conventional Energy and Rural Technology), Trivandrum. It consists of (i) 4 numbers of 30W (nominal) SPV panels, (ii) a 12V 60 AH storage battery, and (iii) an electronic control unit. The electronic control unit has two sections, namely charge controller and inverter. The charge controller ensures that the battery is neither over-charged nor over-discharged, with cut-off voltages at 13.8V and 10.5V respectively. The inverter operates at 20 kHz with a secondary voltage of 200V on load. The Solar panels are mounted on a steel pole, 2.6- m in height and 7.5- cm. in diameter. The battery and electronic control unit are housed in a box mounted on the pole to protect them from rain and dust.

The light-trap was established on top of a hillock at Kariem-Muriem. This hillock is located in the centre of the teak plantations in this area. The trap was operated for a period of 16 months from 23 June 1993 to 15 October 1994. Daily collections of defoliator moths were made during the period 1993-94. The outbreaks, which occurred during this period, were mapped and the dates of start of these outbreaks were estimated as described in Chapter 3. During this period, all the outbreaks that occurred at Kariem Muriem were mapped and based on larval samples collected, the starting date of each infestation was determined as described in Chapter 3. It was examined whether moths were collected in the trap during the start of an outbreak so as to judge if it could be used as a monitoring device.

7.3. RESULTS

The solar light trap developed was found satisfactory. Based on the prototype model described above, a more convenient portable model was designed with the following modifications:

1. The number of solar panels was reduced from 4 to 1.
2. The steel pole was reduced in size and was made collapsible.
3. The walk-in cage was replaced with a smaller cage.

The trap catch during the 16-month period is given in Appendix B and depicted in Fig.7.2. along with the time of occurrence of outbreaks at Kariem Muriem. Distinct period of abundance of moths in the field can be identified. The period immediately after the establishment of the trap (June, 1993) was a time of high abundance of moths. There was a decline in trap-catch during August. There were further increases in the number of moths during the first weeks of September and October. Only very few moths were collected during November (2 moths) and December (1 moth).

In 1994, no moths were collected during January, February and March. The first moth was collected on 2 April. Large number of moths were trapped during the moths of May, June and July beyond which no moths were collected until the end of the study in October. The correspondence between the trap catch and the initiation of an outbreak is depicted in Table 7.1.

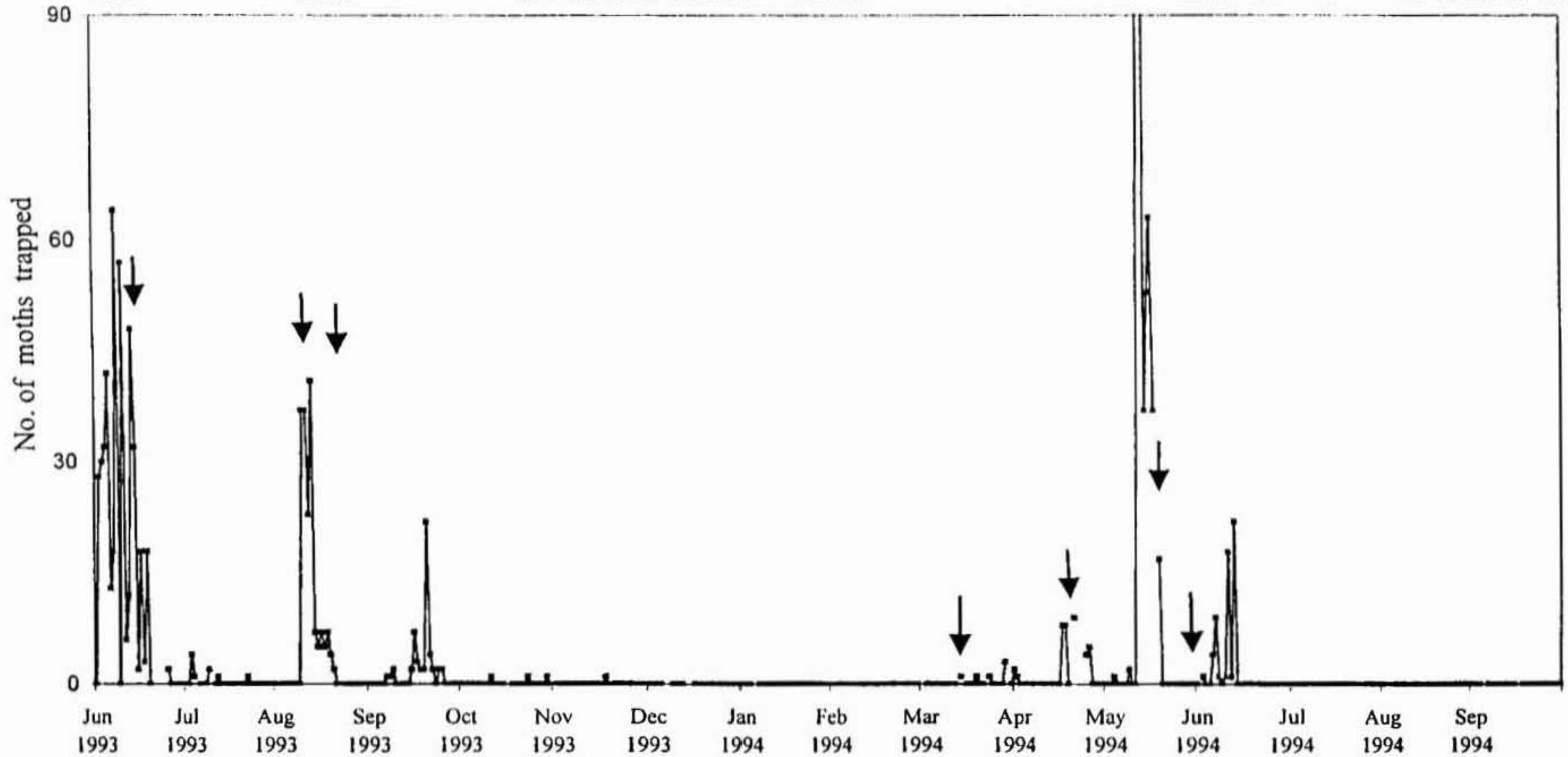

Fig.7.2. Graph showing the number of moths collected in the trap and the occurrence of infestation at Kariem Muriem. Arrows indicate date of occurrence of infestation. Breaks in the line indicate days when the trap was not operated.

Table 7.1. Correspondence between light-trap catch and incidence of outbreak

Sl.No. of outbreak which occurred during the period of light-trap operation	Starting date of outbreak (date of egg laying)	Cumulative number of moths trapped during a 5 day period prior to start of outbreak	Distance between light-trap and the infested site (km)	Area infested (ha)	Whether locally emerged moths are present
1	7 July 1993	145	0.05	52.0	Yes
2	27 August 1993	0	0.5	36.1	No
3	1 September 1993	74	2.0	35.7	No
4	4 April 1994	1	0.5	12.2	No
5	12 May 1994	9	0.05	472.5	No
6	3 June 1994	596	3.0	75.0	Yes
7	12 June 1994	0	0.05	435.3	No

The first outbreak occurred on 7 July, 1993 at an area of 52 ha. which was 0.05 km away from the light-trap. A total of 145 moths were collected during the five day period prior to 7 July. There were locally emerged moths during this period at Kariem-Muriem from an outbreak which occurred on 10 June. The second outbreak was on 27 August 1993 covering an area of 36.1 ha at a distance of 0.5 km from the light-trap. No moths were collected during the days prior to this date. There were no locally emerged moths at Kariem-Muriem during this period. The third outbreak also occurred when there were no locally emerged moths but 74 moths were collected during the days prior to the start of the outbreak. This outbreak occurred at a distance of 2 km away from the light-trap and covered 35.7 ha. The fourth outbreak occurred on 4 April 1994 at distance of 0.5 km from the light-trap and covered an area of 12.2 ha. Only one moth was collected and there were no locally emerged moths. A major outbreak occurred on 12 May 1994 covering an area of 472.5 ha and 0.05 km away from the light-trap. Only 9 moths were collected prior to this outbreak. No locally emerged moths were present during this period. The next outbreak extended to an area of 75 ha at a distance of 3 km from the light-trap. A total of 596 moths were collected on days preceding the start of light-trap. A total of 596 moths were collected on days preceding the start of this outbreak. Locally emerged moths were present during this period. No moths were collected prior to the last outbreak which was 0.05 km away from the trap and which extended to 435.3 ha. There were no locally emerged moths during the period.

It can be seen that out of seven outbreaks which occurred during the study period, occurrence of two outbreaks (sl.nos. 2 and 7) could not be detected by light-trap catch eventhough the sites infested were very close (0.5 and 0.05 km respectively) to the trap. Very few moths were collected during the 4^{th} and 5^{th} outbreaks (1 and 9 respectively) which also occurred near to the light-trap (0.5 and 0.05 km respectively). Only the occurrence of three outbreaks (sl.nos. 1,3 and 6) among the total seven was well indicated by trap catch. Majority of moths were collected during the 1^{st} and 6^{th} outbreaks (145 and 596 respectively) during which moths were emerging locally from earlier outbreaks. Only the occurrence of the third outbreak was well indicated (74 moths were collected) by trap-catch when no locally emerged moths were present. Thus when no locally emerged moths were present, only one of the five impending outbreaks was predictable by a high trap catch.

7.4. DISCUSSION

This study indicates that eventhough the moths were collected in the light-trap during the period of the year when teak defoliator outbreaks are prevalent, it does not always collect moths, which arrive in the plantation for egg laying. Large number of moths was collected while they were emerging from the plantations nearby. But the trap was unable to attract and collect moths every time they arrived at the plantation for egg laying. The reason is not well understood but it appears that the moth aggregation that arrives for egg laying respond primarily to the chemical signals from the host plant.

This study has shown that the light-trap cannot be relied upon as an outbreak detection device. Detection of an outbreak needs ground observations. These observations can be limited to areas, which have tender foliage. If folds are detected, observations have to be made in transects radiating in four directions from the site where folds are detected. At these transects, tender leaves have to be closely observed for the presence of defoliator eggs or first instar larvae. Eggs are oval and white. The first instar larvae will be feeding by scraping the leaves near the veins. This observation is needed because egg laying can occur for more than one day and sites with eggs and first instar larvae can go unnoticed in an observation from ground.

CHAPTER VIII

POPULATION DYNAMICS OF *H. PUERA* - A SYNTHESIS OF AVAILABLE INFORMATION

8.1. INTRODUCTION

The study of population dynamics is an old discipline that antedates the modern science of ecology (Cappuccino, 1995). Insects have been a much-researched group owing to their short-life span and role as pests. Of the various pests, those that dwell in forests have attracted much interest since they occupy relatively natural environment as compared to those in many agricultural systems (Berryman, 1986). *H. puera* outbreaks that occur in teak stands with a normal rotation period of 60 years present a unique case to study population dynamics. Moreover, teak defoliator outbreaks occur more than once every year compared to the 8-11 years frequency seen in the case of many temperate species of forest defoliators (Myers, 1998).

According to a classification scheme based on the spread of outbreaks (Berryman, 1987), teak defoliator outbreaks have been recognized as belonging to the eruptive type (Nair, *et al.*, 1994). The main characteristics of insects that display eruptive outbreaks is that their populations remain at relatively stable levels for long periods but then suddenly erupt to very high densities. These eruptions usually begin in particular localities (epicentres), and then spread over large areas. This theory implied that controlling the initial epicentres could lead to suppression of large-scale outbreaks.

The epicentre hypothesis has practical value, if it is proved that progenies of epicentre populations cause the large-scale outbreaks. This needs simultaneous observation in large areas and precise information on the time of start of each outbreak. Then, based on the generation time needed for each population, we can determine whether the large-scale outbreaks could originate from initial epicentres. Such an attempt was made in the present study. Flight characteristics of moth were also studied to explain the population dynamics exhibited by the insect. Since the spatial scale of the study has considerable bearing on the perception of the phenomena (Solbreck, 1995), observations were carried out in a large geographical area.

This chapter attempts to synthesize the earlier available information and those generated in the present study in the light of recent advancement in theory on insect population dynamics. Important aspects influencing the population dynamics of the insect, namely aggregation, flight, origin of outbreaks, and the pattern of spread of outbreaks are discussed and an attempt is made to develop a theoretical framework appropriate for describing teak defoliator outbreaks.

8.2. AGGREGATION AND FLIGHT OF MOTHS

It has been recognized that the tendency to aggregate is a characteristic of outbreak species of insects (Cappuccino, 1995). In the case of *H. puera*, the sudden appearance of heavy infestation with thousands of larvae per tree, following a period of near absence of infestation had indicated that aggregation of moths occur prior to egg-laying at the site. Moth aggregations have been observed earlier within teak plantation and nearby natural forests (Nair, 1988). In the present study aggregations of moths were observed in teak plantations immediately before the plantation was infested (Chapter 6). These aggregations consisted of uneven aged moths of both the sexes. This indicates that an aggregation is composed of moths that emerged from different sites or moths that emerged from the same site on different days. The fact that aggregations were predominantly found on hillocks suggests that moths use topography as a guiding cue to form aggregation.

Circumstantial evidence for short-range (Nair and Sudheendrakumar,1986) and long-range (Vaishampayan *et al.*, 1987) movement of moths was obtained earlier based on independent studies at Kerala and Madhya Pradesh. In the present study, direct observations revealed two types of flight behaviour in *H. puera*.

1. Dispersal flight: observed during dawn and dusk in all directions within teak plantations at the canopy level,
2. Directional flight: not restricted to dawn and dusk, moths moving in the same direction in a swarm.

8.3. ORIGIN OF OUTBREAKS

This study showed that in 1993, within the nearly 9,000 ha teak plantations at Nilambur, the first outbreaks occurred during the month of February in a few small scattered patches. These patches varied in size from 1.8 to 12 ha. These initial patches could originate in two possible ways:

1. A change in behavior of endemic population of the insects within the area leading to aggregation and mass egg-laying.
2. An influx of moths from a distant area

Correlation between the time of occurrence of first outbreaks and pre-monsoon showers has been observed earlier. Since there is no report on diapause in *H. puera*, rain cannot be a factor that triggers the emergence of moths. Even though new flushes come up profusely after the pre-monsoon showers, it is observed that tender foliage sufficient to support epidemic populations of the insect are present even before the pre-monsoon showers. It could be thought that the first rains could have an impact on the behaviour of moths, inducing them to aggregate. Alternatively, the wind system associated with the pre-monsoon showers can assist in long distance immigration of moths. The present data are not sufficient to prove any one of the above.

8.4 SPATIAL SPREAD OF OUTBREAKS

The spread of outbreaks during a year within nearly 9,000 ha teak plantations at Nilambur can be summarized as follows:

It was observed earlier that initial outbreaks occurred in small patches covering 0.5 – 1.5 ha in area which are widely separated. The present study showed that the initial epicentres could be much larger extending to a maximum of 13 ha (see Section 5.2, Chapter 5). It was noticed that these epicentres originate during the month of February. As discussed above, origin of epicentres remains an unresolved problem. During the months March and April, infestations occur in patches of a wide range of sizes (0.1 to 934 ha), which are still widely separated in space. Most of these outbreaks occur simultaneous with the emergence of moths from the populations during the first phase (the epicenter phase), but some populations occur when there are no locally emerged moths. Widespread outbreaks occur in a large number of patches during May and June. Progenies of populations, which occurred during the build-up phase, could cause all the outbreaks during this phase. While the life stage of the insect is uniform within an outbreak patch, there is considerable difference between patches. This could be because of the fact that moths emerged from different outbreaks that occurred during build-up phase cause these wide spread outbreaks. During July there is a reduction in both the number of patches infested and the size of outbreak patches. All outbreaks that occur during July could be explained as caused by progenies from earlier populations. Outbreaks during this period do not cause further outbreaks in the area even if tender foliage is present. This may be because of collapse of population due to natural mortality factors or the emigration of moths from the area. A few outbreaks covering around 1-40 ha occur during the period August - September. With respect to origin of these outbreaks, this phase resembles the period of epicentres. These outbreaks seldom cause subsequent outbreaks in the area.

8.5. THE BACKGROUND TO WORKING TOWARDS THEORY

The following specific details hitherto generated are relevant to explaining the observed dynamics of teak defoliator outbreaks:

1. At the global scale (encompassing all places were *H. puera* is present i.e., India, Myanmar, Sri Lanka, Indonesia, Papua-New Guinea, the Solomon islands, *etc*) the insect occurs in outbreak density at different places at different times.

2. At a still lower regional scale (for example the Indian Subcontinent) there is a directional progression of outbreaks, which seems to be linked with the movement of monsoon wind system.
3. At the local level (like the teak plantations of Nilambur), outbreaks occur only during some part of the year. During the outbreak period, infestations originate in a few small epicentres. Later, outbreaks spread to larger and larger areas. While most of the outbreaks could be caused by previous outbreaks, a few are not so. During the final phase of the outbreak period, a few outbreaks occur that can only be explained either as caused by long-range migration of moths or by aggregation of moths from the endemic population. After this, the population density remains low until the next year when the sequence of outbreaks is repeated. Thus, the teak defoliator displays population cycles at a frequency of one year.

Various explanatory hypotheses have been proposed for the dynamics of forest lepidoptera that exhibit population cycles (Myers, 1988). These include:

a) Variation in insect quality: Chitty (1967) proposed that density-related selection on genetically controlled variation in behaviour and physiology of animals could provide the basis for self regulation of populations. Experimental proof is still non-existent for this hypothesis (Myers, 1988).

b) Climatic release hypothesis: Uvarov (1931) and Andrewartha and Birch (1954) proposed that weather and climate are major controlling factors of insect abundance. Climate can cause direct and indirect impact on population size, but the hypothesis remains untestable due to the difficulty in differentiating the impact due to climate from that caused by other factors (Myers, 1998).

c) Variation in plant quality / availability: Two hypotheses have been proposed based on the quality of food available for the insect. The first is that the quality of foliage may deteriorate following herbivore damage and thus act in a delayed density-dependent manner to reduce the population size. The other is that the nutritional quality of foliage improves following environmental stress from drought, waterlogging etc. so that the population size increases. The availability of food can also cause population cycles. In a deciduous tree like teak, it is probable that the absence of tender foliage during some part of the year can cause population decline of the herbivore.

d) Disease susceptibility: This hypothesis proposes that as the population of an insect increases, individuals interact more frequently, thus allowing the transmission of disease. Stress associated with food limitation or poor weather could further accentuate the susceptibility to disease, which results in an epizootic. High mortality from disease selects for resistant individuals and the epizootic ends as the host density declines. Sub-lethal effects of disease may reduce vigor and fecundity for several subsequent generations.

e) Metapopulation theory: Metapopulation is a set of local populations inhabiting spatially distinct habitat patches. A conceptually important assumption is that local populations have a significant risk of extinction (Moilanen and Hanski, 1998). The metapopulation is assumed to persist in a stochastic equilibrium between local extinctions and colonizations. Thus migration is a major driving force in metapopulation dynamics.

When we attempt to explain the population dynamics of *H. puera*, it can be seen that no theory can explain it completely but all the theories provide insight into one or the other characteristics of teak defoliator dynamics at the population level. The first theory regarding variation in insect quality is important since morphologically distinct larvae are found in the field which tempted the early workers to classify them as two distinct varieties (see Chapter II). The second hypothesis on climatic release is interesting in the

Chapter II). The second hypothesis on climatic release is interesting in the scenario where the teak defoliator outbreaks start immediately after the pre-monsoon showers. The third hypothesis on variation in plant quality/availabitlity is also important since teak is a deciduous tree which sheds its leaves during winter, thereby creating a time when no food is available for the insect larvae. The fourth theory on disease susceptibility is also of interest owing to the recent discovery of the baculovirus, which can cause wide-spread epizootics and can persist within the host insect. Even though none of the above theories can be explicitly ruled out, the metapopulation theory in which space is identified as a determinant in regulating population dynamics appears to hold good in the case of *H.puera* outbreaks. An attempt is made below to view the population dynamics of teak defoliator in the light of metapopulation theory.

8.6. AN EXPLANATORY MODEL FOR THE POPULATION DYNAMICS OF *H. PUERA*

A schematic diagram showing the population dynamics of *H. puera* is given in Fig. 8.1. The figure is divided into two parts. The upper part above the dotted line indicates the metapopulation, which is the assemblage of several local populations. This metapopulation can extend to the total distribution area and may exist in a high density (epidemic) level in one or the other areas while it remains at low density (endemic) level at the other places. Even when the size of the metapopulation remains stable, at the local level, population density can shift between endemic and epidemic levels. Below the dotted line, the local population dynamics at a place like Nilambur is represented.

At the local level, low density, endemic populations have been observed during the non-outbreak period. The insects are rare and distributed in a disperse manner throughout the plantation. Incidence of first outbreaks (epicentres) at a particular place (of several sq.km in area) can occur either by the aggregation of local endemic population or by immigration of moths from a place under outbreak. Outbreaks occur in shifting large patches following the occurrence of epicentres. These wide-spread outbreaks seem to be caused by progenies of moths emerging from the epicentres. After the wide spread outbreaks, the population density declines to an endemic level. This decline may be due to the impact of density dependent mortality factors like diseases, and depletion of food source. Occurrence of several generations of the insect in the same locality can increase the viral load in the environment, which can lead to the collapse of a later population.

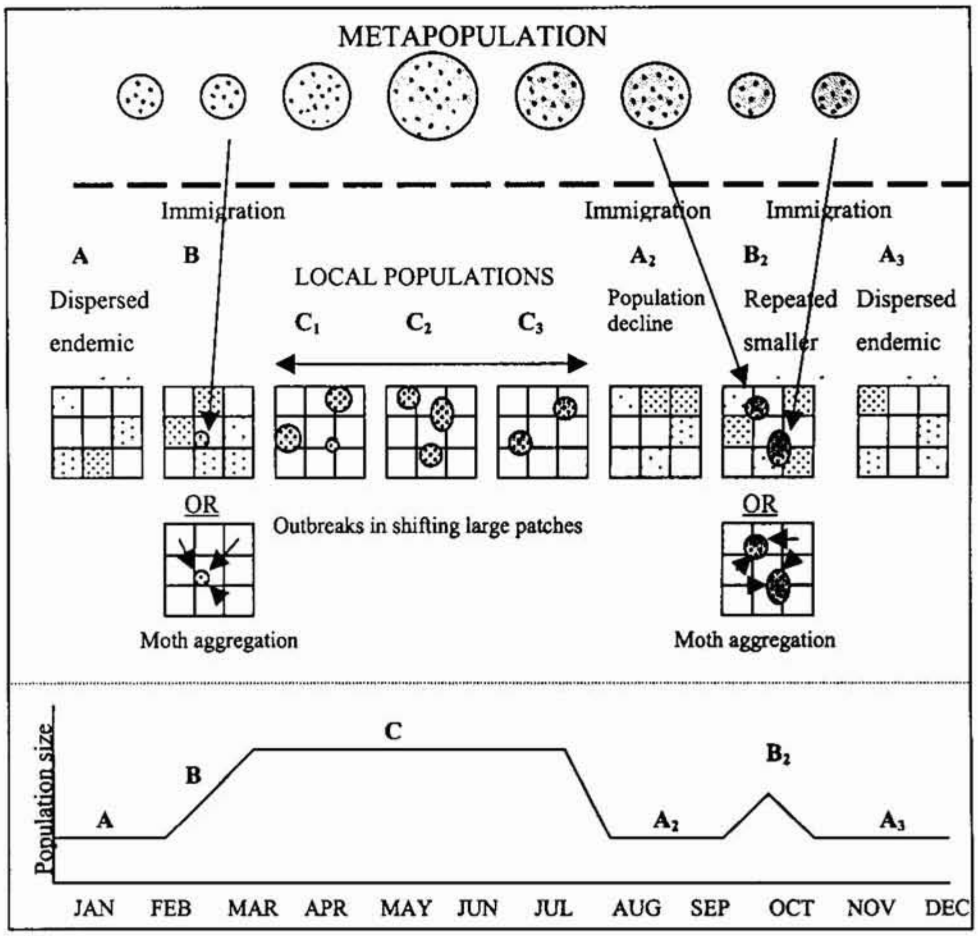

Fig.8.1. Schematic diagram showing the population dynamics of *H. puera*

Subsequent small population peaks occur in September-October (Fig. 8.1) which cannot be caused by progenies of earlier populations. As in the case of initial epicentres, these outbreaks could be caused either by the aggregation of local endemic population or by the influx of moths from far away places. These populations seldom cause further outbreaks in the area and the local population declines to endemic level. This may be due to the reduction in food source since most of the leaves would be mature and not acceptable to the early larval instars.

The graph in Fig 8.1. shows the temporal sequence of shifts in population density. At Nilambur the population density remains at endemic level during January and February (**A**). During late February or March, the initial epicentres occur causing an increase in population density (**B**). From April to July, the population remains at epidemic level, causing large outbreaks at different places (**C**). During August, the population reverts to endemic level ($\mathbf{A_2}$). During September - October further small-scale outbreaks occur ($\mathbf{B_2}$) followed by a period of endemic population ($\mathbf{A_3}$) which extends to February, next year.

At the local level a specific period can be identified during which control operations are feasible. Control of the epicentres and any new populations occurring during the build-up phase can theoretically prevent large-scale outbreaks. This would be an economical way of preventing outbreaks as compared to an attempt to control wide-spread outbreaks. The model also indicates that it will be impossible to prevent all outbreaks by this method of control since the outbreaks which occur during the final phase are independent from the sequence of outbreaks which occur during the early part of the year. But this study has shown that controlling the initial outbreaks can prevent outbreaks in nearly 78% of the total area under outbreaks. The model also indicates that since recolonization can occur from far away habitats, control operations have to be repeated every year.

REFERENCES

Ahmed, M. (1987) Relative resistance of various clones of *Tectona grandis* to teak defoliator, *Hyblaea puera* Cram. (Lepidoptera, Hyblaeidae) in south India. Indian Forester. 113(4): 281-286.

Anderson, H., Durston, B. H. and Poole, M. (1970) Thesis and assignment writing. Wiley Eastern Limited, New Delhi: 135 pp.

Andrewartha, H.G. and Birch, L. C. (1954) The distribution and abundance of animals, xv+782 pp. Chicago.

ARC/INFO (1995) Understanding GIS- The ARC/INFO method: version 7 for UNIX and open VMS. 3rd edition. John Wiley & Sons Inc., New York, NY-10158. 723 pp.

Basu-Chowdhury, J. C. (1971) Interim report on Konny Aerial Spraying Project. Appendix 3 In: Vasudevan K.G., Working plan for Nilambur Forest Division, 1967-68 to 1976-77. Govt.of Kerala, pp.165-168.

Beeson, C. F. C. (1928) The defoliation of teak. Indian Forester. 54(4): 204-215.

Beeson, C. F. C. (1934) The biological control of teak defoliators. Indian forester. 60(10):672-683.

Beeson, C. F. C. (1941) The ecology and control of the forest insects of India and neighbouring countries. Reprint 1961. Govt. of India publication, 767 pp.

Berryman, A. A. (1986) Forest insects: Principles and practice of population management. Plenum Press, New York. 279 pp.

Berryman, A. A. (1987) The theory and classification of insect outbreaks. In: Insect outbreaks (Eds. Barbosa, P. and Schultz, J.C.). Academic Press, California, USA. 577 PP.

Bourdillon, T. F. (1898) Insects attacking teak in southern India. Indian Forester. 24:126-129.

Brown, W. D. and Alcock, J. (1990) Hilltopping by the red admiral butterfly: mate searching along congeners. Journal of research on the Lepidoptera. 29 (1-2): 1-10.

Capuccino, N. (1995) Novel approaches in the study of population dynamics. In: Population dynamics: new approaches and synthesis. Pp 3-16 (Eds. Cappuccino, Naomi and Price, Peter.W.) Academic Press Inc. London.

Chitty, D. (1960) Population processes in the vole and their relevance to general theory. Canadian Journal of Zoology. 38: 99-113.

Hole, R. S. (1904) Note on *Hyblaea puera*. Indian Forester. 30(1): 1-10.

Kadambi, K. (1951) Teak defoliation. Indian Forester. 77(1):64-70.

Khan, A. H. and Chatterjee, P. N. (1944) Undergrowth in teak plantations as a factor in reducing defoliation. Indian Forester. 70: 365-369.

Liebhold, A. M. and Elkinton, J. S. (1989) Characterizing spatial patterns of gypsy moth regional defoliation. Forest Science. 35(2) pp 557-568.

Liebhold, A. M., Rossi, R. S. and Kemp, W. P. (1993) Geostatistics and Geographic information systems in applied insect ecology. Annual review of Entomology. 1993. 38: pp 303-27.

Mackenzie, J. M. D. (1921) Some notes on forest insect pests in Burma. Indian Forester. 47:309-317.

Mathew, G. (1991) Biology, seasonal population trends and impact of the teak carpenter-worm Aleterogystia cadambae (Moore) (Lepidoptera: Cossidae). Annals of Entomology. 9(2): 39-46.

Mohanadas, K. (1995) Population trend of *Hyblaea puera* Cramer (Lepidoptera: Hyblaeidae) in teak plantations and the factors influencing it. Ph.D. thesis. Cochin University of Science and Technology, 159 pp.

Moilanen, A. and Hanski, I. (1998) Metapopulation dynamics: Effects of habitat quality and landscape structure. Ecology. 79 (7): 2503-2515.

Myers, J. H. (1988) Can a general hypothesis explain population cycles of forest lepidoptera? In Advances in ecological research.Vol. 18, Academic Press Inc. (London) pp, 179-242.

Nair, K. S. S. (1980) The problem of insect defoliation in teak- to spray or not to spray. In: Proceedings of second Forestry conference, Dehra Dun, India.

Nair K. S. S. and Sudheendrakumar, V.V. (1986) The teak defoliator, *Hyblaea puera*: Defoliation dynamics and evidences of short-range migration of moths. In: Proceedings of Indian Academy of Sciences (Animal Sciences) 95 (1): 7-21.

Nair, K. S. S. (1987) Life-history, ecology and pest status of the sapling borer *Sahyadrassus malabaricus* (Lepidoptera: Hepalidae). Entomon 12(2): 167-173.

Nair, K. S. S. (1988) The teak defoliator in Kerala, India. In: Forest Insects: Principles and practice of population management. (Ed. Berryman, A.A.) pp 267-289, Plenum Press, New York.

Nair, K. S. S., Mohanadas, K and Sudheendrakumar, V. V. (1995) Biological control of the teak defoliator, *Hyblaea puera* (Lepidoptera: Hyblaidae) using insect parasitoids- problems and prospects. In: Biological control of social forest and plantation crop insects (Ed. Ananthakrishnan, T. N.). Oxford and IBH Publishing Co. Pvt. Ltd.. New Delhi, pp 75-95.

Nair, K. S. S. and Mohanadas, K. (1996) Early events in the outbreak of the teak caterpillar, *Hyblaea puera*. International Journal of Ecology and Environmental Sciences 22: 271-279.

Nair, K. S. S., Biju Babjan, Sajeev, T .V., Sudheendrakumar, V. V., Ali, Mohammed, M. I., Varma, R. V. and Mohanadas, K. (1996) Field efficacy of nuclear polyhedraosis virus for protection of teak against the defoliator, *Hyblaea puera* Cramer (Lepidoptera: Hyblaeidae). Journal of Biological Control. 10: 79 – 85.

Nair, K. S S., Sudheendrakumar, V. V., Varma, R. V., Chacko, K. C. and Jayaraman, K. (1996) Effect of defoliation by *Hyblaea puera* and *Eutectona machaeralis* (Lepidoptera) on volume increment of teak. In: Impact of diseases and insect pests in tropical forests (Eds. Nair, K. S. S., Sharma, J. K. and Varma, R. V.) pp. 257-273 KFRI, FORSPA .

Nair, K. S. S., Sudheendrakumar, V. V., Mohanadas, K and Varma, R. V. (1997) Control of the Teak Defoliator- Past attempts and new promise. In: Teak (Eds. Chand Basha, S, Mohanan, C. and Sankar, S.) Kerala Forest Department and Kerala Forest Research Institute. p 274: 81-83.

Nair, K. S. S., Sudheendrakumar, V. V., Mohanadas, K., Varma, R. V., Mathew, G., Koshy, M. P., and Kedharnath, S. (1997) Search for teak trees resistant to the defoliator, *Hyblaea puera* Cramer (Lepidoptera, Hyblaeidae) In: Ecology and evolution of plant-feeding insects in natural and man-made environments (Ed. Raman, A.) 109-122, International Scientific Publications, New Delhi.

Pinheiro, C. E. G. (1990) Territorial hilltopping of three swallowtail butterflies (Lepidoptera: Papilionidae) in western Brazil. Journal of research on the Lepidoptera. 29 (1-2): 132 – 134.

Rajak, R.C., Agarwal, G. P., Khan, A. R. and Sandhu, S.S. (1993) Susceptibility of teak defoliator (*Hyblaea puera* Cramer) and teak skeletonizer (*Eutectona machaeralis* Walker) to *Beauveria bassiana* (Bals.) Vuill. Journal of Experimental Biology 31:80-82.

Shanmugananthan, K. (1997) Teak plantations and environment. In. Teak: Proceedings of the International Teak Symposium,Kerala,India (Eds. Chand Basha, S., Mohanan, C., and Sankar, S.) 274 pp.

Singh, B. (1955) Description and systematic position of larva and pupa of the teak defoliator, *Hyblaea puera* Cramer (Lepidoptera, Hyblaeidae). Indian Forest Records, Entomology 9(1):16 pp.

Singh, P., Prasad, G. and Johri, A. B. (1978) Aerial spraying of insecticides to control teak defoliators. Indian Forester 104(2): 781-782.

Solbreck, C. (1995) Long-term population dynamics of a seed feeding insect in a landscape perspective. Pp 279 – 301. In: Population dynamics: new approaches and synthesis (Eds. Capuccino, Naomi and Price, Peter. W.) Academic Press. Inc. London.

Southwood, T. R. E. (1976) Ecological methods with particular reference to the study of insect populations. Chapman and Hall, London. 391 pp.

Stebbing, E. P. (1903) The teak defoliator *Hyblaea puera* Cram. Indian Forest leaflet 2, Forest Zoology. 5pp.

Sudheendrakumar, V. V., Mohammed Ali, M. I. and Varma, R. V. (1988) Nuclear Polyhedrosis Virus of the teak defoliator, *Hyblaea puera*. Journal of Invertebrate Pathology 51:307-308.

Sudheendrakumar, V. V. (1994) Reproductive behaviour of *H.puera* and the role of pheromones. In: Development of a management strategy for the teak defoliator, *Hyblaea puera*. (Eds. Nair *et al.*), KFRI research report 95. 121 pp.

Uvarov, B.P. (1961) Quality and quantity in insect populations. Proc. Royal Entomological Society of Canada (C) 25: 52-59.

Vaishampayan, S. M. and Bahadur, A. (1983) Seasonal activity of adults of teak defoliator *Hyblaea puera* and teak skeletonizer: Pyrausta machaeralis (Pyralidae: Lepidoptera) monitored by light trap catch. In: Insect interrelations in forest and agro ecosystems (Eds. Sen-Sarma, P. K, Kulshrestha, S. K., Sangal, S. K.) Jugal Kishore & Co. Dehra Dun 137- 146.

Vaishampayan, S. M., Verma, R. and Bhowmick, A. K. (1987) Possible migration of teak defoliator, *Hyblaea puera* Cramer (Lepidoptera, Hybaeidae) in relation to the movement of the south-west monsoon as indicated by light trap catches. Indian Journal of Agricultural Science 57(1): 41-46.

Zacharias, V. J. and Mohandas, K. (1990) Bird predators of the teak defoliator *Hyblaea puera*. Indian Journal of Forestry 13(2):122-127.

APPENDIX A

ALGORITHM FOR COMPUTATION OF AUTOCORRELATION INDICES

The general notation used in spatial autocorrelation formulas and their interpretation is as follows:

n – the total number of cells in a layer: N rows x N columns

i,j – any two adjacent cells

z_i – the value of attribute of the cell i

c_{ij} – the similarity of i's and j's attributes: $(z_i-z_j)^2$

w_{ij} – the similarity of i's and j's locations, $w_{ij} = 1$ if cells i and j are directly adjacent and 0 other wise

σ^2 - the sample variance: $(z_i - z_m)^2 / (n - 1)$ where z_m is the mean cell value for the grid

In the terms of the above notation, spatial autocorrelation is a measure of the attribute similarities in the set of c_{ij} with the locational similarities of the set of w_{ij}, and then summing the results into a single index.

The formula for calculating the Geary index is:

$$c = w_{ij} \; c_{ij} /(2 (w_{ij})(z_i - z_m)^2) /(n - 1))$$

where,

$$w_{ij} = 4 * n$$

The formula for calculating the Moran index is

$$c = \Sigma \Sigma w_{ij} c_{ij} /(\Sigma \Sigma w_{ij})(\Sigma (z_i - z_m)^2 / n)$$

where,

$$\Sigma \Sigma w_{ij} = 4 * n$$

APPENDIX B

LIGHT-TRAP DATA IN RELATION TO INCIDENCE OF OUTBREAK AND LOCAL MOTH EMERGENCE

Date	* No. of moths trapped	Incidence of outbreak	Local emergence of moths	Date	*No. of moths trapped	Incidence of outbreak	Local emergence of moths
23.6.93	0	Nil	Nil	31.7.93	2	Nil	Present
24.6.93	28	Nil	Nil	1.8.93	N.O.	Nil	Present
25.6.93	30	Nil	Nil	2.8.93	0	Nil	Present
26.6.93	32	Nil	Nil	3.8.93	1	Nil	Present
27.6.93	42	Nil	Nil	4.8.93	0	Nil	Present
28.6.93	13	Nil	Nil	5.8.93	0	Nil	Nil
29.6.93	18	Nil	Nil	6.8.93	0	Nil	Nil
30.6.93	64	Nil	Present	7.8.93	0	Nil	Nil
1.7.93	0	Nil	Present	8.8.93	0	Nil	Nil
2.7.93	57	Nil	Present	9.8.93	0	Nil	Nil
3.7.93	6	Nil	Present	10.8.93	0	Nil	Nil
4.7.93	12	Nil	Present	11.8.93	0	Nil	Nil
5.7.93	48	Nil	Present	12.8.93	0	Nil	Nil
6.7.93	32	Nil	Present	13.8.93	1	Nil	Nil
7.7.93	2	Yes	Present	14.8.93	0	Nil	Nil
8.7.93	18	Nil	Present	15.8.93	0	Nil	Nil
9.7.93	3	Nil	Nil	16.8.93	0	Nil	Nil
10.7.93	18	Nil	Nil	17.8.93	0	Nil	Nil
11.7.93	0	Nil	Nil	18.8.93	0	Nil	Nil
12.7.93	N.O.	Nil	Nil	19.8.93	0	Nil	Nil
13.7.93	N.O.	Nil	Nil	20.8.93	0	Nil	Nil
14.7.93	N.O.	Nil	Nil	21.8.93	0	Nil	Nil
15.7.93	N.O.	Nil	Nil	22.8.93	N.O.	Nil	Nil
16.7.93	N.O.	Nil	Nil	23.8.93	0	Nil	Nil
17.7.93	2	Nil	Nil	24.8.93	0	Nil	Nil
18.7.93	0	Nil	Nil	25.8.93	0	Nil	Nil
19.7.93	0	Nil	Nil	26.8.93	0	Nil	Nil
20.7.93	0	Nil	Nil	27.8.93	0	60	Nil
21.7.93	0	Nil	Nil	28.8.93	0	Nil	Nil
22.7.93	0	Nil	Nil	29.8.93	0	Nil	Nil
23.7.93	0	Nil	Nil	30.8.93	0	Nil	Nil
24.7.93	0	Nil	Nil	31.8.93	37	Nil	Nil
25.7.93	4	Nil	Nil	1.9.93	37	Yes	Nil
26.7.93	1	Nil	Nil	2.9.93	23	Nil	Nil
27.7.93	N.O.	Nil	Present	3.9.93	41	Nil	Nil
28.7.93	0	Nil	Present	4.9.93	7	Nil	Nil
29.7.93	0	Nil	Present	5.9.93	5	Nil	Nil
30.7.93	0	Nil	Present	6.9.93	7	Nil	Nil

Date	*No. of moths trapped	Incidence of outbreak	Local emergence of moths	Date	*No. of moths trapped	Incidence of outbreak	Local emergence of moths
7.9.93	5	Nil	Nil	26.10.93	0	Nil	Nil
8.9.93	7	Nil	Nil	27.10.93	0	Nil	Nil
9.9.93	4	Nil	Nil	28.10.93	0	Nil	Nil
10.9.93	2	Nil	Nil	29.10.93	0	Nil	Nil
11.9.93	0	Nil	Nil	30.10.93	0	Nil	Nil
12.9.93	N.O.	Nil	Nil	31.10.93	1	Nil	Nil
13.9.93	0	Nil	Nil	1.11.93	0	Nil	Nil
14.9.93	0	Nil	Nil	2.11.93	0	Nil	Nil
15.9.93	0	Nil	Nil	3.11.93	0	Nil	Nil
16.9.93	0	Nil	Nil	4.11.93	0	Nil	Nil
17.9.93	0	Nil	Nil	5.11.93	N.O.	Nil	Nil
18.9.93	0	Nil	Nil	6.11.93	N.O.	Nil	Nil
19.9.93	N.O.	Nil	Yes	7.11.93	0	Nil	Nil
20.9.93	0	Nil	Yes	8.11.93	0	Nil	Nil
21.9.93	0	Nil	Yes	9.11.93	0	Nil	Nil
22.9.93	N.O.	Nil	Yes	10.11.93	0	Nil	Nil
23.9.93	0	Nil	Yes	11.11.93	0	Nil	Nil
24.9.93	0	Nil	Yes	12.11.93	1	Nil	Nil
25.9.93	0	Nil	Yes	13.11.93	0	Nil	Nil
26.9.93	0	Nil	Yes	14.11.93	N.O.	Nil	Nil
27.9.93	1	Nil	Yes	15.11.93	0	Nil	Nil
28.9.93	1	Nil	Yes	16.11.93	0	Nil	Nil
29.9.93	2	Nil	Yes	17.11.93	0	Nil	Nil
30.9.93	0	Nil	Yes	18.11.93	1	Nil	Nil
1.10.93	0	Nil	Yes	19.11.93	0	Nil	Nil
2.10.93	0	Nil	Yes	20.11.93	N.O.	Nil	Nil
3.10.93	N.O.	Nil	Nil	21.11.93	0	Nil	Nil
4.10.93	0	Nil	Nil	22.11.93	0	Nil	Nil
5.10.93	2	Nil	Nil	23.11.93	0	Nil	Nil
6.10.93	7	Nil	Nil	24.11.93	0	Nil	Nil
7.10.93	3	Nil	Nil	25.11.93	0	Nil	Nil
8.10.93	2	Nil	Nil	26.11.93	0	Nil	Nil
9.10.93	2	Nil	Nil	27.11.93	0	Nil	Nil
10.10.93	22	Nil	Nil	28.11.93	N.O.	Nil	Nil
11.10.93	4	Nil	Nil	29.11.93	0	Nil	Nil
12.10.93	2	Nil	Nil	30.11.93	0	Nil	Nil
13.10.93	0	Nil	Nil	1.12.93	0	Nil	Nil
14.10.93	2	Nil	Nil	2.12.93	0	Nil	Nil
15.10.93	2	Nil	Nil	3.12.93	0	Nil	Nil
16.10.93	0	Nil	Nil	4.12.93	0	Nil	Nil
17.10.93	N.O.	Nil	Nil	5.12.93	N.O.	Nil	Nil
18.10.93	0	Nil	Nil	6.12.93	0	Nil	Nil
19.10.93	0	Nil	Nil	7.12.93	1	Nil	Nil
20.10.93	0	Nil	Nil	8.12.93	0	Nil	Nil
21.10.93	0	Nil	Nil	9.12.93	0	Nil	Nil
22.10.93	0	Nil	Nil	10.12.93	0	Nil	Nil
23.10.93	0	Nil	Nil	11.12.93	0	Nil	Nil
24.10.93	N.O.	Nil	Nil	12.12.93	N.O.	Nil	Nil
25.10.93	0	Nil	Nil	13.12.93	0	Nil	Nil

* N.O. indicates days on which the light-trap was not operated.

Date	*No. of moths trapped	Incidence of outbreak	Local emergence of moths	Date	*No. of moths trapped	Incidence of outbreak	Local emergence of moths
14.12.93	0	Nil	Nil	1.2.94	0	Nil	Nil
15.12.93	0	Nil	Nil	2.2.94	0	Nil	Nil
16.12.93	0	Nil	Nil	3.2.94	0	Nil	Nil
17.12.93	0	Nil	Nil	4.2.94	0	Nil	Nil
18.12.93	N.O.	Nil	Nil	5.2.94	0	Nil	Nil
19.12.93	0	Nil	Nil	6.2.94	N.O.	Nil	Nil
20.12.93	0	Nil	Nil	7.2.94	0	Nil	Nil
21.12.93	0	Nil	Nil	8.2.94	0	Nil	Nil
22.12.93	0	Nil	Nil	9.2.94	0	Nil	Nil
23.12.93	0	Nil	Nil	10.2.94	0	Nil	Nil
24.12.93	0	Nil	Nil	11.2.94	0	Nil	Nil
25.12.93	N.O.	Nil	Nil	12.2.94	0	Nil	Nil
26.12.93	N.O.	Nil	Nil	13.2.94	0	Nil	Nil
27.12.93	N.O.	Nil	Nil	14.2.94	0	Nil	Nil
28.12.93	0	Nil	Nil	15.2.94	0	Nil	Nil
29.12.93	0	Nil	Nil	16.2.94	0	Nil	Nil
30.12.93	0	Nil	Nil	17.2.94	0	Nil	Nil
31.12.93	0	Nil	Nil	18.2.94	0	Nil	Nil
1.1.94	N.O.	Nil	Nil	19.2.94	0	Nil	Nil
2.1.94	N.O.	Nil	Nil	20.2.94	N.O.	Nil	Nil
3.1.94	N.O.	Nil	Nil	21.2.94	0	Nil	Nil
4.1.94	0	Nil	Nil	22.2.94	0	Nil	Nil
5.1.94	0	Nil	Nil	23.2.94	0	Nil	Nil
6.1.94	0	Nil	Nil	24.2.94	0	Nil	Nil
7.1.94	0	Nil	Nil	25.2.94	0	Nil	Nil
8.1.94	0	Nil	Nil	26.2.94	0	Nil	Nil
9.1.94	N.O.	Nil	Nil	27.2.94	N.O.	Nil	Nil
10.1.94	0	Nil	Nil	28.2.94	0	Nil	Nil
11.1.94	0	Nil	Nil	1.3.94	0	Nil	Nil
12.1.94	0	Nil	Nil	2.3.94	0	Nil	Nil
13.1.94	0	Nil	Nil	3.3.94	0	Nil	Nil
14.1.94	N.O.	Nil	Nil	4.3.94	0	Nil	Nil
15.1.94	0	Nil	Nil	5.3.94	0	Nil	Nil
16.1.94	N.O.	Nil	Nil	6.3.94	N.O.	Nil	Nil
17.1.94	0	Nil	Nil	7.3.94	0	Nil	Nil
18.1.94	0	Nil	Nil	8.3.94	N.O.	Nil	Nil
19.1.94	0	Nil	Nil	9.3.94	0	Nil	Nil
20.1.94	0	Nil	Nil	10.3.94	0	Nil	Nil
21.1.94	0	Nil	Nil	11.3.94	0	Nil	Nil
22.1.94	0	Nil	Nil	12.3.94	0	Nil	Nil
23.1.94	N.O.	Nil	Nil	13.3.94	N.O.	Nil	Nil
24.1.94	N.O.	Nil	Nil	14.3.94	0	Nil	Nil
25.1.94	0	Nil	Nil	15.3.94	0	Nil	Nil
26.1.94	0	Nil	Nil	16.3.94	0	Nil	Nil
27.1.94	0	Nil	Nil	17.3.94	0	Nil	Nil
28.1.94	0	Nil	Nil	18.3.94	0	Nil	Nil
29.1.94	0	Nil	Nil	19.3.94	0	Nil	Nil
30.1.94	N.O.	Nil	Nil	20.3.94	N.O.	Nil	Nil
31.1.94	0	Nil	Nil	21.3.94	N.O.	Nil	Nil

* N.O. indicates days on which the light-trap was not operated.

Date	*No. of moths trapped	Incidence of outbreak	Local emergence of moths	Date	*No. of moths trapped	Incidence of outbreak	Local emergence of moths
22.3.94	0	Nil	Nil	10.5.94	N.O.	Nil	Nil
23.3.94	0	Nil	Nil	11.5.94	N.O.	Nil	Nil
24.3.94	0	Nil	Nil	12.5.94	N.O.	Yes	Nil
25.3.94	0	Nil	Nil	13.5.94	4	Nil	Nil
26.3.94	0	Nil	Nil	14.5.94	5	Nil	Nil
27.3.94	N.O.	Nil	Nil	15.5.94	0	Nil	Nil
28.3.94	0	Nil	Nil	16.5.94	0	Nil	Nil
29.3.94	N.O.	Nil	Nil	17.5.94	N.O.	Nil	Nil
30.3.94	0	Nil	Nil	18.5.94	0	Nil	Nil
31.3.94	0	Nil	Nil	19.5.94	0	Nil	Nil
1.4.94	N.O.	Nil	Nil	20.5.94	0	Nil	Nil
2.4.94	1	Nil	Nil	21.5.94	0	Nil	Nil
3.4.94	N.O.	Nil	Nil	22.5.94	1	Nil	Nil
4.4.94	0	Yes	Nil	23.5.94	0	Nil	Nil
5.4.94	0	Nil	Nil	24.5.94	0	Nil	Nil
6.4.94	0	Nil	Nil	25.5.94	0	Nil	Nil
7.4.94	1	Nil	Nil	26.5.94	0	Nil	Nil
8.4.94	0	Nil	Nil	27.5.94	2	Nil	Nil
9.4.94	0	Nil	Nil	28.5.94	0	Nil	Nil
10.4.94	N.O.	Nil	Nil	29.5.94	0	Nil	Nil
11.4.94	1	Nil	Nil	30.5.94	116	Nil	Nil
12.4.94	0	Nil	Nil	31.5.94	327	Nil	Nil
13.4.94	0	Nil	Nil	1.6.94	37	Nil	Yes
14.4.94	N.O.	Nil	Nil	2.6.94	53	Nil	Yes
15.4.94	0	Nil	Nil	3.6.94	63	Yes	Yes
16.4.94	3	Nil	Nil	4.6.94	37	Nil	Yes
17.4.94	N.O.	Nil	Nil	5.6.94	N.O.	Nil	Yes
18.4.94	0	Nil	Nil	6.6.94	17	Nil	Yes
19.4.94	2	Nil	Nil	7.6.94	0	Nil	Nil
20.4.94	1	Nil	Nil	8.6.94	0	Nil	Nil
21.4.94	0	Nil	Nil	9.6.94	0	Nil	Nil
22.4.94	0	Nil	Nil	10.6.94	0	Nil	Nil
23.4.94	0	Nil	Nil	11.6.94	0	Nil	Nil
24.4.94	N.O.	Nil	Nil	12.6.94	0	Yes	Nil
25.4.94	0	Nil	Yes	13.6.94	0	Nil	Nil
26.4.94	0	Nil	Yes	14.6.94	0	Nil	Nil
27.4.94	0	Nil	Yes	15.6.94	0	Nil	Nil
28.4.94	0	Nil	Yes	16.6.94	0	Nil	Nil
29.4.94	0	Nil	Yes	17.6.94	0	Nil	Nil
30.4.94	0	Nil	Yes	18.6.94	0	Nil	Nil
1.5.94	N.O.	Nil	Nil	19.6.94	N.O.	Nil	Nil
2.5.94	0	Nil	Nil	20.6.94	1	Nil	Nil
3.5.94	0	Nil	Nil	21.6.94	0	Nil	Nil
4.5.94	0	Nil	Nil	22.6.94	0	Nil	Nil
5.5.94	8	Nil	Nil	23.6.94	4	Nil	Yes
6.5.94	8	Nil	Nil	24.6.94	9	Nil	Yes
7.5.94	0	Nil	Nil	25.6.94	1	Nil	Yes
8.5.94	N.O.	Nil	Nil	26.6.94	0	Nil	Yes
9.5.94	9	Nil	Nil	27.6.94	1	Nil	Yes

* N.O. indicates days on which the light-trap was not operated.

Date	*No. of moths trapped	Incidence of outbreak	Local emergence of moths	Date	*No. of moths trapped	Incidence of outbreak	Local emergence of moths
28.6.94	18	Nil	Yes	16.8.94	0	Nil	Nil
29.6.94	1	Nil	Yes	17.8.94	0	Nil	Nil
30.6.94	22	Nil	Yes	18.8.94	0	Nil	Nil
1.7.94	0	Nil	Yes	19.8.94	0	Nil	Nil
2.7.94	0	Nil	Yes	20.8.94	0	Nil	Nil
3.7.94	N.O.	Nil	Yes	21.8.94	N.O.	Nil	Nil
4.7.94	0	Nil	Yes	22.8.94	0	Nil	Nil
5.7.94	0	Nil	Yes	23.8.94	0	Nil	Nil
6.7.94	0	Nil	Yes	24.8.94	0	Nil	Nil
7.7.94	0	Nil	Nil	25.8.94	0	Nil	Nil
8.7.94	0	Nil	Nil	26.8.94	0	Nil	Nil
9.7.94	0	Nil	Nil	27.8.94	0	Nil	Nil
10.7.94	N.O.	Nil	Nil	28.8.94	N.O.	Nil	Nil
11.7.94	0	Nil	Nil	29.8.94	0	Nil	Nil
12.7.94	0	Nil	Nil	30.8.94	0	Nil	Nil
13.7.94	0	Nil	Nil	31.8.94	0	Nil	Nil
14.7.94	0	Nil	Nil	1.9.94	0	Nil	Nil
15.7.94	0	Nil	Nil	2.9.94	0	Nil	Nil
16.7.94	0	Nil	Nil	3.9.94	0	Nil	Nil
17.7.94	N.O.	Nil	Nil	4.9.94	N.O.	Nil	Nil
18.7.94	0	Nil	Nil	5.9.94	0	Nil	Nil
19.7.94	0	Nil	Nil	6.9.94	0	Nil	Nil
20.7.94	0	Nil	Nil	7.9.94	0	Nil	Nil
21.7.94	0	Nil	Nil	8.9.94	0	Nil	Nil
22.7.94	0	Nil	Nil	9.9.94	0	Nil	Nil
23.7.94	0	Nil	Nil	10.9.94	N.O.	Nil	Nil
24.7.94	N.O.	Nil	Nil	11.9.94	0	Nil	Nil
25.7.94	0	Nil	Nil	12.9.94	0	Nil	Nil
26.7.94	0	Nil	Nil	13.9.94	0	Nil	Nil
27.7.94	0	Nil	Nil	14.9.94	N.O.	Nil	Nil
28.7.94	0	Nil	Nil	15.9.94	0	Nil	Nil
29.7.94	0	Nil	Nil	16.9.94	0	Nil	Nil
30.7.94	0	Nil	Nil	17.9.94	0	Nil	Nil
31.7.94	0	Nil	Nil	18.9.94	0	Nil	Nil
1.8.94	0	Nil	Nil	19.9.94	0	Nil	Nil
2.8.94	0	Nil	Nil	20.9.94	N.O.	Nil	Nil
3.8.94	0	Nil	Nil	21.9.94	N.O.	Nil	Nil
4.8.94	0	Nil	Nil	22.9.94	0	Nil	Nil
5.8.94	0	Nil	Nil	23.9.94	0	Nil	Nil
6.8.94	0	Nil	Nil	24.9.94	0	Nil	Nil
7.8.94	N.O.	Nil	Nil	25.9.94	0	Nil	Nil
8.8.94	0	Nil	Nil	26.9.94	0	Nil	Nil
9.8.94	0	Nil	Nil	27.9.94	0	Nil	Nil
10.8.94	0	Nil	Nil	28.9.94	0	Nil	Nil
11.8.94	0	Nil	Nil	29.9.94	0	Nil	Nil
12.8.94	0	Nil	Nil	30.9.94	0	Nil	Nil
13.8.94	0	Nil	Nil	1.10.94	N.O.	Nil	Nil
14.8.94	N.O.	Nil	Nil	2.10.94	N.O.	Nil	Nil
15.8.94	0	Nil	Nil	3.10.94	0	Nil	Nil

* **N.O.** indicates days on which the light-trap was not operated.

Date	*No. of moths trapped	Incidence of outbreak	Local emergence of moths	Date	*No. of moths trapped	Incidence of outbreak	Local emergence of moths
4.10.94	0	Nil	Nil	10.10.94	N.O.	Nil	Nil
5.10.94	0	Nil	Nil	11.10.94	0	Nil	Nil
6.10.94	0	Nil	Nil	12.10.94	N.O.	Nil	Nil
7.10.94	0	Nil	Nil	13.10.94	0	Nil	Nil
8.10.94	0	Nil	Nil	14.10.94	0	Nil	Nil
9.10.94	0	Nil	Nil	15.10.94	0	Nil	Nil

* **N.O.** indicates days on which the light-trap was not operated.