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STUDIES ON THE SEASONAL INCIDENCE OF DEFOLIATORS AND THE EFFECT OF DEFOLIATION ON VOLUME INCREMENT OF TEAK

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ABSTRACT

The seasonal incidence of defoliation and its effect on growth of teak plantations were studied at Nilambur, Kerala. Experimental plots established in a 4-year-old plantation were either given selective protection against the two dominant defoliators or left unprotected, over a period of 5 years. The defoliation trend was studied by fortnightly visual scoring. Measurements made on trees felled during the first and second mechanical thinnings were used to establish empirical mathematical relationship between GBH and height on the one hand and volume on the other. Using this relationship, the volumes of the experimental trees were determined at the beginning and end of the experiment. Increments were compared using statistical methods in which the initial volume and the number of neighbours of each tree were used as covariates.

Hyblaea puera (Lepidoptera, Hyblaeidae) and ***Eutectona machaeralis*** (Synonyms ***Pyrausta machaeralis, Hapalia machaeralis)*** (Lepidoptera, Pyralidae) were the most dominant defoliators. Although the latter was present in small numbers almost throughout the growth season, defoliation caused by it was (1) infrequent over years, (2) generally of low intensity, and (3) occurred late in the season when the leaves were old and rate of growth was low. Defoliation by ***H. puera*** on the other hand, was a regular annual feature, with one or two waves of epidemic defoliations between late April and July, followed in some years by another lighter defoliation between August and October. Analysis of the temporal and spatial distribution of ***H. puera*** infestation and certain behavioural characteristics of populations suggested short-range migration of moths. A model of population dynamics is proposed based on the findings, according to which, with the onset of general flushing of teak in March-April, the population starts building up, generation by generation, and when a critical density is reached, the newly emerged moths migrate a minimum distance, perhaps 5 to 10 km. Such migration facilitates exploitation of new food sources and escape from larval parasites. Generally, after one or two epidemics, the population declines due to leaf maturity, natural enemies and density dependent food depletion. Until the next flushing season, the population remains small and non-migratory, but active. This residual population is believed to survive mostly in natural forests which provide a small, but continuous supply of tender host leaves during the ‘off-season’, due to natural phenological variation. This cycle of ups and downs, with attendant transition between migratory and nonmigratory phases is repeated every year. If some steps of the proposed model are confirmed by further study, simple methods could be devised to manage the pest by regulating the early build-up phase.

Generally the trees were in full flush by late April and leaf-fall occurred from December to February. Monthly basal area increment followed a bell-shaped curve, with the highest increments in June, July, August and September.

The most serious impact of defoliation was loss of volume increment, although in 2 to 4-year-old saplings, defoliation was sometimes followed by die-back of the leading shoot, which in rare cases led to forking. ***E. machaeralis*** had no significant impact on increment, but ***H. puera*** caused loss of 44% of the potential increment in volume during the experimental period. When the gain due to protection is expressed as percentage increase over the normally realized unprotected yield, it amounted to 80%. The general applicability of this estimate and its practical significance are discussed. It is concluded that because of changes in stand dynamics brought about by improved growth, it is not possible to quantity the benefit in terms of volume gain for the entire rotation, until adequate models of stand dynamics have been developed. However, the study showed that the benefits are so large that attention must now be focussed on development of suitable methods of protection, rather than more precise estimation of the benefits. Control of ***H. puera*** is worthwhile, but control of ***E machaeralis*** is not. Protection during the early years will be more beneficial because of the greater absolute increment.

I. INTRODUCTION

In India, two species of caterpillars cause epidemic defoliation of teak plantations-Hyblaea puera, commonly known as the teak defoliator and *Eutectona* maachaeralis (Synonyms; Pyrausfa rnachaeralis, Hapalia machaeralis) , commonly known as the teak skeletoniser. For anyone who has witnessed the active progress of an epidemic of these caterpillars in a teak plantation, it is an unforgettable experience. When an epidemic is in progress, almost every leaf of every tree in the affected area may be seen to harbour dozens of actively feeding caterpillars and the continuous fall of their droppings (faecal pellets) produce the; sound of a mild drizzle of rain. The plantation is criss-crossed by silken threads spun by the caterpillars on which they descend to lower leaves and the ground. One cannot walk through the plantation without gathering many caterpillars on his body and clothing. In a week or so of the build-up, the green parts of all leaves are consumed. The leaf skeletons remain on the trees for some days and later fall off, making a thick cover on the ground. The spectacular nature of such epidemics creates an impression of serious damage to trees. However, reflushing follows within a week or two, and the trees hold a bounty of new leaves again. At this time, it may appear as if nothing had happened.

In most teak plantations, insect epidemics are a regular annual feature, but the frequency of serious defoliations may vary. Before this study was undertaken, discussions with forest officers showed that there was no consensus of opinian on the effect of defoliation, While some felt that serious loss of wood increment occurred, others felt that loss, if any, was negligible. Although statements like "the defoliated plantations are a most depressing sight and measures to control the insects appear an urgent necessity" (Champion, 1934b) have been made, a critical review of the literature (Section 2.2) showed that loss due to defoliation was still an impression.

However, attempts have been made to standardise methods to control the defoliators by aerial spraying of chemicals. Trials were made first in 1965 in Kerala (Basu-Chowdhury, 1971), where about 76 ha of teak plantations at Konni were sprayed with endrin and later in 1978 in Madhya Pradesh (Singh, 1980), where about 560 ha of teak plantations at Raipur were sprayed with different chemicals. In a paper entitled 'The problem of insect defoliation of teak—to spray or not to spray', Nair (1980) cautioned against this trend and wrote, "Before we undertake further aerial spraying trials, we must generate basic data on the economics of loss due to defoliation and the nature and causes of fluctuation in the pest population. Only then will we be able to decide on the best strategy to deal with the problem of insect defoliation of teak".

The primary objective of this study was to determine whether or not insect-caused defoliation led to loss of wood increment under normal plantation conditions and to quantify the loss, if any. This was accomplished by appropriate experiments and measurements carried out over a 5-year-period in selected teak plantations at Nilambur. The experimental approach (Section 3.1.2) was designed to overcome the shortcomings of earlier attempts to estimate loss. This opportunity was also used to gather information on various aspects of the ecology and population dynamics of the two major defoliators. Development of methods of control was not included in the objectives of this study, but the new insight gained on the population dynamics of the major pest, *Hyblaea puera* suggests new approaches towards its management.

The report is organized into five major sections. This introductory section is followed by a critical review of pertiment information on the biology and ecology of the insects and past attempts to quantify their impact on growth of the tree. This is followed by a section on Materials and Methods in which one subsection describes the study site, experimental approach and general methods, and another describes the methods used for volume prediction and the findings which form the basis for further studies on the increment. In addition, each section contains details of methods specifically applicable to that section. The large section dealing with Results and Discussion is divided into major subsections on the biological aspects of the pests, the normal growth pattern of teak, and the impact of defoliation on growth—loss of increment and die-back of leading shoot of saplings. The report has been so organized that readers not interested in the biological aspects of the pests may skip the sections 2.1, 4.1.2 and 4.1.3 and get a summary of the defoliation trends from section 4.1.1. The last section puts the results of this study into perspective in relation to the practical significance of defoliation and the prospects of managing the major pest, *Hyblaea puera*.

2. REVIEW OF LITERATURE

2.1. BIOLOGY AND SEASONAL INCIDENCE OF TEAK DEFOLIATORS

A complete list of the insects associated with the living teak tree includes 187 species (Mathur, 1960; Mathur and Singh, 1960), of which most are leaf feeders. The most dominant of them are caterpillars, beetles and grasshoppers, but as noted earlier, only two of the caterpillars, viz., ***Hyblaea puera*** (teak defoliator) and ***Eutectona machaeralis*** (teak skeletoniser) have been noted so far in epidemics. ***H. puera*** larvae consume the entire leaf leaving only the major veins. ***E. machaeralis*** larvae on the other hand, consume only the green layer of the leaves, leaving all the veins intact, which characteristic has earned for it the popular name, 'skeletoniser'. Feeding by both insects leads to defoliation, or loss of leaves, because the heavily damaged leaves fall off after a few days. Studies on the biology and seasonal incidence of these two major pests are reviewed separately below. This is followed by a brief summary of other pertinent investigations on the defoliators.

2.1.1. ***Hyblaea puera*** Cramer (Lepidoptera. Hyblaeidae)

This species is distributed in the Oriental and Australian regions, in South Africa, parts of East Africa and West Indies (Beeson, 1941; Browne, 1968). Its life history has been studied in some detail in India and Burma since the early work of Stebbing (1908 a) and a good summary is given by Beeson (1941).

Normally, the life cycle of ***H. puera*** is completed in 2 to 4 weeks, the exact length being determined primarily by climatic conditions, particularly, the temperature. The female moths lay about 500 to 600 eggs on an average during a period of about a week. The eggs are laid singly on tender leaves and the first and second instars feed mainly on the leaf surface. From the third instar onwards the larva cuts out a leaf flap, folds it over and fastens it with silk and feeds from within. There are 5 larval instars, the 5th entering pupation. According to Beeson (1941) pupation may occur within a triangular leaf fold cut specially and strongly spun together; between juxtaposed leaves or leaf skeletons bound by silk; or when the host leaves are completely stripped, on other foliage in the undergowth in the soil cover.

Although teak is the principal food plant, many other species of the family Verbenaceae are known to support ***H. puera,*** particularly the genera ***Callicarpa, Premna*** and ***Vitex.*** In addition, many species of the family Bignoniaceae and at least one each of Araliaceae, Juglandaceae and Oleaceae have been recorded as alternative hosts (Beeson, 1941). Although specific observational records are wanting, it is believed (Beeson, 1941 : p471) that in India, ***Premna*** and ***Vitex*** serve as important sources of food during the period when teak is either leafless or possesses only aged and tough leaves.

The effect of climatic factors on the length of the life-cycle has been worked out in field-insectaries at several places in India and Burma. Specific details are available for Nilambur, Coorg, Bombay, Hoshangabad and Dehra Dun (Beeson, 1941). These data showed that the insect can complete a series of at least 14 generations per year in southern India and Burma and 10 in northern India. In northern India (Dehra Dun), the moths are believed to hibernate for a period of about 3 months during winter (December to February) and in central India (eg. Hoshangabad) aestivation (in unknown developmental stage) has been suspected (Beeson, 1941, pp. 467-68). However, adequate evidence on the occurrence of hibernation or aestivation has not been presented. Apparently, these inferences were based on rearing data obtained from field insectaries. There is very little systematically recorded data on the seasonal incidence of natural infestation, although it is generally known that each year the population is lowest during the seasons of mature foliage and leaf-fall and highest during the pre-monsoon season. According to Beeson (1941), the season of abundance is April to early June in Nilambur, May-June in Coorg and July in Bombay and Dehra Dun. This corresponds to the pre-monsoon season; infestations are rare during periods of heavy rainfall. Sometimes, a second phase of abundance occurs in August-September in Nilambur, October in Coorg, and September in Dehra Dun. No noticeable defoliation occurs during the rest of the year. Observations at Nilambur (Beeson, 1928) showed that the distribution of the population was not necessarily uniform; heavy defoliation occurred in small uncorinected patches and the location of these patches changed irregularly. Except for this study in which field patrolling staff were employed to score the block-wise intensity of defoliation at monthly intervals, no continuous observations are available on the incidence of defoliation in a given locality.

Recently, based on light trap catches of moths for two years at Jabalpur, Madhya Pradesh, Vaishampayan and Bahadur (1983) reported a high population of ***H. puera*** in July and August (and upto the first week of September in one year), followed by a sudden decline and total absence during the rest of the year. They concluded that the insect does not breed in the area on any host plant during the period of about 9 months from September to next July and suggested that they either migrate or enter diapause as pupae or adults. Their evidence for migration or diapause was the sudden appearance of the moth in large numbers after an “absolute absence” for a period of at least 6 months and the sudden decline. In a subsequent paper based on a study of moths caught in the light trap, Vaishampayan *et al.* (1984) showedthat during the early part of the season the proportion of females, the maturity level of the ovary and the fat body content of females were higher than during the later part and suggested that they indicated the occurrence of a migratory phase—“immigration in July and migration in August”.

2.1.2. *Eutectona machaeralis* (Walker) (Lepidoptera, Pyraustidae)

This species is distributed in the Indo-Malayan Region upto Australia (Beeson, 1941; Browne, 1968). Teak is the chief host, but some species of ***Callicarpa*** serve as alternate food plants. The life history has been studied in some detail since the early work of Stebbing (1908 b); the brief notes that follow are mainly based on the information summarised by Beeson (1941).

Normally the life-cycle is completed within a month, the exact duration depending primarily on temperature. The moths are known to exhibit seasonal variations in the wing colouration ranging from pale colours in the dry hot season to darker colours in the cold season. The ratio of females to males is reported to be very high.The female moth lays an average of 250 eggs singly on the leaf. There are 5 larval instars. Feeding superficially to begin with, the larvae later consume the leaf tissues between the network of veins, thereby skeletonising the leaves. Pupation occurs within a thick shelter-web on green or fallen teak leaves. The larvae generally feed on mature, tough leaves, unlike ***H. puera,*** but when given the choice, they will select younger and softer leave? on which the rate of growth is faster (Beeson, 1941 : p520).

The rate of development is influenced by climatic factors. In field insectaries, 14 complete generations were found possible in southern India, 13 in Burma and 10 in northern India. At Dehra Dun in northern India the larvae are reported to hibernate for a period of 3 to 6 months during the cold season between November and March, but no hibernation occurs in southern India, although considerable prolongation of the larval period of some individuals has been noted (for example at Coorg) (Beeson, 1941: p518).

Comparatively little information is available on seasonal incidence of infestation under natural conditions. General observations summarised by Beeson (I 941) indicate epidemic level infestation\ towards the end of the growing season — in November at Nilambur, in October to January at Coorg, in September at Bombay and central India, in October-November at Dehra Dun, and in October to December in Burma. Infestation has also been noted in April-May at Nilambur, and May-June at Bombay and central India. Khan and Chatterjee (1944) reported sudden appearance of heavy infestation in Tithimatty and Nagerhole Ranges of Coorg in October, causing complete defoliation. They suspected that the moths migrated from another area (Kannoth, Wynad) about 35 km away where an infestation occurred about a month earlier. The following studies were reported after the present investigations began. In a light trap study of moths at Jabalpur, Madhya Pradesh over a two-year period, Vaishampayan and Bahadur (1983) found presence of moths from July to December..

with the maximum catches in the months of August-September in one year and in October in another year. The monthly catch per trap ranged from 4 in December 1978 to 48,655 in August 1979. The population was very low or nil for about *6* to 7 months from December to next June. They found no breeding of the pest on any host plant during this 'off-season' in the teak forests surveyed in Madhya Pradesh and noted that their observations were contrary to the reported continuous breeding of the pest. In a study at Prabhunagar forest in Karnataka, Patil and Thontadarya (1983 a) determined the seasonal activity of the insect by weekly sampling of larvae on trees and by trapping the moths using a petromax light trap. They found that the larvae were present throughout the year, although the population was small during January to March. Adults were more prevalent in late September to November and the larval population was also generally high during this period. Larval sampling indicated two to three peaks per year (in April/May/June, August/September and October/November/December) which were rather indistinct and the timing of the peaks varied between years and between plots (crops of different height). In general, their data showed prevalence of the larvae during October to December in 1978 and August to November in 1979. They also recorded a sudden increase in the adult population in late September which they attributed to possible occurrence of moth migration as suggested by some earlier authors. Their unpublished observations (B. V. Patil, personal communication, April 1985) also indicate occurrence of "partial diapause" of larvae during November to March and migration of moths at certain times.

2.1.3 Other studies on teak defoliators

Although the economic significance of infestation by the two major defoliators has not been adequately worked out, some progress has been made in research towards control of the pests. It has been recognized that direct control measures like spraying are difficult because the life-cycles of the pests are short and the foci of infestation shift constantly. This would necessitate regular surveilance for immediate detection of incipient outbreaks and "spraying gangs that could act with the speed of a fire-fighting organization" (Beeson, 1941 : p. 729). During the 1930's extensive surveys have been carried out both in plantations and natural forests to understand the inter-relationships between the teak defoliators, their natural enemies (parasites and predators) and other caterpillar hosts of the natural enemies. Both ***H. puera*** and ***E. machaeralis*** were found to be attacked by a large number of natural enemies and a scheme for biological control using silvicultural measures to augment the efficacy of natural enemies was formulated (Beeson, 1934). Mainly, these measures include, (1) Subdivision of the planting area into blocks, 8 to 16 ha in area, and maintaining strips of pre-existing forests in between as natural enemy reserves and improvement of these reserves by promoting desirable plant species and eliminating undesirable ones. Desirable plants are those which support alternative hosts of the parasites of teak defoliators and undesirable ones are those which serve as alternative hosts of the teak defoliators themselves. Lists of such plants were prepared (Beeson, 1941:pp. 731-732), (2) Maintenance of a varied flora of desirable species under teak canopy to support parasitas, (3) lntroduction of selected species of natural enemies in localities where there is a deficiency in the natural enemy complex.

The above scheme of biological control was neither experimentally proved effective nor practised, due to obvious difficulties in implementation and evaluation. Although introduction of one parasite from northern India *(Cedria paradoxa)* and another from Burma *(Bessa remota)* was tried in 1937 and 1938, there were no follow-up observations. Very recently, Patil and Thontadarya (B. V. Patil, Personal communication) investigated the bionomics, life tables and biocontrol of *E. machaeralis* in Karnataka, but much of the results are still unpublished. *E. machaeralis* was found to have a high complement of natural enemies in Karnataka — 43 species of parasites, 60 species of predators and 3 species of pathogens (Patil and Thontadarya, 1983 b). The pathogens were the fungus, *Beaveria bassiana* (Bals.) Vuill (Patil and Thontadarya, 1981) and the bacteria. *Bucil/us cereus* Frankland and *Serratia marcescens* Bizio. Over a quarter of 180 larvae collected in November 1977 in Shimoga district of Karnataka were infected by the fungus.

Other recent investigations on the teak defoliators include the following. Banerjee (1975) reported that sterility could be induced in both sexes of *E. machaeralis* under laboratory conditions by oral administration of the chemosterilants tepa. metepa or hempa to larvae or by dipping the pupae in solutions of metepa. Kedharnath and Singh (1975) reported that clones of teak showed natural variation in susceptibility to *E. machaeralis* under the test conditions in the laboratory. Singh and Gupta (1978) evaluated several insecticides against *E muchaeralis* in laboratory conditions. Field evaluation of some insecticides has been carried out by aerial spraying, first at Konni, Kerala in 1965 (Basu-Chowdhury, 1971) and later at Raipur, Madhya Pradesh in 1978 (Singh, 1980).

2.2. EFFECT OF DEFOLIATION ON GROWTH OF TEAK

The economic loss that may result from defoliation has been a subject of more speculation than scientific investigation. In the first quarter of this century, it was generally believed that loss due to defoliation amounted to between one third and one half of the potential volume increment (see Beeson, 1928; Minchin, 1929). These were nothing more than opinions influenced by the ravaged appearance of heavily defoliated plantations.

The earliest attempt to calculate the financial loss resulting from defoliation was that of Mackenzie (1921). Using arbitrarily estimated values for the loss in wood increment, he showed that defoliation may result in significant financial loss.

He estimated that 8.3% of the annual increment in volume was lost due to defoliation in Burma and 6.6%, in Nilambur, India. These estimates rested on two assumptions— (1) During the year in which severe defoliation occurred, half the potential increment for that year was not realized, and (2) Severe defoliation occurred once every 6 or 7 years. Thus, for Nilambur plantations with a rotation period of 75 years (acording to Mackenzie, 1921), severe defoliation was assumed to occur during 10 years of the rotation period, resulting in loss of 5 years' growth, i.e., loss of l/l5th or 6.6%, of the potential growth. Both of his above assumptions are not acceptable in the absence of experimental or observational evidence, and therefore the conclusion is not valid.

One of the oft-quoted estimates of loss due to defoliation is that of Beeson (1931. 1941) who made a slight improvement over Mackenzie's estimate. While Mackenzie assumed that severe defoliation occurred once every 6 or 7 years, Beeson replaced this assumption by observation. He made monthly records (visual estimate) of the intensity of defoliation during the 8-9 months of growth season for each of the 350 compartments of teak plantations in Nilambur covering an area of about *2000* ha for a period of 4 years from 1926 to 1930. Out of 11,700 observations thus obtained (an average of 34 per compartment over 4 years) he found that the frequency of occurrence of severe defoliation was 8.2 per cent. (This amounts to about 3 severe defoliations within a 4-year period, in contrast to Mackenzie's assumption of one severe defoliation within a period of 6 to 7 years. Beeson's estimate of the loss in increment, however, was still dependent on one major assumption—that the loss from each lsevere defoliation was equivalent to loss of one month's growth (compared to Mackenzie's assumption of loss of half year's growth). Based on this assumption and the observed frequency of incidence of severe defoliation, Beeson (1931) calculated that loss due to defoliation amounted to 8.2% of the annual volume increment. Beeson himself discussed the many assumptions implicit in such a calculation and stated "these assumptions invalidate the conclusions drawn, but by making them, the conclusion becomes one stage better than a guess". Further Observations in the same area (a total of 16,300 observations) revealed (Beeson, 1941) that severe defoliation occurred 9 percent of the time and he revised his earlier estimate of the loss to 13% Of the normal current annual increment and gave some financial loss figures. He did not explain the basis for such an upward revision of the estimate.

The only other reported study on increment loss due to defoliation is that of Champion (1934 b). He selected 100 saplings from a 3-year-old teak plantation in Dehra Dun, classified them into four comparable sets of 25 saplings each and subjected them to different levels of artificial defoliation (including non-defoliated control). Based on measurements of diameter at breast height, basal area and height. of the experimental saplings, he concluded that three complete strippings of-leaves in the same season (on 13 June, 9 July and 17 August) caused a loss of 65% of the normal increment. He also reported that in addition to loss of increment, repeated heavy defoliation resulted in weakening of leading shoot with consequent forking and even mortality. Taking a mean annual increment of about 100 c.ft. per acre for quality Class I (Bourne's yield table volume for Nilambur) and an average royalty of Rs. 2-00 per c.ft. of timber, Champion calculated that the loss amounted to Rs. 130 per acre per year (Rs. 325 per ha per year) of severe defoliation. Substituting an average 1981 seigniorage rate of about Rs. 1500-00 per cu m. for Kerala and using the same method of calculation, the loss amounts to about Rs. 6880-00 per ha per year of severe defoliation. This is an enormous loss, if true. There are several pitfalls in this calculation. The experiments were performed on 3-year-old saplings, about 5 cm in d.b.h. and 3.6 m high. The results cannot be applied to plantations of all ages. Dehra Dun, where the experiments were conducted, is outside the natural teak-growing belt and the stress due to defoliation may act synergistically with stress due to other factors such as low temperature during winter. Most importantly, artificial stripping of leaves, however carefully performed, cannot simulate natural insect defoliation. Under plantation conditions, the magnitude of loss will depend on several factors — the age of the plantation, the time of defoliation in relation to the seasonal growth pattern of teak, the frequency and duration of the leafless periods, the quantity of foliage lost in relation to the total quantity of foliage, etc. We must also take into account possible compensatory growth adjustments in the tree due to increased light penetration through the canopy, enrichment of soil with the excreta and dead bodies of insects, etc. Champion (1934 b) himself stressed the need for further investigations to derive more conclusive and dependable results.

It is clear that wo do not yet have a realistic estimate of the loss in increment in plantations under natural conditions of insect defoliation although Beeson's (1941) estimate of 13% loss has been repeatedly quoted by subsequent writers and has received wide recognition, by a process of uncritical reiteration.

Another type of damage attributed to heavy defoliation, particularly in young plantations, is die-back of the leading shoot, resulting in epicormic branching and further loss of quality (Dawkins, 1921; Laurie and Griffith, 1942; Khan and Chatterjee, 1944). As noted above, Champion (1934 b) reported that repeated heavy defoliation of saplings resulted in weakening of the leading shoot and consequent forking. Khan and Chatterjee (1944) reported that following a complete defoliation by ***E. machaeralis*** in October, 52% of the saplings in a 3-yr-old plantation showed die-back of leading shoots to a length of 15 to 30 cm. They also reported that saplings upto 10 years old were susceptible to such damage. However follow-up observations on the persistence of forking and its long term impact have not been made.

3. MATERIALS AND METHODS

3.1. STUDY SITES AND GENERAL METHODS

There were two main components of the study — (1) experiments to quantify growth loss from defoliation, and (2) biological and ecological observations on the defoliators. The major part of the study was carried out in the Karulai Range of Nilambur Forest Division, where experiments laid out to quantify growth loss also provided opportunity for observations on the biology and seasonal incidence of the defoliators. Additional observations were made in other places to gather certain specific information on the insects or their impact; these will be described in the appropriate context in different sections.- Information given here pertains to the main study site at Nilambur. It is further restricted to the general methods.

3.1.1. The study area

The general study area (Fig. 1) was Karimpuzha in the Karulai Range of Nilambur Forest Division. This is a large teak plantation area, on the banks of the river Karimpuzha, with over 2,500 ha under plantations of assorted age, some in the second rotation. For details of climate, soil, etc. refer Vasudevan (1971). The experiments were laid out in two blocks of plantations raised in the year 1974 (4-yr-old at start of experiment.)

3.1.2. The experimental approach

The short-comings of earlier attempts to estimate loss due to defoliation were discussed in Section 2.2. One of the methods now commonly used world-wide is comparison between the growth rates of the same tree during periods of occurrence and nonoccurrence of defoliation, based on increment core sampling. This is usually possible when a wave of defoliation occurrs continuously over a period, say, 4 to 5 Years, and then subsides completely for another few years as in the case of spruce budworm or pine saw-fly in the temperate forests. For our problem. the best approach was to compare the increment of trees that have been experimentally protected from defoliation with that of trees left unprotected during the same period.

Because the defoliations caused by ***H. puera*** and ***E. machaeralis*** were well separated in time, it became possible to study the impact of both species separately. In one set of plots (TI) we controlled the defoliation throughout the year by prophylactic application of insecticide whenever there was threat of attack from either species. In another set of plots (T2) protection was given during the early part of the season only. This facilitated distinction between the impacts of the two insects since noticeable defoliation by ***E. machaeralis*** occurred only in November or afterwards, just prior to natural leaf fall. A third set of plots (T3) was left without any protection.

Growth loss is often expressed as loss in increment of diameter or basal area or height. While these growth measures are sufficient to decide whether significant loss of increment occurs, they do not lend themselves to conversion into economic terms. Where relationships between the width of growth ring and corresponding volume increment are already available from other forest mensuration studies, loss in volume have also been computed. In the present study, our objective was to estimate the loss in volume. Although general as well as local volume tables are available for teak, none of them can be considered accurate enough for the present purpose. The following method was therefore employed.

The experiment was started when the first mechanical thinning of the plantation was carried out in the 4th year, during which half the number of trees were felled as per standard silvicultural practice. Detailed measurements were made on felled trees from which the volume of each tree was calculated. Then the mathematical relationship between volume on the one hand and GBH and top height on the other was determined empirically. Using this function, the initial volume of the standing experimental tree was estimated. The treatments were continued until the next

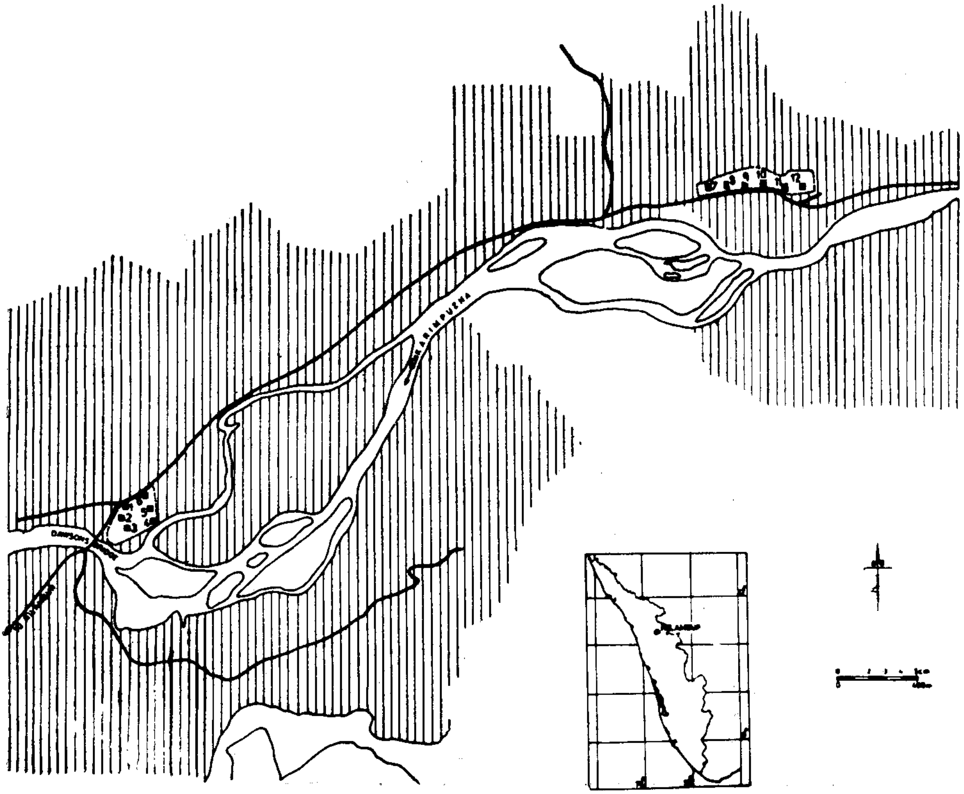

Fig. 1. **Location of the general study area and the experimental plots at Nilambur. The hatched area represents teak plantations.**

mechanical thinning was carried out at the end of the 8th year and the tree volumes were again determined. Fresh measurements were made on trees felled at this time to derive volume—GBH-top height relationships applicable to 8-yr-old standing trees.

The plots established for these measurements were also used for measurement of defoliation levels and observations on insect activity.

3.1.3. Lay-out of plots

Twelve plots, 400m2 each, were established in two separate blocks of 1974 plantations (Fig.1). The first block was located near Dawson's Bridge and the second about 4 km away at Mundakkadavu. The area in between was mostly covered by older teak plantations. The 12 plots were assigned serial numbers. with

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Plot chart.1974 Plantation, Korulai, Nilambur.
Plot No. 1
Date of observation:
Notes:

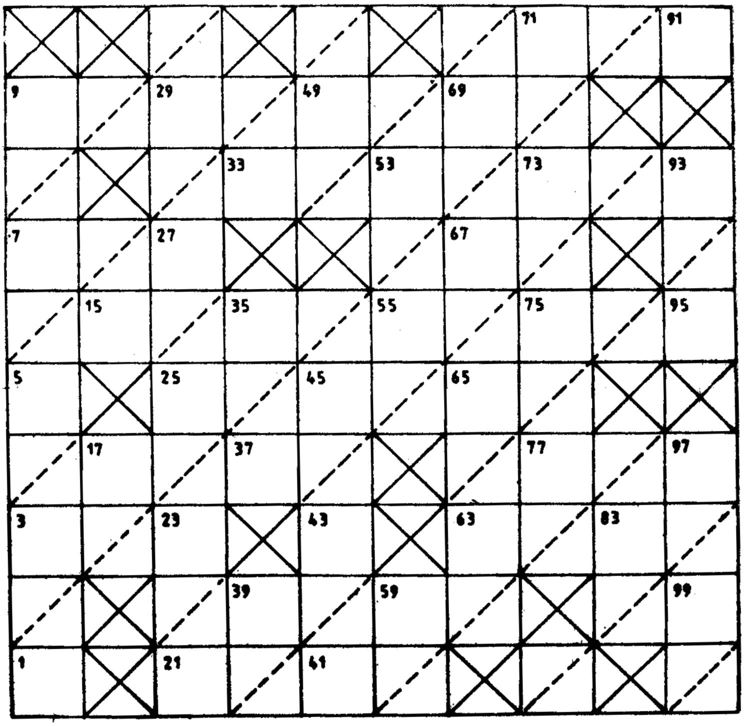


Fig. 2. A typical plot chart. Missing trees are indicated by cross lines and the rows of trees felled in the first mechanical thinning by diagonal dashed lines.

plots 1 to 6 located in Block I and plots 7 to 12 in Block 11. Plots 1 to 6 and 12 were square (20m x 20m) and the others rectangular (10m x 40m).

In each block, each treatment was allotted to two plots at random. Thus there were 4 replicates each of the 3 treatments.

Within a plot, serial numbers were assigned to each planting site in a definite order, irrecpective of whether the trees were present or not and the numbers were marked on a plot chart. The respective tree numbers were used in all subsequent records. After the first mechanical thinning in July 1978, fresh plot charts were prepared showing the location of standing trees and the tree numbers. Cyclostyled copies of these charts (Fig. 2) were used to record pertinent information regarding the trees, throughout the experimental period.

3.1.4. Data collected

3.1.4.1. Tree measurements

In 1978, all measurements were made between 20 June and 6 July, during which period the first mechanical thinning was carried out. The breast height (1.37m above ground) of all trees were marked as per standard slvicultural practice and GBH measurements were taken with a metal tape. Thinning was then carried out by the Forest Department as usual, as part of the regular thinning of the entire plantation. The following measurements were taken on the felled trees — (i) top height, i.e., height upto the tip of the leading shoot, measured with a tape, (ii) underbark girth of the main bole and of all branches, at every 50 cm interval, down to 1lcm overbark girth. After the thinning, top hieghts of the standing trees were measured with a tape attached to a reed pole.

In all plots receiving complete protection, the GBH of each tree was measured at monthly intervals for about three growth seasons to determine the normal growth pattern. In addition, the GBH of all experimental trees were measured annually at the end of the growing season, to make interim comparisons.

Final measurements were taken in the last week of December 1982, when the regular second mechanical thinning was carried out. Thus the total experimental period encompassed nearly 5 growth seasons, from July 1978 to December 1982. The same measurements taken in 1978 were repeated in 1982 on both standing and felled trees. For measuring the top height, many trees had to be climbed part way to reach the reed pole to the top.

All measurements were made by **us** with the help of colleagues; no unskilled labour was used.

Basal area (BA) was calculated from the GBH using the formula,

$$BA = \frac{(GBH)^2}{4\pi}$$

3.1.4.2. Defoliation rating

The experimental trees were observed roughly at fortnightly intervals throughout the experimental period and the intensity of defoliation recorded. The defoliation intensity of each tree was rated visually by comparing its crown with a fully-leaved crown. The intensity was classed into 4 main classes at intervals, 25% except that two additional classes were included to distinguish near-total freedom from defoliation and near-total defoliation (Table 1). These classes designated by scores were entered in the observation sheets. During periods when the defoliators were not active, a general score for the plot was sufficient in place of individual tree scores. Defoliation was finally expressed as percentage of leaf loss by reconverting the scores. To calculate the plot averages, the midpoints of the defoliation classes (Table 1) were used.

Table 1. Scores used for rating intensity of defoliation

Score (Class)	Percentage of defoliation compared to fully-leaved crown	Midpoint of defoliation percentage
1	0 - 5	2.5
2	6 - 25	15.5
3	26 - 50	38.0
4	51 - 75	63.0
5	76 - 95	85.5
6	96 - 100	98.0

Along with defoliation rating, the flushing level was also rated to gather information on normal tree phenology and changes brought about by defoliation. The score system used is given in Table 2. According to this system, the cycle of normal leaf development will be registered as follows.

0 0 - 1 - 2 - 3 - 2 - 1 - 0 -

This scoring was mainly used to understand the phenological state of the trees in qualitative terms; experience showed that the method was not suitable for quantification.

During each observation, notes were also made on the insects present and their developmental stages, occurrence of natural leaf fall, etc.

Table 2. Scores used for rating flushing level

Score	Description of category
0	All leaves mature, no new leaf
00	Leafless
1	Low level flushing
2	Medium level flushing
3	High level flushing

3.1.5. Application of control measures

Control measures were applied in T1 plots (full protection) whenever the mean defoliation percentage in T3 plots (untreated control) rose above 2.5 and qualitative observations showed that feeding stages of insects were present. Qualitative observations were necessary because, according to the scoring method, defoliation percentage continued to be high until reflushing was complete, even when the insects were not present. Minor damage by miscellaneous insects and by residual populations of ***E. machaeralis*** were ignored. During the high-risk period from April to July, in addition to regular fortnightly observations, frequent checks were made to discover infestation. Because of the sudden appearance of ***H. puera*** infestations, a mild degree of damage, not exceeding loss of about 15% of the foliage, occurred in some plots on some occasions before control operations could be carried out. In the year 1980, such damage was more than negligible, amounting to loss of between 20 and 65% of the foliage in the various plots during an infestation which occured in May. In practice, not more than 3 or 4 insecticidal sprays were required. In T2 plots (partial protection) control measure was applied except in November and December and in T3 plots no control measure was applied.

When an infestation was present or imminent, the trees were sparayed until dripping, with 0.2% DDT in water. An emulsified concentrate of DDT was used and 0.5 ml of a sticker-spreader was added per 10 litre of water. A rocker sprayer, fitted with a hyjet gun was used. In later years, the top portion of the tree crowns were reached by using ladders or climbing up adjacent trees. DDT was preferred over other insecticides because of easy availability and effectiveness; environmental considerations were not applicable in these small-scale experimental sprayings.

3.1.6. Maintenance of plots

The plots, including one row of border trees, were fenced with barbed wire, after the first mechanical thinning. Before fencing, wild elephants destroyed a few experimental trees in some plots; he fencing was mainly intended to prevent cattle grazing and human disturbances but may have deterred elephants also. The plots were weeded annually in November-December to prevent wild fire. The fence was temporarily removed during the second mechanical thinning, but has been replaced, so that the plots can be identified for future observations, if necessary.

3.1.7. The growth year

Phenological observations (Sections 4.2) showed that leaves appearing in March-April often persisted even after December. To indicate clearly the growth season in which insect-attack, natural leaf fall, etc. occurred, the growth year covering the 12 month period commencing on 1 April and ending on 31 March is used throughout this report, instead of the calender year. This corresponds to the 'Forest Year' as defined by the British Forestry Commission.

3.2. CHOICE OF MATHEMATICAL MODEL FOR VOLUME PREDICTION

As indicated earlier, the volumes of standing experimental trees were determined from mathematical relationship established between GBH and top height on the one hand and volume on the other. To derive this relationship detailed measurements as described in Section 3.1.4.1 were made on trees felled in the 5th and 9th year (during the 1st and 2nd mechanical thinnings). The methods used for volume prediction and the results are presented here.

3.2.1. Calculation of the volume of felled trees

The underbark volume of each felled tree was determined by adding the volumes of each 50 cm segment. The volume of each 50 cm segment was calculated from the girths at either end, considering it as a frustrum of a cone, by the formula

$$V = \frac{l}{12\pi}(g1^2 + g1g2 + g2^2)$$

Where V is the volume;

l is the length of the segment (= 50 cm);

g1 is the girth at bottom end; and

g2 is the girth at top end.

Use of this formula for 50 cm long segments gave the same effect as using Newton's formula on 1 m long segments. Newton's formula (also called prismoidal formula) is considered the most accurate for calculation of the volume of billets (Chathurvedi and Khanna, 1982). The volume of branchwood, if any, (down to 11cm girth overbark) was added to that of the main bole.

3.2.2. Models tested for volume equations

A large number of mathematical models have been suggested by various authors for prediction of the volume of standing trees from diameter (or girth) and height (Chathurvedi and Khanna, 1982). We tested multiple linear regression equations of several forms (Table 3) fitted by the method of least squares, with volume as the dependent variable and GBH (overbark) and top height as independent variables, and chose the best-fitting equation. Data for each Block (6 plots) were pooled and analysed separately for each age-group. The number of felled trees available was 194 each in Blocks I and II at the beginning of the experiment and 74 in Block I, and 94 in Block I1 at the end.

The computer facility at the University of Kerala was used to run the multiple linear regression programmes, and to predict the volumes of standing trees using the selected equation.

In some equations the variables were transformed to natural logarithms. In such cases, the coefficient of determination cannot be used to compare the fitness of the models, and to overcome this difficulty, use of another index of fitnesc has been suggested (Furnival, 1961). This 'Furnival index' was calculated as follows.

Where the dependent variable (V) is not transformed,

$$\text{Furnival index} = \sqrt{\text{Error Mean Square}}$$

Where the dependent variable (V) is transformed to natural logarithm.

$$\text{Furnival index} = \sqrt{\text{Error Mean Square}} \text{ X Geometric mean of V}$$

The lowest value of Furnival index indicates the best fit.

3.2.3. Selection of model

Table 3 shows the Furnival index as well as the coefficient of determination for each tested function. The lowest value of the Furnival index is marked by double underline and the second lowest by single underline. Highest values of the coefficient of determination are similarly marked. In both blocks in boths years, functions using log transformed variables gave the lowest Furnival index, compared to function9 using non transformed variables Among these functions, log V f (D^2 log D, log H) was the best for Block I, 1978 and Block 11, 1982 and the second best for the other two blocks. Log V = f (log D, log H) was the best for Block I, 1982 and log V = f (log D2H) the best for Block 11, 1978. Thus the function which best fitted the largest number of trees was log V = f (D^2, log D, log H). It was also

Table 3. Comparison of different functions of diameter and height for prediction of volume

Function*	4th year				9th year			
	Block I		Block II		Block I		Block II	
	A	B	A	B	A	B	A	B
$V = f(D^2H)$	2.8425	0.9276	1.5165	0.9664	6.7518	0.9571	8.8498	0.9597
$V = f(D^2, D^2H)$	2.7981	0.9303	1.5195	0.9665	6.3277	0.9629	8.5622	0.9627
$V = f(D^2, H, D^2H)$	2.8003	0.9306	1.4808	0.9683	6.3514	0.9632	8.1196	0.9669
$V = f(D^2, DH, D^2H)$	2.7978	0.9307	1.4733	0.9687	6.3447	0.9633	7.8168	0.9694
$V = f(D, D^2H, DH, H^2)$	2.8814	0.9267	1.5042	0.9675	6.4735	0.9623	7.9614	0.9686
$V = f(D^2, H^2, D^2H, DH^2)$	2.8123	0.9303	1.4707	0.9689	6.4026	0.9631	7.3528	0.9732
$V = f(D, D^2H, DH, DH^2)$	2.7540	0.9337	1.4318	0.9707	6.3403	0.9644	7.2906	0.9740
$V = f(D, H, D^2, H^2, DH, D^3, H^3, D^2H, DH^2)$	2.9909	0.9230	1.3185	0.9758	5.7672	0.9724	11.5639	0.9364
$\log V = f(\log D^2H)$	2.1537	0.9482	1.3190	0.9777	4.4874	0.9777	6.0532	0.9759
$\log V = f(\log D, \log H)$	2.1388	0.9492	1.3541	0.9766	4.2706	0.9801	6.0395	0.9763
$\log V = f(D^2, \log D, \log H)$	2.1063	0.9511	1.3218	0.9778	4.2964	0.9802	5.6584	0.979

* Where V is the volume; D is diameter calculated from girth; and H is the top height.

A, Furnival index; B, Coefficient of determination.

suitable for all the remaining trees since the difference in the Furnival index between this and the best-fitting one for each block was small. This function was therefore chosen to predict the volumes of trees in all the plots. With respect to the coefficient of determination, this function was the best for both blocks in both years, the values ranging between 0.9511 and 0.9802 (Table 3).

Thus the volume of all standing trees was estimated using the equation,

$$\log V = b_0 + b_1 D^2 + b_2 \log D + b_3 \log H$$

in which age and block-specific constants were substituted. These constants are given in Table 4.

Table 4. Estimated constants for volume prediction

Constaht	4-yr-old trees		9-yr-old trees	
	Block I	Block II	Block I	Block II
bo	-7.06714600	-9.85629600	-6.44729800	-6.15010700
b l	-0.00685444	-0.00552777	-0.00043266	0.00252992
b2	3.09878000	2.71265000	2.60622000	1.50464000
b3	0.52616200	1.05026000	0.52677300	0.8 1687400

4. RESULTS AND DISCUSSION

4.1. SEASONAL INCIDENCE OF DEFOLIATORS AND THE DYNAMICS OF DEFOLIATION

4.1.1. General findings

Over a 5-year-period of observations in teak plantations at Karulai, Nilambur, four species of insects were found to cause measurable defoliation- *Hyblaea* puera, Eutectona machaeralis, an unidentified curculionid and an unidentified chrysomelid. Leaf feeding insects of minor importance were other lepidopteran larvae, ***Myllocerus*** beetles and grasshoppers, all noticed in small numbers at various periods, but causing no measurable damage.

This is the first study in which detailed systematic records of defoliation have been maintained for a long, continuous period. Fig. 3 shows the average expectation of defoliation due to all insects in a growth year. The four curves show the defoliation trends recorded over four years, each curve representing the defoliation percentage averaged over the four untreated experimental plots. It may be seen that defoliation occurred regularly between April and July.

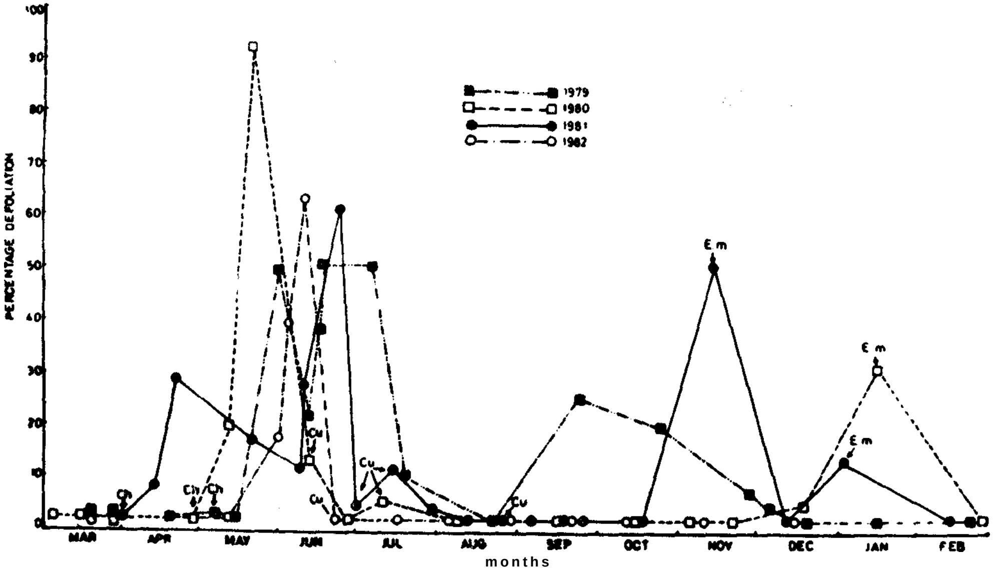


Fig. 3. Seasonal incidence of defoliation in teak at Nilambur. Each curve represents the percentage defoliation averaged over the four experimental plots. The periods of activity of each insect is indicated – Ch, Chrysomelid; Cu, Curculionid; f. m., ***Eutectona machaeralis;*** Unlabelled, ***Hyblaea puera.***

Usually, complete stripping of the young foliage occurred at least once during this period, caused by ***H. puera,*** the most dominant pest. (The mean defoliation percentages plotted do not reveal the occurrence of total defoliation because it occurred at different times in different plots; so that when averaged over plots for a given date, the precentages have been lowered; for details see Section 4.1.2.). In some years there was a subsequent Peak of ***H. puera*** defoliation in August (see Section 4.1.2.2.), September or October. Again, in some years, defoliation occurred towards the end of the growth season, caused by ***E. machaeralis*** which also sometimes resulted in complete stripping of the leaves. The study has yielded much new information on the dynamics of defoliation in teak plantations and on the ecology and seasonal infestation patterns of the two major pests, ***H. puera*** and ***E. machaeralis.*** These two insects are therefore dealt with in detail below. Fig. 3 is only intended to show the general trend of defoliation in teak plantations. Since no further reference will be made to the other two defoliators which caused measurable defoliation, brief notes on them are given here.

The chrysomelids were active during the early part of the growth season (Fig. 3) and mostly confined their feeding on tender !eaves. The heavily damaged !eaves dried up (Fig. 4) while less damaged leaves were perforated. The beetles tend

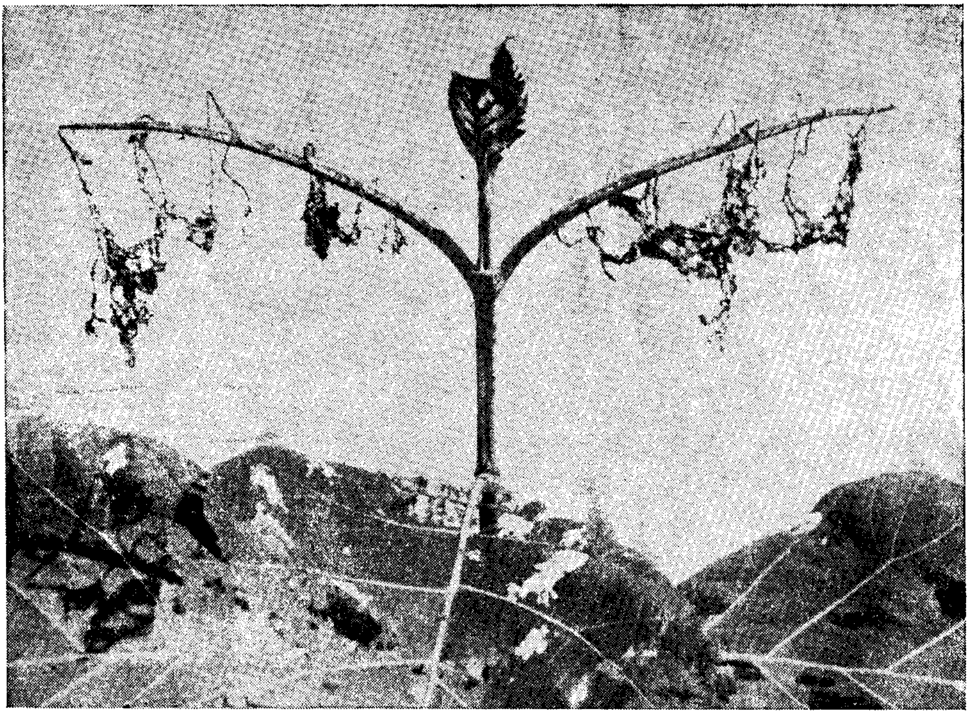


Fig. **4.** C'hrysomelid damage to tender leaves of teak sapling.

to aggregate and feed selectively on tender leaves and characteristically roll down the leaves when disturbed. Damage caused by these beetles can sometimes be mistaken for low intensity damage by ***H. puera*** larvae. The highest level of defoliation caused by these beetles was about 2.5%.

The curculionid beetles were active during June, July and August (Fig. 3) and caused emargination and perforation of leaves, particularly of the new flush of leaves formed after defoliation by *H.* ***puera.*** The highest level of defoliation caused by these beetles was about 15%.

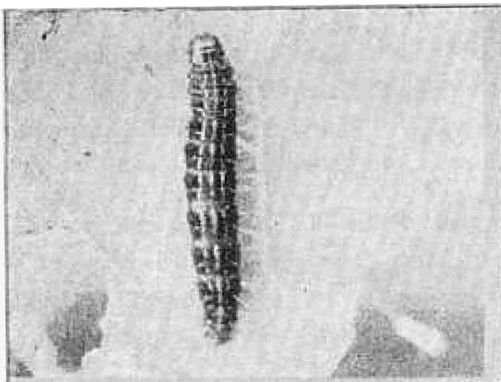
4.1.2. Hyblaea puera

4.1.2.1. General observations on biology

The biology of ***H. puera*** and the nature of damage caused by it are well known and were summarised in Section 2.1.1. For the sake of completeness and ready reference, the insect and the damage it causes are shown in Figs. 5 to 8. Detailed observations on infestation characteristics and habits of the larvae will be discussed below but observations on pupation habits are noted here. According to Beeson (1941), in ***H. puera,*** pupation may occur within a triangular leaf fold cut specially and strongly spun together; between juxtaposed leaves or leaf skeletons bound by silk; or when the host leaves are completely stripped, on other foliage in the undergrowth or in the soil cover. In all our observations, we found pupation to occur on the ground, under a thin layer of soil or litter. The pupae were enclosed in a loosely built cocoon made of pieces of dry or decayed leaves held together with silken threads or of soil particles stuck together with silk. Pupae were not found on green or freshly fallen leaves above ground, although this mode of pupation was common in ***E machaeralis.***

4.1.2.2. Annual defoliation trends

These results are based on fortnightly observations in the four untreated experimental plots at Karulai as described in Section 3.1.4.2. Continuous observations were available for four complete growth years from 1979 to 1982. According to the scoring system employed for defoliation rating, even when there was no defoliation by ***H. puera,*** the trees would receive Score 1, indicating loss of 2.5% (mid-point of the range) of the foliage. This system was followed since grazing by at least a few insects like beetles and grasshoppers could be expected most of the time. For the present study on ***H. puera,*** a defoliation percentage of 2.5 or below (plot average) was taken as zero, unless qualitative observations showed the presence of larvae.



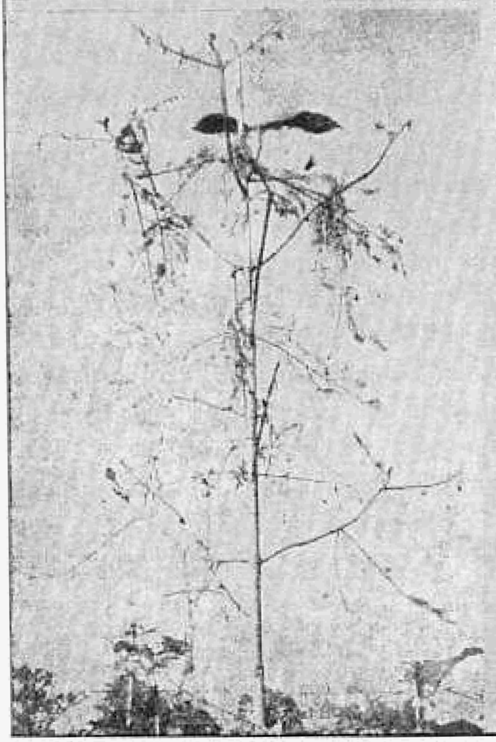


Fig. 5. **A nearly full-grown larva of** ***Hyblaea poera.***
Fig. 6. ***Hyblaea puera*** **moth.**
Fig. 7. **A sapling defoliated by** ***Hyblaea puera.***
Fig. 8. **An older teak tree heavily infested by** ***Hyblaea puera.*** **The mature larvae have begun to descend for pupation.**

Fig. 9 shows the defoliation caused by ***H. puera*** in the four untreated experimental plots during the four years from 1979 to 1982. No other insect caused measurable defoliation during the periods when ***H. puera*** was prevalent and it was therefore possible to separate the defoliation curve for ***H. puera.*** This defoliation curve is a faithful representation of the population curve of ***H. puera*** larvae, except that when the trees are totally defoliated, any increase in the population of larvae will not be reflected. Thus no comparison of population size between years is possible With this restriction, the defoliation curve can be used to study the population dynamics of the insect. A study of the defoliation curves and simultaneously recorded qualitative ob servations showed the following.

The number of population peaks varied from one to three per year. The first peak occurred in the third week of April (year 1981), third week of May (year 1980) or the first to second week of June (years 1979 and 1982). Usually it occurred during the pre-monsoon season (Fig. 9). There was no apparent temporal correlation between the subsequent peaks and the rainfall.

In some years (1980 and 1982) the first peak itself was large, causing total defoliation in most plots, but in other years (1979, 1981), the first build-up was smaller.

A second peak occurred in three of the four years. In 1979 and 1981 it was high in most plots causing near total defoliation, but in 1982 it was very small and was noticed only in the two plots located in Block I. It was also small in one of the plots in Block I1 in 1981. The interval between the first and second peaks ranged from 18 to 60 days. In the same year (1979) it was 30 days in Block I, but only 18 days in Block 11. In 1981 and 1982 it was 60 days in most plots. The life cycle of ***H. puera*** is usually completed in 18 to 27 days (Beeson, 1941: unpublished observations from our laboratory) and the varying intervals between the two population peaks suggest that the second peak does not necessarily represent the second generation of the insect. This is particularly evident from the data for 1979, when the first peak occurred on the same date in both the blocks. but under the same climatic conditions the second peak occurred after 18 days in Block I1 and after 30 days in Block I.

A third peak was noticeable only in 1979. In Block 11 it was very small and occurred about 30 days after the second peak. That it represented a new generation of larvae was confirmed by qualitative observations. In Block I, the third peak was higher and occurred about 75 days after the second peak. In both the plots, this peak was flatter than earlier peaks suggesting that the insect population had a mixed age-structure, representing larvae of more than one overlapping generations.

In general, while plots within the same block showed similar trends, the synchronization between the population peaks in the two blocks (separated by a distance of about 4 km) was poor. Rarely, some peaks not represented in the study plots were observed in adjacent areas. One such peak occurred in early August 1980, causing heavy defoliation in about half a hectare.

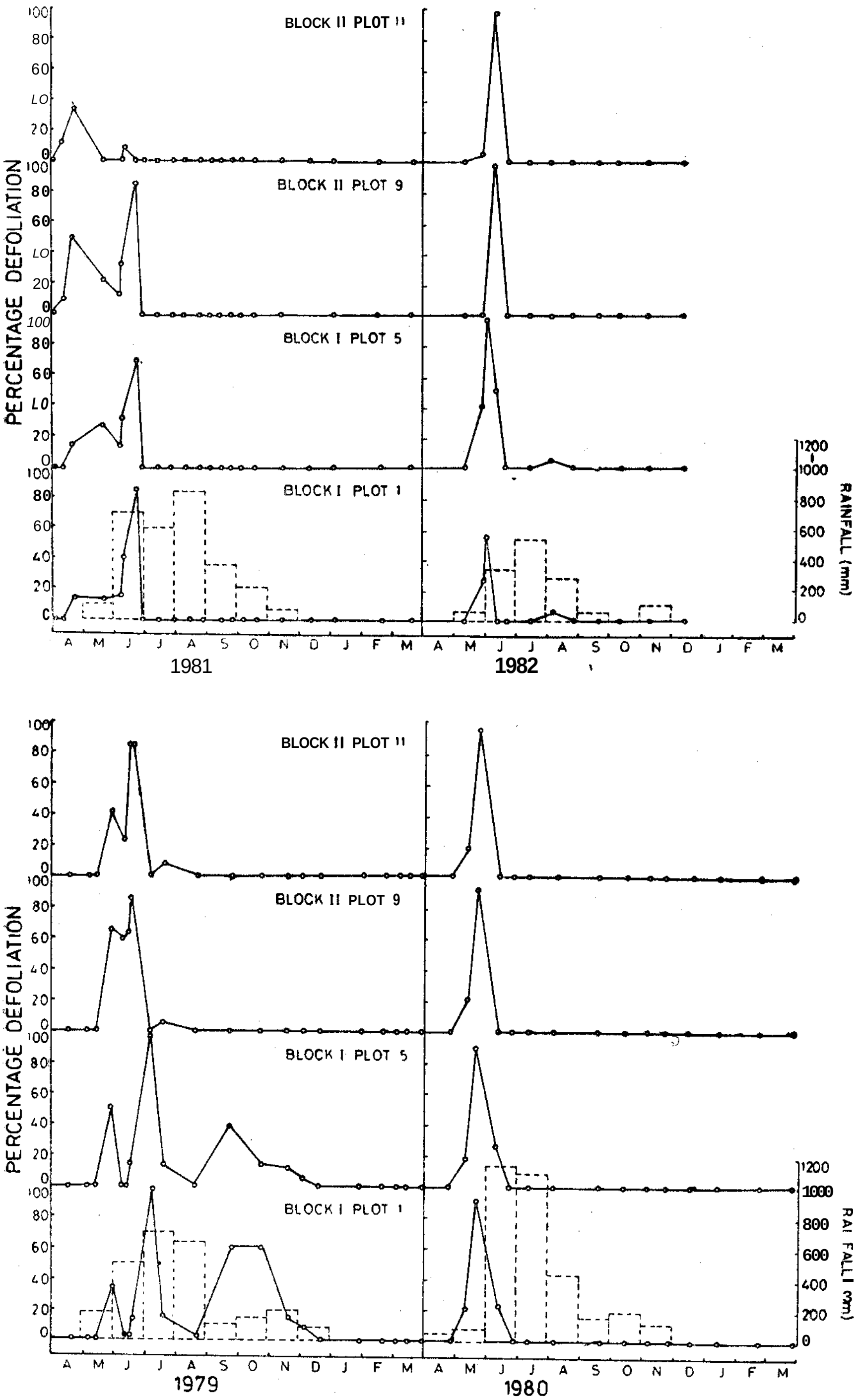


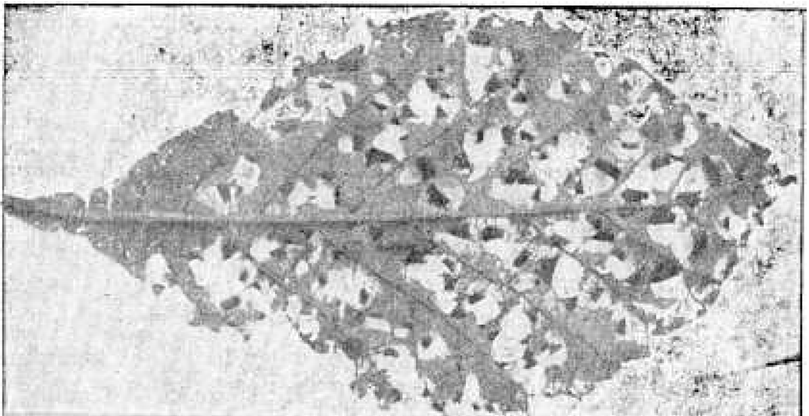
Fig. 9. **Seasonal incidence of defoliation caused by *Hyblaea puera* in the four untreated experimental plots at Nilambur, over the four-year period. The bars show monthly rainfall.**

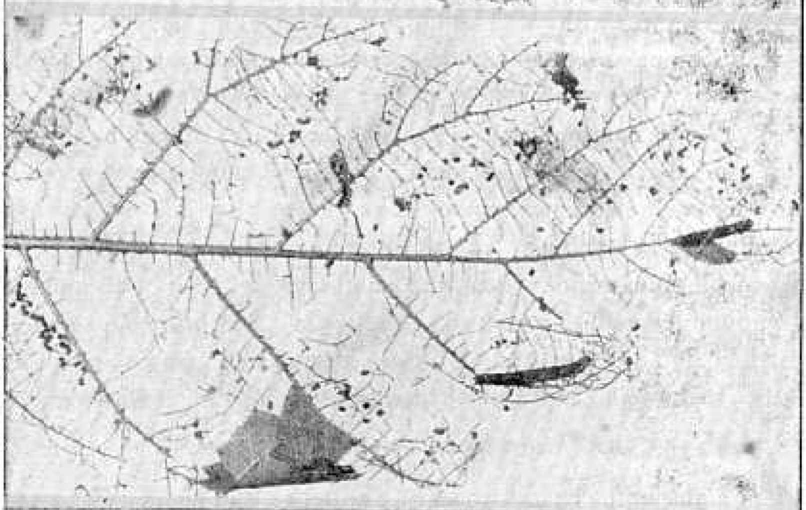
4.1.2.3. Infestation characteristics

These observations started fortuitously when one of us noticed a sudden build-up of ***H. puera*** infestation on teak trees surrounding his residential quarters situated within the Institute Campus, in a belt of degraded natural forest (moist deciduous) in the Peechi Range of Trichur Forest Division. Teak was the dominant tree species in the hilly area surrounding the house. There were about 30 trees scattered around the house, all of them above 75 cm in girth. In addition, there was a large number of naturally regenerating teak saplings on the ground, all of them less than 2 m high (due to illicit removal of older saplings). Following the heavy infestation, clear-cut evidence of moth emergence was obtained from moths attracted to normal domestic lights. Trapping was not feasible because the moths were attracted to all the domestic lights and it was neither possible to set up traps on all of them nor to regulate the domestic use of lights over the entire period of moth emergence. But it was possible to judge the abundance of moths without counting them. During periods when moth emergence was expected, at least some lights were put on throughout the night and observations were made intermittently. Except for a street light at a distance of about 50 m and a few lights on other houses at a distance of over 100 m, there were no sources of light in the immediate surroundings. Following moth emergence, the trees and saplings around the house were kept under general observation for over 11 months to discover new infestations; close examinations were made at least once a week, usually on Sundays.

Detailed observations on infestation characteristics started on the morning of 14 April 1984 when a large population of approximately 3-days old larvae was noticed on some trees in the observation area for the first time jn the year. A single dead moth was found inside the house the previous day. In the immediate vicinity of the house, infestation was confined to 8-10 trees. At this time, the teak trees had a full flush of new leaves but there were differences in leaf maturity. Trees with comparatively tender leaves were the most heavily infested, with the larval population distributed throughout the canopy, although the concentration was greater on the most tender terminal leaves (Fig. 10). Trees with comparatively older leaves had a smaller larval population, mostly confined to the topmost and peripheral layer of the canopy consisting of tender leaves. The infestation was spread over a vaguely delimited patch, and similar trees in adjacent areas were unaffected. In other areas within the Institute Campus, similar or larger patches of infestation were found at the same time, but some areas were free of infestation. These larval populations differed in age only by a day or two.

On **15** April, small larvae were seen hanging on silken threads and many of them landed on lower leaves. By 17th evening, some trees that had tender





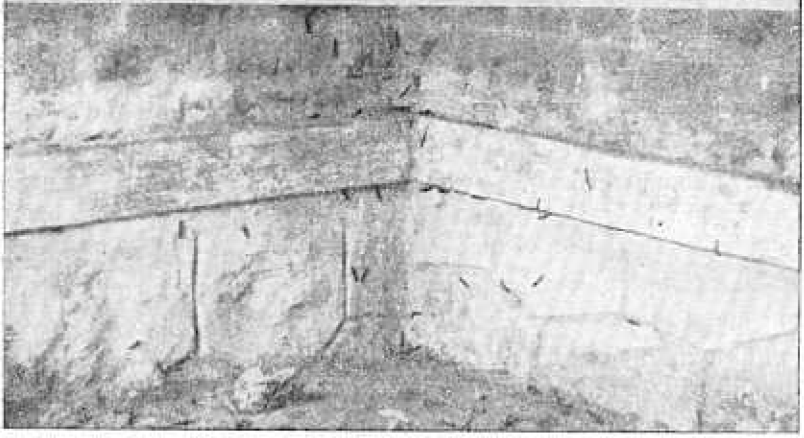


Fig. 10. A heavily infested tender leaf harbouring about 80 young larvae within small leaf folds.

Fig. 11. Older larvae feeding on mature of a sapling. Note one larvae within the leaf fold at bottom.

Fig. 12. Mature larvae wandering and crowding on wall prior to pupation.

foliage were completely stripped, only the petioles and larger veins remaining. The larvae then moved to adjacent tree'; which had older foliage. Some larvae also descended to the ground and fed on saplings (Fig, 11). Where the initial population was small and confined to tender leaves at the top. the larvae, after consuming the tender leaves, descended to older leaves of the same tree and continued feeding. In many trees, all the older leaves were eaten up by larvae which migrated either from the upper canopy or from adjacent trees. Usually the population of larvae on infested trees was very high, and the sound of faeca! pellets falling continuously on the lower leaves and on dry leaves on ground could be heard very clearly. like a mild drizzle of rain, particularly when the larvae were older and the faecal pellets larger. Feeding continued throughout the night, with the sound of the falling faecal pellets leaving an unforgettable impression. By 19th morning, most larvae were nearly mature and they descended to the ground. They were seen wandering all over the ground (Fig. 12), with some continuing to feed on the leaves of saplings. Some larvae also nibbled on the leaves of lantana. Thus, many trees were completely stripped of leaves in a matter of 5 days since the infestation was noticed. By 19th evening, large numbers of larvae were seen crawling over the walls of the house. Small numbers of larvae still continued to feed and move from tree canopy to ground over the next two days. On 22 April, pupae were noticed for the first time, on the ground, under dry leaves. Some pupae were also found on the bare walls and floor of the house. Feeding larvae were not noticed any more.

On 25th night moths began appearing at light. Large numbers were attracted to domestic lights in the following days. A few were also seen during early mornings resting on the leaves of teak saplings and sometimes on other plants. The moth population reached a peak on 28th and declined thereafter, reaching very low levels on 1st and 2nd May and nil on 3rd. From these observations, the period from egg laying to peak moth emergence was estimated to be about 20 days (from 8 to 28 April).

Since a large population of moths was present in the observation area, a much bigger second infestation was anticipated. However, no significant infestation occurred in spite of the presence, in the same area, of trees possessing tender foliage (including those partially refoliated after the insect attack). Nowhere in the campus was a significant infestation noticed. However, a small number of larvae were seen on saplings. They were first noticed on 29 April, and on subsequent days a few eggs and a few more larvae of mixed age were seen, again on saplings. Mature larvae were seen on 8 and 11 May, alongwith younger larvae. Young larvae were again noticed on 23 May, all in small numbers on tender leaves of saplings. Older trees were not infested, although stray larvae were found on tender leaves of lower branches. These observations showed that a small, new, uneven-aged population survived on saplings, but not on older trees.

No larvae were seen in the area after the end of May, until late September when small numbers were again noticed on saplings. A small population, with overlapping generations was found also in October, November and January, causing minor, but visible defoliation of saplings, particularly in October-November. Although a few larvae occurred on the lower branches of trees. none were seen in the top canopy.

4.1.2.4. Spatial distribution of infestation

Since the characteristics of ***H. puera*** infestation at Peechi suggested migration of moths, a survey was conducted soon after the first population build-up at Peechi in 1984 to study the pattern of spread of infestation. An aerial survey would have been the best, but in the absence of such facilities, a ground survey was made. A large extent of roadside teak plantations along the Western Ghats in Kerala and part of Karnataka, as well as some strips of teak-bearing natural forests were covered within a period of 8 days. Travelling along the road by jeep, the loci of infestation in roadside teak plantations were detected and recorded by noting down the kilometer reading. Old as well as current infestations were easily detected from a distance and closer observations were made for confirmation.

Fig. 13 shows the survey route and the major locations where old or new infestations were noticed between 15 and 22 May 1984. In southern Kerala covered first, a distance of over 30 km from Kulathupuzha to Konni via Achencoil was travelled through teak plantations and it was found that extensive defoliation had already taken place by 15 May. Field notes made earlier in this area in connection with another study revealed that two waves of defoliation had already occurred, the first around 10 April, in small patches, and the second around 23 April, over more extensive areas. A few moths and a few late larvae were seen, but there was no visible fresh damage. Longer distances were covered north of Trichur, of which about 135 km along the road had bordering teak plantations. Of this, about 27 km in total showed plantations which had already suffered defoliation. The new flushes indicated that infestation had occurred 2 or 3 weeks earlier. An extent of about 30 km, distributed over different areas, showed plantations with currently active infestation. The larvae were in different stages of maturity at different observation sites, but within a continuous patch of infestation the population was even-aged. Some typical examples of the distribution

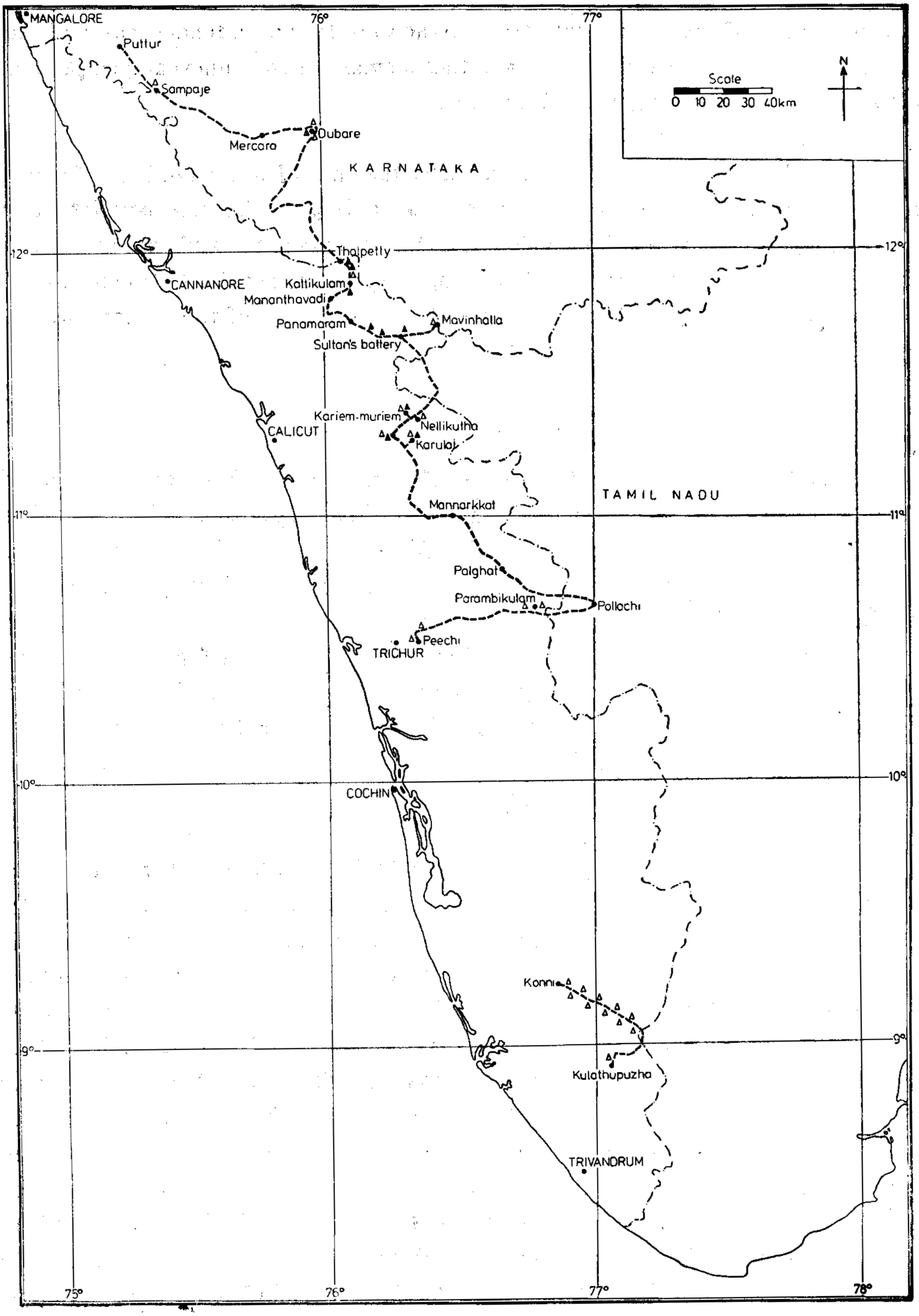


Fig. 13. Map of showing the survey route and the major locations where defoliation was noticed. Old defoliation is indicated by open triangles and current defoliation by closed triangles.

of old and new infestations are shown in Fig. 14. It is evident that infestation occurred in discontinuous patches. Patches of current infestation were separated from patches of old infestation by a few kilometers.

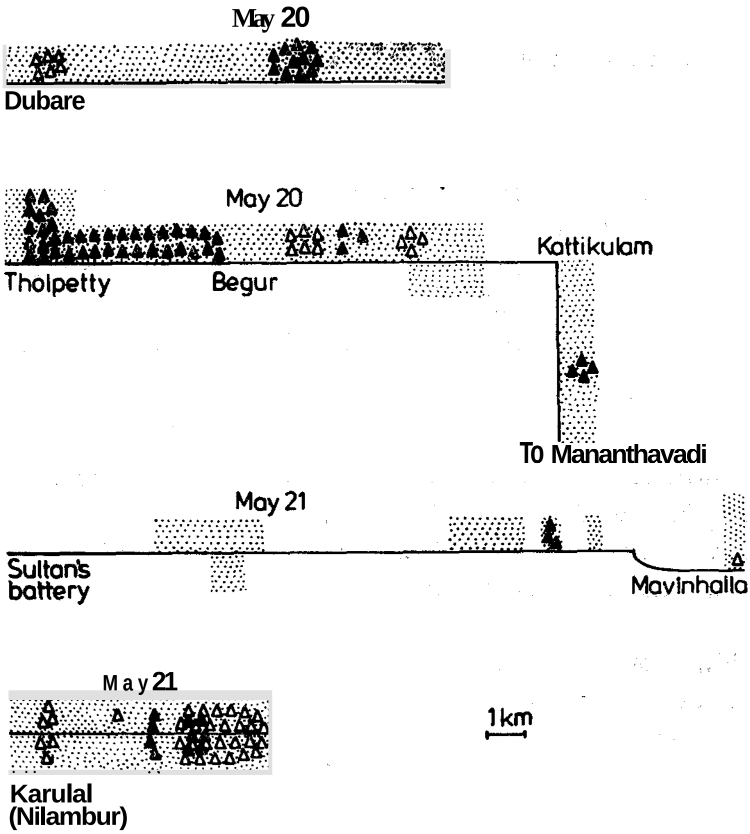


Fig. 14. **Spatial distribution of *Hyblaea puera* infestation in selected road-side teak plantations. The plantations are shown by stippling, patches of old infestation by open triangles and patches of current infestation by closed triangles.**

At Nilambur, where there were extensive plantations, reinfestation of the same plantation was found in some places, viz., Kariem-Muriem, Karulai and Aravallikkavu. At Kariem-Muriem very young larvae were present on 21 May on trees which had begun to reflush after a previous defoliation in the last week of April. Field notes showed that there was yet another previous infestation in the first to second week of April, confined to some patches of this area. At Aravallikkavu, a large population of small larvae was present on tress which had been previously defoliated and which had by then developed a new pair of leaves just reaching one quarter of the full size. It was evident that these larvae would not be able to complete the development on the available foliage. The quick succession of a new generation of larvae indicated that they did not represent the progeny of the previous generation in the same plantation.

In addition to plantations, over a distance of about 100 km along the survey route there were isolated teak trees, forming a more or less continuous chain, particularly between Nilambur and Parambikulam via Mannarghad. These trees were not attacked, except at one place about 20 km north of Sultan's Battery.

In a natural forest near Mavinhalla, where teak was prevalent, most trees were free of infestation. But at one location, about 10 trees within a radius of about 50 m were affected. A few trees in the centre showed heavy defoliation but in surrounding trees most damage was confined to the top. About 50 m away from this patch, another tree was attacked, but only the top leaves were damaged, and the surrounding trees were free of infestation. A larger patch of defoliation within a natural forest stand was also noticed at Anakkad, near Kushalnagar in Karnataka.

4.1.2.5. Miscellaneous observations

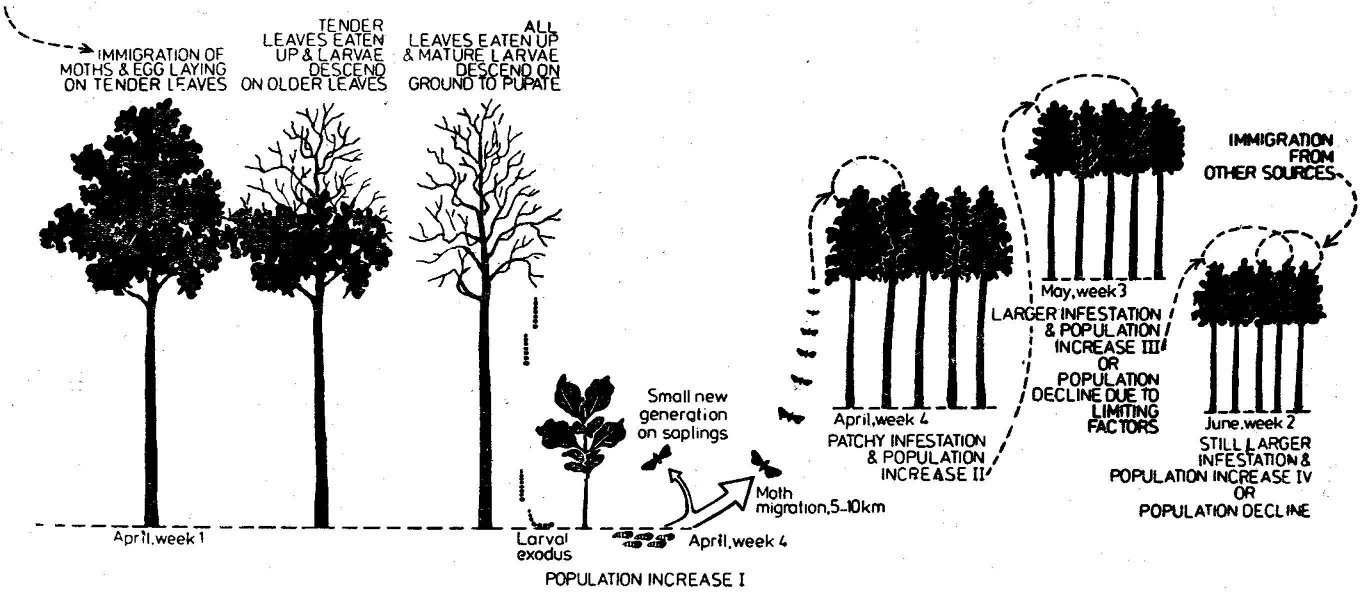
We maintained field notes on insect infestation of teak in different parts of Kerala whenever field trips were made in connection with various other investigations. Perusal of these field notes of several years revealed that small numbers of active larvae have been observed at many places during the 'off-season'. These included, other than those already noted, records of larvae in the months of October (12 to 19 Oct. 1978 and 21 Oct. 1980 at Nilambur; 21 Oct 1980 at Peechi), November (5 Nov. 1980 at Nilambur; 24 Nov. 1982 at Thenmala; 11 Nov. 1983 at Peechi; 16 Nov. 1984 at Konni), December (13 Dec. 1976 and 14 Dec. 1982 at Nilambur; 11 Dec. 1980 at Peechi) and March (15 March 1984 at Kulathupuzha). Of these, the one in November 1983 at Thenmala was a fairly heavy incidence confined to a group of nursery beds and adjacent 2- to 3-yr-old saplings. The one in March 1984 at Kulathupuzha was a typical patchy infestation on tree tops. Similar concentration of young larvae on the top canopy of trees was also seen at Nilambur on some occasions during May-June. All others were sightings of small numbers of larvae on young plantations.

4.1.2.6. Discussion

Several characteristics of infestation revealed by this study indicate migration of the moths. These include (1) the sudden, heavy infestation of trees, (2) concentration of egg-laying on the top canopy of trees to the exclusion of saplings at ground level during the early part of the year, (3) failure of the large population of newly emerged moths to give rise to a significant new generation of larvae in the same locality, (4) the distribution of infestation in discrete patches, well separated in space during the early build-up phase, and (5) the varying intervals between successive defoliation peaks, which show that the peaks represent, not the generation peaks, but waves of moth immigration (except during the later part of the year when overlapping generarions occurred, as in 1979). Such overwhelming evidence in favour of migration has not been reported earlier, although the recent reports of Vaishampayan and Bahadur (1983) and Vaishampayan et *al.* (1984) suggested the possibility of migration.

The migration of moths appears to begin in April-May and end by June-July in most years, i.e., it is mostly confined to the two to three months period preceding the onset of heavy monsoon rains. In some years a further wave of migration seems to have occurred in August-September since sudden defoliation without continuous previous generations was noticed. For example, at Nilambur such a wave of defoliation occurred in 1979 in Block I, in 1980 in an area outside the study plots and in 1982, again in Block I (though the peak was very small). Beeson (1928) also reported occurrence of a wave of heavy defoliation in September-October at Nilambur. There is no evidence of migration after this period. The flat peaks of defoliation in October and November 1979 in the Nilambur study plots (Fig. 9) show the existence of a resident population of the insect representing overlapping generations. The sightings of larvae, albeit in small numbers, in October, November, December, January and March at Peechi and other places also indicate the presence of a resident population of the insect following the migratory phase. This is not reflected in the defoliation curves for most years, apparently because the populations were *too* small to cause measurable defoliation. A residual, nonmigratory population also existed during the period in which migration occurred, as clearly shown by the observations at Peechi. Such a residual population was also seen at Konni following heavy defoliation. They confined their feeding chiefly to the understorey.

Based on absolute absence of moths in the light trap for a period of 6 months from January to June at Jabalpur, Vaishampayan and Bahadur (1983) concluded that ***H. puera*** does not breed in the same area on any host plant during this season, which necessitated postulation of either migration to some other areas for off-season breeding or occurrence of diapause in the pupal or adult stage. Our observations show that the insect is active throughout the year although the population may be very low and undetectable when the search is confined to a small area. In the absence of other information, a study of Fig. 9 would have also led to a similar conclusion, that the insect is totally absent for a long period from July to next April-May in most years and at least for a period of about 4 months from December through March in all years. But pooling the observations for all places and all years, it may be seen that the insect was recorded throughout the year, except in February. The rarity of sightings during December to March, the normal leafless



POPULATION BUILD UP OF HYBLAEA PUERA
IN TEAK PLANTATIONS
(Partly hypothetical)

Fig. 15, Schematic diagram showing the proposed model of population dynamics of *Hyblaea puera* in teak plantations.

period of teak, is understandable since most observations were made in plantations. Although teak is deciduous, observations have shown that in natural forest there is enough phenological variation among individual trees within an area and among populations of trees located in different areas within a larger geographical region that tender leaves are available continuously, though not at the same place, to sustain a residual population of larvae. ***H. puera*** is also known to survive on many alternate hosts (Beeson, 1941). In the light trap study of Vaishampayan and Bahadur (1983) the trap was located about 20 to 30 km away from the teak forest. The possibility of a residual population not being picked up due to the long distance and the lack of responsiveness of the moths at this season (the moths may travel such long distances only during the migratory phase) cannot be ruled out.

The occurrence of a residual population during the off-season can be taken as evidence against diapause, although it is theoretically possible to argue that the entire population need not undergo diapause. But as will be shown later, the comparative scarcity of the insect during the 'off-season' can be explained otherwise, without postulating diapause. Other evidences against diapause are the temporal and spatial discontinuity of the first major infestation. If the insects have been in diapause, within a locality; they should become active at about the same time and be distributed more uniformly. These considerations clearly rule out diapause.

While the occurrence of migration is a certainty, the details remain to be worked out. All major defoliations in India have been noticed between April and September and there is no record of large-scale off-season breeding anywhere though this was suspected by Vaishampayan and Bahadur (1983). If the existence of a residual population during the off-season as suggested by the present study is accepted, it is no longer necessary to look for places where large-scale off-season breeding may occur. In the light of our present understanding, we propose a tentative model of the population dynamics of ***H. puera*** (Fig. 15). According to this model, during the off-season, a residual, active population of the insect exists on host trees which posses tender foliage suitable for ovi position and survival of the early larval instars. Such a population is more likely to occur in natural forests because of continuous availability of tender foliage due to natural phenological variation of teak, and occurrence of alternate hosts. With the onset of general flushing during February-March, the population starts increasing, generation by generation, as more and more tender foliage becomes available. When the population density reaches a critical level, the migratory behaviour is triggered. Larval crowding leading to exodus movement of full grown larvae to pupation sites probably plays an important role in initiating the migratory behaviour. The subsequent steps, which lead to a large increase in the population are shown in Fig. 15

The population build-up may proceed in the general direction of early flushing to late flushing areas. A south to north trend in the progress of infestation is indicated by our limited spatial distribution study. Heavy defoliation of small groups of isolated teak trees inside natural forests have been noticed prior to occurrence of large-scale defoliation in plantations. Such early build-ups which may start in March or so, with the beginning of general flushing may usually escape attention. What usually catches the eye are comparatively larger infestations in plantations, beginning in April-May. Vaishampayan an Bahadur (1983) were able to trap large numbers of moths at least 20-30 km away from teak forests, which suggests that the moths are able to migrate at least 20 km, and probably more. Recent studies on the armyworm moth, ***Spodoptera exempta*** in Kenya using radar and infra-red optical techniques (Riley, *et al.*, 1983) indicate that these moths climbed to altitudes of several hundreds of meters above ground level and covered at least 20 km downwind during the first half of the night. Studies by Rose *et al.* (1983) on the same species indicated that the moths could migrate at least 140 km downwind probably in one night. ***H. puera*** also probably has the potential to migrate long distances. But, based on our observations on the distribution of attack, which indicated a minimum distance of 4 to 5 km between old and new infestation sites during the build-up phase, we postulate that the moths normally migrate short distances of 5 to 10 km when suitable host trees are available within this distance. There is not enough evidence to support this hypothesis because even long-distance migration in small groups can lead to the observed distribution pattern. But normally, in long-distance migration, one may expect bigger swarms which may infest a larger area. It appears that the moths are capable of migrating long distances, but the flight is cut short when plantations with tender foliage are available, probably because of the arrestant effect of a characteristic olfactory profile of newly flushed teak plantations. However, a minimum distance of 4 to 5 km may be covered before they settle.

The increase of the insect population in geometric progression as a result of continuous generations which exploit newer and newer territory by gypsy-like migrations, is curtailed by several factors. During June-July, the heavy monsoon with spells of continuous rainfall may adversely affect the survival of the insects either directly or indirectly. The most important limiting factors, however, are (1) leaf maturity, (2) natural enemies, and (3) density-dependent food depletion. The moths lay eggs only on tender leaves and apparently the early instars are able to survive only on them. In Kerala, most trees have fully mature leaves by July and they are no longer suitable for sustaining a large population of larvae, particularly the early instars. A number of predators and parasites are known to attack ***H. puera*** larvae (Chatterjee and Misra, 1984). Some of them have been found very effective; for example, on one occasion, a large, epidemic-level population of ***H. puera*** larvae at Pullamkandam near Peechi was found devastated by parasites. When examined on 9 June 1977, almost every larva, mostly middle-aged, was dead or moribund and the few active ones had fresh eggs of a tachinid parasite on the body surface. A batch of 200 larvae collected and kept in small groups with food. yielded only one adult moth and a dead pupa; the remaining larvae yielded unidentified hymenopteran parasites and a tachinid parasite which was later identified as ***Palexorista solennis.*** Recent investigations (Sudheendrakumar, 1985) have revealed that the early generations are comparatively free of parasites but later generations suffer heavy mortality due to hymenopteran and tachinid parasites. Dead larvae showing typical symptoms of bacterial disease have also been found occasionally. and in the laboratory bacterial disease is a major problem in rearing the insect. Viral diseases are also suspected in the field. During epidemics heavy predation by birds also contribute to mortality. The third major limiting factor, density-dependent food depletion, operates when a previously defoliated plantation is re-infested within a short period. Examples of this situation may be more prevalent in large contiguous plantations, as observed at Aravallikkavu and other places at Nilambur. Due to the combined action of these mortality factors, the population crashes down and returns to the residual level, usually by July and sometimes after another peak in August-September, in Kerala. This cycle of ups and downs is repeated every year.

The gypsy-like, short-range migration confers two major advantages to the insect: (1) In the same way as continuous cultivation in the same area would deplete the fertility of the soil, continuous generations of the insect in the same area would lead to depletion of the food resource. Movement facilitates discovery and utilization of areas with new flush of leaves and the benefit is comparable to that arising from shifting cultivation. The sites of earlier infestation can be utilized again after the trees have put forth a new flush of leaves. (2) Migration is a method of escape from larval parasitism since the progenies of the early generations move away from the parasite population built up during their development. But with larger spread of the population, the parasites also catch up. The parasites appear to be the most dominant limiting factor in the population dynamics of ***H. puera.***

As is obvious, some steps of the above model of population dynamics need confirmation. If confirmed, simple methods can be employed to control the epidemics of this insect which has been found to cause serious loss of increment (Section 4.3). In large plantation areas it is possible to locate the sites of initial build-up by surveilance during critical periods. Control operations can be carried out in the affected patches to prevent emergence of the moth population and its subsequent spread to other areas. Application of a biocide or chemical insecticide over the ground on which the mature larvae decend to papate may prove useful. This will be much simpler, economical and environmentally less hazardous than aerial application of insecticides that has been tested in the past against ***H. puera.***

4.13. *Eutectona machaeralis*

The fortnightly observations in the four untreated experimental plots at Nilambur yielded information on the seasonal incidence of ***E. machaeralis*** also. The methods of study were the same as described earlier.

Figs. 16 and 17 show the ***E. machaeralis*** larva and the typical damage caused.

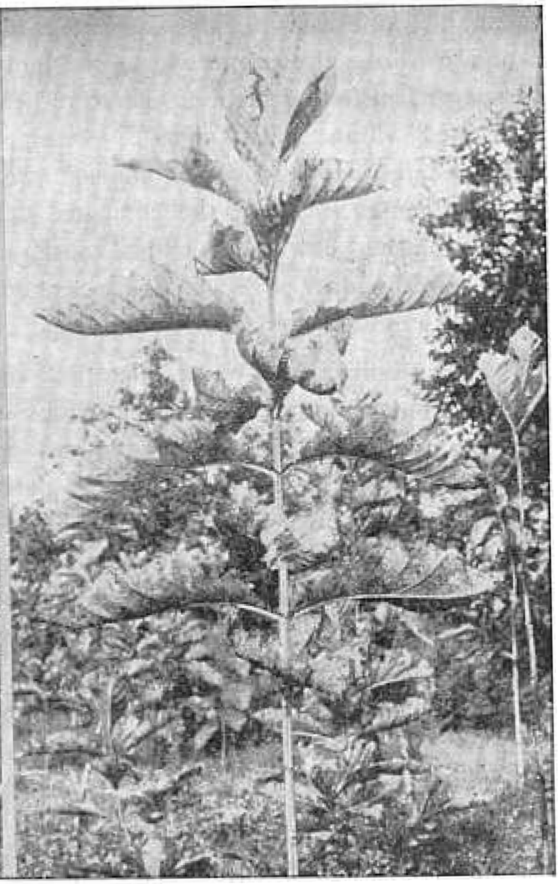


Fig. 16. Larva of Eutectona rnachaeralis.

Fig. 17. Teak saplings skeletonised by *E. rnachaeralis.* The leaves, though intact, have no **green matter and are drying up. Leaf shedding has already taken place in the saplings on the right.**

During the 5-year period from 1978 to 1982* no measurable defoliation occurred, except in 1980 and 1981. either in the experimental plots or in adjacent areas at Nilambur. The seasonal distribution of infestation in the growth years, 1980 and 1981 is shown in Fig. 18. It may be seen that measurable defoliation occurred only in November, December or January. In 1980, about 35% defoliation occurred in most plots, and about 14%, in one plot. In 1981, almost total (98%) defoliation occurred in both the plots of Block 11, while in the two plots of Block I, the intensity of defoliation was low (14 to 39%). In addition, in Block I the defoliation occurred at least a month later than in Block 11. Although measurable defoliation occurred only in some years as noted above, small numbers of larvae were present at other times, particularly in May and June and October to January. They were not seen from July to September and February to April in the experimental plots.

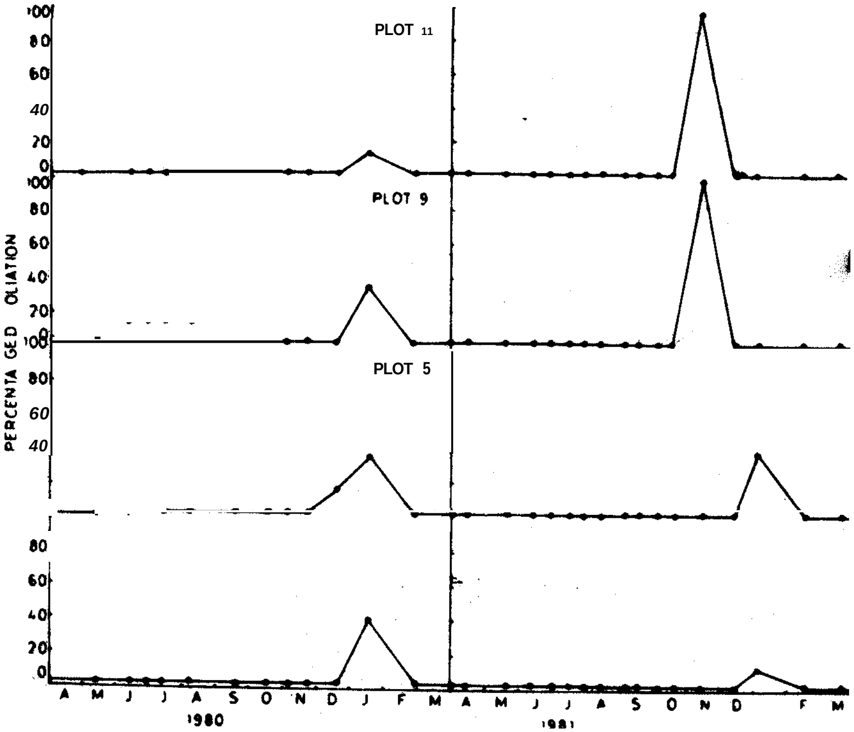


Fig. 18. Seasonal incidence of defoliation caused by *Eutectona macheralis* in the experimental plots at Nilambur.

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* **For practical purposes, the year 1978 for which data were gathered starting from June/July can be included since usually *E. machaeralis* was active only during the latter part of the year; the year 1982 is also included because unscheduled observations were made upto March 1983 in spite of termination of regular scoring in December 1982.**

General observations elsewhere have also shown that,November to December is the period when the larvae are most prevalent and visible defoliation occurs; this is followed by May-June when small number of larvae are seen but defoliation is not noticeable. In general observations, at least a few larvae have been noticed in all months except February-March and July-August, but no intensive search was made.

A wave of vety heavy defoliation by ***E. machaeralis*** was noticed in November 1976, before systematic observations started. During this period, epidemics occurred in most teak plantations throughout Kerala. At Nilambur, peak defoliation occurred around 10-15 November. Such heavy and wide-spread build-up of ***E. machaeralis*** has not been noticed in Kerala for the last 8 years since November 1976. During that epidemic, the extensive plantations at Nilambur, both young and old, presented the typical spectacle of an epidemic — theplantation being criss-crossed by larvae hanging on silken threads, continuous fall of the faecal pellets creating the sound of a mild drizzle of rain and a carpet of pellets on the floor, a variety of birds feeding on the larvae on tree tops, and brownish, skeletonized leaves holding on to the trees precariously, only to fall to the ground when a mild wind blows. Slight differences were found in the intensity of defoliation in adjacent areas and some patches temporarily escaped defoliation, but in general, the infestation was heavy and widespread.

The present study has shown that defoliation by ***E. macheralis*** is not.a regular, annual phenomenon in teak plantations in Kerala. Although localized near-total defoliation occurred at ‘times during the course of 8 years from 1976 to 1984, a widespread epidemic occurred only once, in November’ 1976. In most years, measurable defoliation either did not occur, or did not lead to loss of more than about 40% of the foliage, once. In adition, generally, the defoliation occurred only towards the end of the growing season when the leaves were old, These observations suggest that defoliation by ***E. macheralis*** is unlikely to lead to economic damage. This question is examined further in section 4.3 in the light of increment data.

Our findings on the seasonal abundance of ***E. machaeralis*** is in general agreement with previous information available for southern India (Beeson, 1941; Khan and Chatterjee 1944; Patil and Thontadarya, 1983) which indicate epidemic level infestations towards the ‘end of the growing season and low level infestations in May-June (Section 2.1.2). It is interesting to note that while about 14 generations per year have been found theoretically possible at Nilambur (Beeson, 1941), the insect was not abundant throughout the year. Migration as well, as “partial diapause” have been suggested (B.V.Patil, personal communication) to account for the periodic peaks of infestation. Our data are insufficient to support any of these postulates. Much of the data of Patil and Thontadarya which suggest “partial diapause” as well as migration based on the study at Dharwad are still not availableto permit critical evaluation. Our data for 1981, showing about a month’s difference in the infestation time between Blocks I and 11, suggest that "diapause" is unlikely to explain the preceding absence of infestation. If diapause occurred, its termination could be expected to occur simultaneously in the two blocks separated only by a distance of 4 km, leading to simultaneous infestation. These cons-iderations tend to suggest migration as the determinant of variability in the occurrence of infestation in time and space. Further investigations are necessary to explain the intermittent ‘absence’ of the insect in teak plantations within a year, high population levels towards the end of the growth, season and the apparently erratic occurrence of epidemics over the years.

4.2. PHENOLOGY OF TEAK AND ANNUAL GROWTH CURVE

Very little information is available on the seasonal progress of growth in teak. Champion (1934a) studied the height growth of teak saplings at Dehra Dun (where there is a, distinct winter season) and found that height increment followed a single curve with single maximum, growth commencing on 26 May and ceasing on 22. September No published reports could be found on the seasonal progress of diameter or basal area growth. Phenological observations are, however, available. Troup (1921) recorded that in general, new leaves appear from April to June according to locality and season, and they remain until March or even later; in dry situations and seasons the leaves fall from November to January. He also stated that as a rule, the trees are leafless throughout the greater part of the hot season.

At Dehra Dun, over a 20-year period, new flushing occurred as early as 25 April or as late as 2 June and leaf fall occurred in late March to mid-May, (Krishnaswamy and Mathuda, 1954). Although Dehra Dun is outside the natural teak zone, these observations indicate’ that about a month’s variation in the time of flushing and leaf fall may occur, depending upon yearly climatic variation.. Phenological variation may also occur due to provenance differences; Kaushik (1956) observed that the so-called ‘Teli’ variety of teak in the North Canara Division of Karnataka flushed at least one month in advance of the normal variety. In the present study, site-specific information on the phenology and seasonal progress of growth was obtained .

4.2.1. Phenology of leaves

In addition to fortnightly observations on flushing as described in Section 3.1.4.2., leaf fall was studied by setting up litter traps in two plots (plot Nos. 2 and 5 in Block I) which were fully protected from insect damage. The trap consisted of bamboo baskets, 80 cm in diameter and 25 cm in depth. Twenty baskets were used per plot covering about 2.5% of the area. The litter was collected at monthly intervals, dried in an oven at 80°C for 24 h and weighed. As far as possible, the collections were made on the 30th of each month so as to estimate the monthly litter fall. When the collection dates differed, monthly figures were estimated using the rates for the period of measurement.

The time of flushing showed some variation between trees, apparently due to genetic differences, and between years, apparently due to variations in weather. In general, flushing began in late March and the trees were in full flush by late April (Fig. 19). New leaves continued to appear for many weeks and the trees had a high Proportion of tender foliage during May and June. Normal leaf fall began in

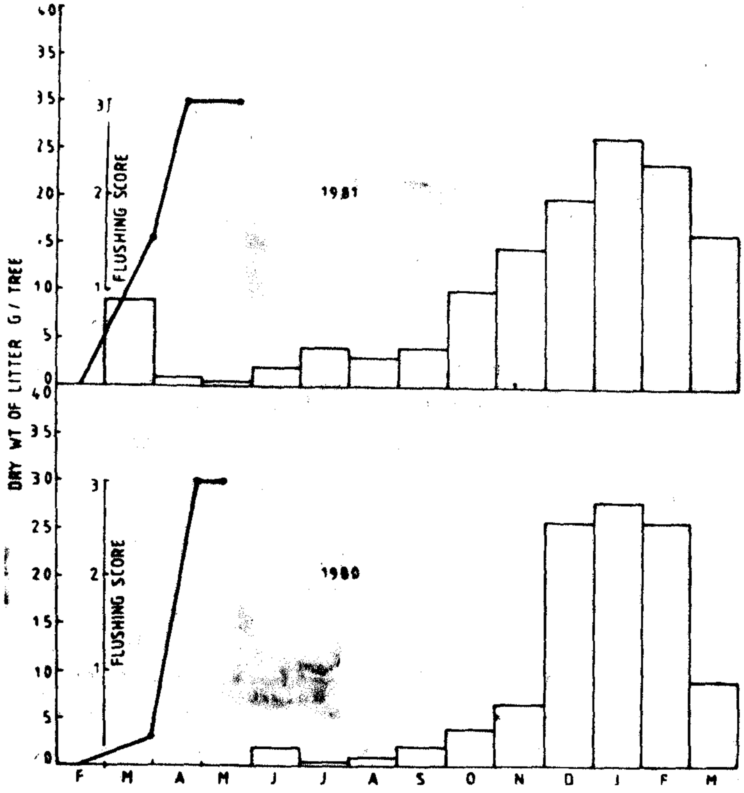

Fig. 19. The bars represent litter fall in plots protected from defoliators (mean of Plots 2 and 5). The line shows the flushing score at the beginning of the growth year.

October, reached a peak in January and was nearly completed in March (Fig 19). Thus the period of absolute leaflessness was very short, although heavy leaf fall continued over a period of 3 months from December to February. Our data do not agree with the general statement of Troup (1921) that as a rule, the trees are leafless throughout the greater part of the hot season; this may perhaps apply only to the dry deciduous zone. Phenological differences due to age also needs to be studied.

4. *2.* 2. Annual growth curve

To study the seasonal growth pattern, the BA increment in all the four fully protected plots (2,5,10,12) was determined from GBH measurements made at monthly intervals for about three growth seasons (June 1979 to December 1981). Measurements were usually made on the 30th of the moth, but when the measurement dates differred, monthly figures were estimated from the rates for the actual period of measurement.

The mean basal area increment per tree in each of the fully protected plots during the years 1980 and 1981 and part of 1979 is shown in Fig. 20. In general, growth began in April and ended by December. As expected, the growth curve was bell-shaped; the rate of growth being comparatively high in June, July, August and September, during which period the BA increment amounted to about 4 cm^2 per tree per month. The comparatively smaller increment in June 1980 was probably due to the inadvertant exposure of the ‘protected’ plots to defoliation (Section 3. 1. 5). The small variations between years is probably due to differences in weather conditions. In general, growth appeared to be continuous, but a small secondary peak occurred in November 1979 and December 1980. The significance of the sharp depression in BA increment noticed in plot No. 2 after the first peak both in 1980 and 1981 (Fig. 20) is not understood. A correspanding but much smaller depression was noticed in some of the other plots also. Further studies are required to understand whether these trends are real and indicate discontinuous or cyclic growth. In a study of the seasonal progress of height growth in a few tree species Champion (1934 a) found that in teak the height increment curve (based on a few saplings studied at Dehra Dun) had a single maximum but some species had secondary maxima, and some had more complex curves with two or more primary maxima. No reports are available on the seasonal progress of basal area growth in teak.

The purpose of this study was to gather general information on the growth pattern of teak, in order to fully appreciate the impact of defoliation caused by insects during various months. From the phenological data, it is obvious that defoliations during May, June and July caused by ***H. puera*** (Section 4.1.2) is likely to have serious impact on growth, whereas defoliations in November, December and January caused by ***E. machaeralis*** (Section 4.1 3.) will be less damaging since the leaves are senescent and leaf fall has already begun (Fig. 19). These expectations were, in fact, confirmed by the results (see Section 4. 3).

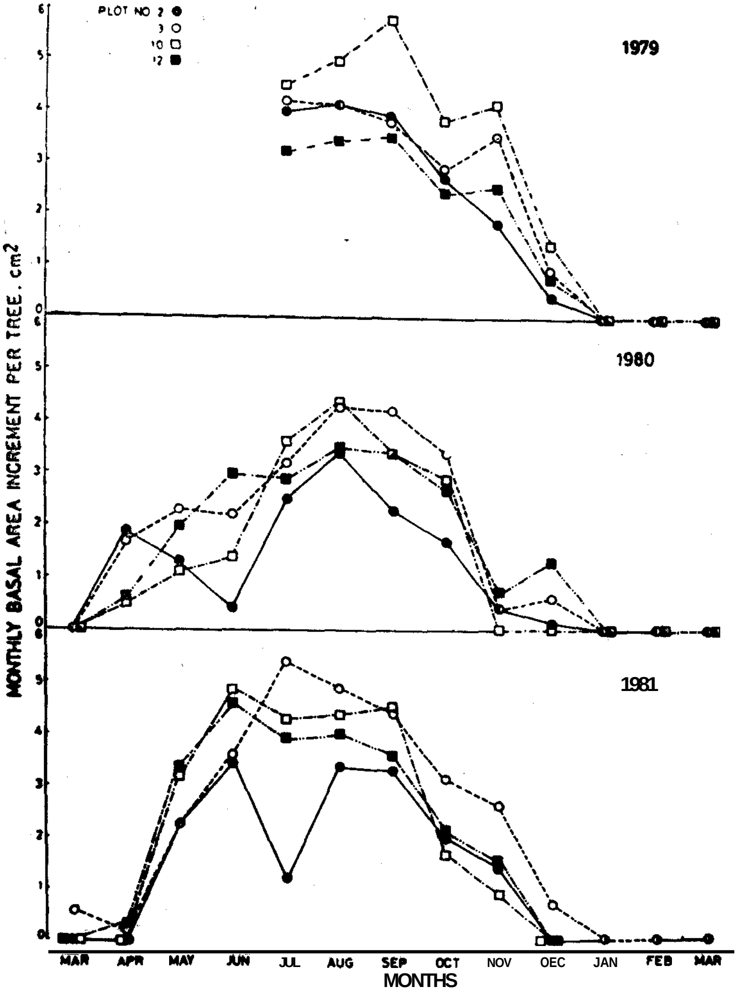

Fig. 20. Rate of basal area increment in the fully protected experimental plots of teak in the years 1979 to 1981.

The present study also provides basic data on the phenology of leaves and the normal seasonal growth pattern of teak at Nilambur. Such ecological data have not been reported earlier and are usually difficult to obtain because the results will be vitiated by the almost regular occurrence of insect-caused defoliation. The present data from 6- to 7-yr-old plantations will be generally applicable to younger plantations at Nilambur. General observations indicated that leaf fall occurs earlier at Peechi,

4.3. EFFECT OF DEFOLIATION ON GROWTH OF TEAK: LOSS OF INCREMENT

Estimation of the suspected loss of increment due to defoliation was the chief objective of this project. The general experimental design and methods were described in section 3. To recapitulate briefly, three sets of 4 plots, each containing about 50 trees (4-yr-old) were subjected to one of three treatments—full protection (Tl), partial protection (T2) or no protection (T3). Their growth performance was assessed and compared at the end of a 5-year experimental period. The primary measurements made were the GBH and height, from which the basal area and volume of timber were estimated. Basal area (BA) refers to the area of the cross-section of a stem at breast height. It is better than girth or diameter for comparison of growth since the quantity of increment depends not on the increment of girth or diameter alone, but also on the diameter of the cross-section of the stem on which it accrues. Empirically fitted mathematical functions were used to estimate the volume. The final volume of about half the number of trees in each plot was available from measurements made on felled trees and these were used directly instead of predicted values.

Comparison of treatment effects was made separately for height, BA and volume. The increment in height, BA and volume of each experimental tree during the 5-year period was determined by subtracting the final value from the initial. The mean increments among plots receiving different treatments were compared statistically to determine the significance of the differences. The increment put forth by a tree, say in BA or volume, may depend largely on the initial measurements of the tree. In addition, the presence or absence of neighbouring trees may influence the increment. To take these influences into account, the data were subjected to analysis of covariance with these two factors, e., initial measurement and number of neighbours, as ancillary variables. The analysis was carried out using a computer, by the matrix approach (Searle, 1971). Since the underlying model had better explanatory power in the log scale the data were transformed to log scale before analysis.

4.3.1. Parameters of the experimental plots before starting the experiment

Table 5 shows the basic details of the experimental plots before the start of experiment. The number of experimental trees per plot ranged from 22 to 47 immediately after the 4th year thinning. Each plot was planted originally with 100 trees and theoretically about 50 trees were to be expected after the first thinning. The differences were due to tree mortality attributable to various reasons and mechanical felling of some rows of trees irrespective of the presence or absence of trees in the adjacent rows. A few trees in some plots that were damaged by elephants were

Table 5. Parameters of the experimental plots at the start of experiment

Block No.	Sl. No.	No. of trees before first thinning	Mean GBH ± S.D. (cm)	Mean height ± S.D. (m)	No. of trees after thinning	Treat-ment	No. of trees at end of expt.
I	1	78	22.9 ± 7.2	7.9 ± 2.1	37	T3	28
	2	76	21.9 ± 6.4	8.0 ± 2.0	36	T1	33
	3	57	23.7 ± 7.0	8.4 ± 2.3	29	T1	21
	4	57	22.1 ± 5.8	7.3 ± 1.9	25	T2	21
	5	62	24.1 ± 6.6	8.6 + 1.8	30	T3	27
	6	79	18.2 ± 5.2	5.9 ± 1.4	40	T2	33
I1	7	69	22.7 ± 4.3	8.2 ± 1.2	23	T2	21
	8	91	21.5 ± 4.4	7.6 ± 1.7	47	T2	44
	9	56	22.1 ± 6.2	7.4 ± 1.7	28	T3	22
	10	68	21.8 ± 5.1	7.5 ± 1.6	22	TI	20
	11	72	22.3 ± 5.7	8.4 ± 1.8	38	T3	35
	12	54	22.2 ± 5.8	8.3 ± 2.0	28	T1	26

treated but not observed. After the first thinning, each tree should theoretically have four neighbouring trees located at the original diagonal distance between trees (2.8 m); the number of neighbours of each tree was determined and used in the analysis.

4. 3. 2. Increment during the experimental period

Table *6* shows the mean measurements of the experimental trees at the beginning and end of the experiment after 5 years of growth. In unprotected plots the GBH increased from about 24 cm to 38cm, and the height from about 8.7 m to 11.1 m. The basal area per tree increased from about 50 cm^2 to 117 cm^2 and the volume per tree from about 12 x 103 to 44 x 10^3 cm^3 These raw measurements indicate a higher increment of GBH and height in protected trees which result in increased BA and volume.

Increment in height, BA and volume of the experimental trees under each treatment, derived from Table 6, are shown in Table 7, which show again that both treatments caused an increase in the height, BA, and volume. Adjusted mean increments are given in Table 8. Statistical significance of the differences in increment among the three sets of plots are examined below.

4. 3. 3. Significance of the differences in increment

4. 3. 3. 1. Height

The unadjusted mean height increment per tree ranged from about 1.3 to 4.8m in plots under different treatments (Table 7). The treatment averages were about 2.5 m for untreated control, 4.4 m for partial protection and 4.1m for full protection. Analysis of covariance (Table 9a) showed that the differences in increment were mainly attributable to the highly significant ($P < 0.01$) influences of (1) treatments, (2) blocks and (3) block x treatment interaction. Between plots (within block) variation also contributed to differences in increment although the level of significance was lower ($P < 0.05$). There was also a highly significant ($P < 0.01$) interaction between blocks and treatments.

Pair-wise comparisons between treatments after eliminating the influence of other factors showed that both T1 and T2 (full and partial protection) differred significantly ($P < 0.01$) from T3 (untreated control), but not between themselves (Table 9b). The treatment means adjusted by regression for variation in the initial height and number of neighbours (Table 8) show that the height increment in the treated plots (average of T1 and T2) was about 101% higher than in the untreated plots.

Table 6. Mean measurements of experimental trees before and after the treatments

Treat-ment	No, of Trees	GBH (cm)		Mean height (m)		Mean basal area per tree (cm^2)		Mean volume per tree (cm 3 x 10^3)	
		Initial	Final	Initial	Fina!	Initial	Final	Initial	Final
Untreated control (T 3)	28	25.4	36.8	8.58	10.40	53.5	113.0	12.58	38.18
	27	25.4	36.9	9.13	10.54	54.1	113.5	13.62	42.74
	22	24.4	39.2	8.05	11.14	49.9	129.5	11.77	48.16
	35	22.4	37.5	8.48	12.14	41.8	113.1	10.51	46.77
Mean	28	24.4	37.6	8.66	11.06	49.8	117.3	12.12	43.96
Partial protection (T 2)	21	23.6	45.5	7.71	12.51	46.1	169.8	10.32	67.23
	33	18.4	35.4	6.17	9.98	28.7	105.8	5.46	34.47
	21	22.0	45.3	8.16	12.87	40.4	170.1	9.92	79.20
	44	21.2	36.6	7.79	12.11	36.8	113.7	8.50	46.11
Mean	30	21.3	40.7	7.46	11.87	38.0	139.9	8.60	56.75
Full protection (T 1)	33	23.5	39.4	8.65	12.03	45.8	125.3	11.08	47.10
	21	24.5	44.2	8.90	13.06	50.6	159.2	12.61	65.77
	20	21.7	40.6	7.86	12.06	39.5	135.4	9.54	58.43
	26	23.5	42.0	8.86	13.34	44.9	147.2	12.19	65.98
Mean	25	23.3	41.6	8.57	12.62	45.2	141.8	11.36	59.32

Under each treatment the first two rows represent Block I and the next two represent Block 11.

Table 7. Unadjusted mean increments of height, basal area and volume per tree under different treatments

Treatment	Height (m)	BA (cm^2)	Volume ($cm^3 \times 10^3$)
Untreated control	1.82	59.5	25.60
	1.29	59.4	29.I2
(T3)	3.09	'19.2	36.38
	3.66	71.3	36.26
Mean	2.47	67.4	31.84
Partial protection	4.80	123.7	56.70
	3.80	77.1	29.01
(T2)	4.71	129.7	69.28
	4.33	76.9	37.61
Mean	4.41	101.9	48.15
Full protection	3.38	79.4	36.02
	4.16	108.5	53.16
(TI)	4.20	95.9	48.89
	4.48	102.3	53.79
Mean	4.06	96.5	47.97

Table 8. Adjusted mean increments of height, basal area and volume per tree under different treatments

Treatment		Height increment/tree (m)	BA increment/tree (cm^2)	Volume increment ($cm^3 \times 10^3$)
'Control	(T3)	1.97^{a}	54.9^{a}	23.2^{a}
Partial protection	(T2)	4.07^{b}	97.7^{b}	45.4^{b}
Full protection	(T1)	3.83^{b}	83.1^{b}	37.9^{b}

Under each colum, figures superscribed by the same letter do not differ significantly; those superscribed by different letters differ significantly ($P<0.01$).

4. 3. 3. 2. Basal area

The unadjusted mean basal area increment per tree ranged from about 59 to 130 cm^2 in plots under different treatments (Table 7). The treatment averages were about 67 cm^2 for untreated control, 102 cm^2 for partial protection and 97 cm^2 for full protection. Analysis of covariance (Table 10 a) showed that the differences in increment were mainly attributable to the highly significant ($P < 0.01$) influence of (1) treatments, (2) initial BA, and (3) No. of neighbours. The blocks also influenced the increment at a lower level of significance ($P < 0.05$). There was no interaction between blocks and treatments.

Pair-wise comparisons between treatments after eliminating the influence of other factors showed that both T1 and T2 (full and partial protection) differed significantly ($P < 0.01$) from T3 (untreated control) but not between themselves (Table 10b). The treatment means ajusted by regression for variation in the initial BA and number of neighbours (Table 8) show that the BA increment in the treated plots (average of T1 and T2) was about 65% higher than in the untreated plots.

4. 3. 3. 3. Volume

The unadjusted mean volume increment per tree ranged from about 26×10^3 to 69 x 103 cm3(Table 7). The treatment averages were about 32×10^3 cm^3 for untreated control and 48×10^3 cm^3 for both partial protection and full protection. Analysis of covariance (Table 11a) showed that the differences in increment were mainly attributable to the highly significant ($P < 0.0l$) influence of (1) treatments, (2) initial volume and (3) number of neighbours. Differences in volume increment were also attributable, at a lower level of significance ($P < 0.05$), to (1) variation between blocks, (2) variation between plots within blocks, and (3) interaction between blocks and treatments.

Pair-wise comparison between treatments after eliminating the influence of other factors showed that both T1 and T2 (full and partial protection) differed significantly ($P < 0.01$) from T3 (untreated control), but not between themselves (Table 11 b). The treatment means adjusted by regression for variation in the initial volume and number of neighbours (Table 8) show that the volume increment in the treated plots (average of T1 and T2) was about 80% higher than in the untreated plots.

4. 3. .4. Sources of variation

The statistical analysis has revealed the factors other than treatment which cause variation in the increment. Their levels of significance are shown in Table 12, assembled from Tables 9, 10 and 11. It is evident that while the BA and volume

Table 9a. Analysis of covariance table — height increment

Source of variation	**df.**	**Adj. SS**	**MS**	**F**
Blocks	1	13 73	13.73	39.33**
Treatment	2	38.82	16.41	47.03**
Regression on initial height	1	1.75	1.75	5.02^{ns}
Regression on no. of neighbours	1	1.07	1.07	3.06^{ns}
Block X Treatment (Interaction)	2	12 23	6.1 1	17.52**
Between plots, within block	6	2.09	0.35	2.15*
Between trees, within plots	317	51.42	0.16	

**Significant at $P<0.01$ *Significant at $P<0.05$ ns, not significant

Table 9b. Comparisons between treatments

Hypothesis	F
T1 = T3	64.10**
T2 = T3	73.81**
T1 c T2	0.51^{ns}

**Significant at $P<0.01$ * Significant at $P<0.05$ ns, not significant

Table 10a. Analysis of covariance table - Basal area increment

Source of Variation	df.	Adj. SS	MS	F
Blocks	1	2.74	2.74	10.54*
Treatments	2	18.28	9.14	35.19**
Regression on initial BA	I	26.58	26.58	102.36**
Regression on no. of nieghbours	1	5.67	5.67	21.85**
Block x Treatment (Interaction)	2	2.56	1.28	4.92^{ns}
Between plots, within block	6	1.56	0.26	2.24^{ns}
Between trees, within plots	317	36.75	0.12	

**Significant at P<0.01 *Significant at P<0.05 ns, not significant

Table l0b. Comparisons between treatments

Hypothesis	F
TI = T3	31.30**
T2 = T3	59.27**
TI = T2	4.15^{ns}

**Significant at P< 0.01 *Significant at P<0.05 ns, not significant

Table 11. Analysis of covariance table — volume increment

Source of Variation	df.	Adj **SS**	**MS**	**F**
Blocks	1	5.03	5.03	12.84*
Treatment	2	25.08	12.54	31.99**
Regression on intitial volume	1	61.73	61.73	157.47**
Regression on No. of neighbours	1	6.01	6.01	15.32**
Bolck xTreatment (Interaction)	2	7.08	3.54	9.03*
Between plots, within block	6	2.35	0.39	2.40*
Between trees, within plots	317	51.87	0.16	

**Significant at $P < 0.01$ *Significant at $P < 0.05$ ns, not significant

Table 11b. Comparisons between treatments

Hypothesis	F
T1 = T3	31.30**
T2 = T3	59.27**
T1 = T2	4.15^{ns}

*Significant at $P < 0.01$ *Significant at $P < 0.05$ ns, not significant increments were influenced by the initial values and the number of neighbours, the height increment was not. That height increment of trees is least affected by factors other than site quality is well known (Chathurvedi and Khanna, 1984) and the present finding is in agreement with this. Table 12 also points to the fact that there was significant difference between blocks, in the increment; the difference being more pronounced with respect to height increment for which there was also a highly significant interaction between blocks and treatments. To understand this further, adjusted values were derived for each block (Table 13). When gain in increment in the treated plots (T1 and T2 are combined since there was no significant difference between the two) is expressed as percentage gain over untreated controls of the same block (Table 14) it becomes evident that the gain in Block I was much higher than that in Block 11. While in Block I there was about 112% increment in volume over the control, in Block I1 this increment was only about 53%. This explains the significant block x treatment interaction brought out by the statistical analysis.

Table 12. Levels of significance of various sources of variation in height, basal area and volume

Source of variation	Height	BA	Volume
Treatment	**	**	**
Regression on initial value	ns	**	**
Regression on No. of the neighbours	ns	**	**
Blocks	**	*	*
Blocks X Treatment	**	ns	*
Between plots, within Block	*	ns	*

** Significant at P<0.01 * Significant at P<0.05 ns, not significant

Table 13. Adjusted mean increments of height, basal area and volume per tree in each block, under different treatments

Treatment	Height increment (m)		BA increment (cm^2)		Volume increment ($cm^3 \times 10^3$)	
	Block I	Block I1	Block I	Block 11	Block I	Block I1
Control (T3)	1.21	3.23	53.4	56.4	18.3	29.4
Partial protection (T2)	3.78	4.40	117.2	81.5	42.4	48.7
Full protection (TI)	3.59	4.09	94.8	72.9	35.0	41.0

Table 14. Mean gain in increment of treated plots (TI and T2) expressed as a percentage over the increment of the respective untreated control

Block	Height	Basal area	Volume
Block 1	204.5	98.5	111.5
Block II	31.4	36.9	52.6

4. 3. 5. Discussion

Although speculations in the past had indicated serious loss of increment due to defoliation, no proof has been obtained so far to confirm this under natural conditions. The present study demonstrates for the first time that in teak plantations, natural, insect-caused defoliation leads to significant loss of increment. We have also been able to quantify the loss in terms of volume of timber, for the first time.

There was no significant difference in increment between fully protected and partially protected trees. Full protection prevented damage by ***H. puera*** and ***E. machaeralis,*** while partial protection prevented damage by ***H. puera*** only. These results show that ***E. machaeralis*** had no impact on increment. This could be attributed to three reasons. (1) ***E. machaeralis,*** unlike ***H. puera,*** did not cause defoliation every year. During the 5-year period, measurable defoliation occurred only in two years (Section 4.1.3). (2) When defoliation occurred, its intensity was generally low, with less than 40% of the foliage being lost except on some occasions. (3) The defoliation occurred during the last part of the growth season when the rate of increment was very low (Section 4.2). Although we cannot conclude that defoliation by ***E. machaeralis*** will not cause any loss of increment, it is obvious that during the 5-year experimental period it had no significant impact. Based on the 5-year records of infestation (Section 4.1.3.) and the results of the experiment reported here, we may safely generalize that ***E. machaeralis*** is not a serious pest.

All the observed loss in increment is therefore attributable to ***H. puera***. As noted earlier (Table 14), greater loss (or greater gain due to protection) occurred in Block I. This was apparently due to the greater intensity of defoliation suffered by the untreated plots in Block I. A comparison of the defoliation curves between the two blocks (Fig. 9) shows this clearly, particularly in the years 1979 and 1981. When the defoliation percentage recorded at simultaneous intervals were added up for each block for the 4 years from 1979 to 1982, block I scored 1301 and Block 11,899. Apart from this difference, the number of times defoliation occurred per year and the interval between consecutive defoliations will influence the increment more profoundly.

Table 15 gives a summary of the quantification of loss. In this table, the increments for TI and T2 plots have been averaged (since there was no significant difference between the two), to arrive at the increment of protected plots. Since volume is the most important measure of increment, which is itself a function of BA and height, further discussions are based on volume.

Table **15.** Mean increment per tree during the 5-year experimental period

Treatment	Height (m)	BA (cm^2)	Volume (cm^3 × 10^3
Unprotected	1.97	54.9	23.2
Protected (mean of T1 and T2)	3.95	90.4	41.7

Over the experimental period of five years, the mean volume increment of an unprotected tree was 23.2 x 10^3 cm^3 while that of a protected tree was 41.7 X 10^3 cm^3. The difference in increment between the two which represents the quantified impact of defoliation can be expressed in two ways—as gain in increment due to protection or as loss in increment due to defoliation, depending on whether the increment of the unprotected tree or that of the protected tree is taken as the base value or reference point. Table 16 shows the impact expressed in both ways. The gain in volume due to protection amounted to 80% of the increment of unprotected trees. Expressed as loss due to defoliation. 44%/, of the potential increment (i.e. increment in the absence of defoliation) was lost due to defoliation.

Table 16. Effect of defoliation and protection from it on increment

Method of calculation	Height	BA	Volume
Gain in increment due to protection (see Table 15), expressed as a percentage of the increment in the untreated control	101	65	80
Loss in increment due to defoliation (see Table 15), expressed as a percentage of the increment in the protected trees	50	39	44

Estimates of loss ranging from 6.6 to 65% in volume were arrived at by different workers in the past, but as discussed in detail in Section 2.2, all these estimates involved one or more untenable assumptions. Out estimate of 44%; loss of the potential volume increment is in striking contrast to Beeson's (1941) estimate of 13% loss which somehow has come to be generally accepted and quoted repeatedly by various writers. At the other extreme, Champion (1934) placed the loss at 65%, based on artificial defoliation experiments on saplings. Ours is the first study in which loss in volume under natural conditions of defoliation has been quantified. Considering that ***H. puera*** causes 1 to 3 total or near-total defoliations per year (Section 4.1.2) during the peak growth season (Section 4.2), our estimate of 44% loss of the potential volume increment appears reasonable. This estimate is an average over the 5-year period of study. The exact gain or loss during an year will depend upon the intensity, frequency and time of occurrence of defoliation which may show spatial and temporal variation, but the present estimate should be generally applicable. although not for every year in every locality. It must also be noted that this estimate was obtained from 4 to 9-year-old plantations. Its applicability to older plantations and its economic significance will be discussed in Section 5.

4-4 EFFECT OF DEFOLIATION ON GROWTH OF TEAK: DIE-BACK OF LEADING SHOOT OF SAPLINGS

In young plantations of teak, defoliation may cause die-back of the leading shoot of saplings which is believed to lead to forking and, in rare cases, even mortality of saplings (Dawkins, 1921; Champion, 1934; Laurie and Griffith, 1942). Depreciation due to forking of the bole has been considered the most serious aspect of the damage (Champion, 1934b). Previous literature on this topic consists essentially of incidental observations which lack details and have been reviewed in Section 2.2. Dawkins (1921) reported that nearly all saplings in some 2- and 3-year-old plantations in Burma were affected. Khan and Chatterjee (1944) reported damage to 52% of saplings in a 3-year-old plantation at Tithimatty, Karnataka, India. In the present study, observations were made on the prevalence of leading shoot die back (LSD) in some plantations and its long-term impact on the tree form. In addition, some experiments were conducted to examine whether defoliation per se could cause die-back.

The experiments and observations reported in this Section were not made in the main study area and plots described in section 3. A separate subsection on Materials and Methods is therefore included below.

4.4.1. Materials and Methods

*4.4.1.1. **Occurrence of** LSD*

Although planned systematic observations were not made, between the years 1977 and 1982, several young plantations of teak in the Nilambur Division were kept under general surveilance to study the frequency of occurrence of die-back. The die-back was quite conspicuous when it occurred and no special effort was necessary to discover it.

4.4.1.2. Damage intensity

The extent of damage was studied in two plantations in which incidence was noticed in 1977, one at Pullamkandam in Trichur Forest Division and the other at Aravallikavu in Nilambur Forest Division. At Pullamkandam, situated about 10 km north-east of Trichur, the plantation was about three years old when the observations were made in January 1977. About 2.5% of the saplings in the 47 ha plantation raised at 2m x 2m spacing, were sampled. The whole area of the plantation was divided into 73 grids, 80m x 80m, in a map, the grids numbered sequentially and 8 grids chosen at random. The general location of these grids were identified at site and from each grid, a plot, 40m x 40m, was used for the survey (see Fig. 21.)

The saplings were about 5 to 8m tall (exact measurements were not made) and had an average girth of 16 cm at breast height (mean of 160 saplings representing 20 samples per plot). They were examined by bending the leading shoot using a pole fitted with a hook.

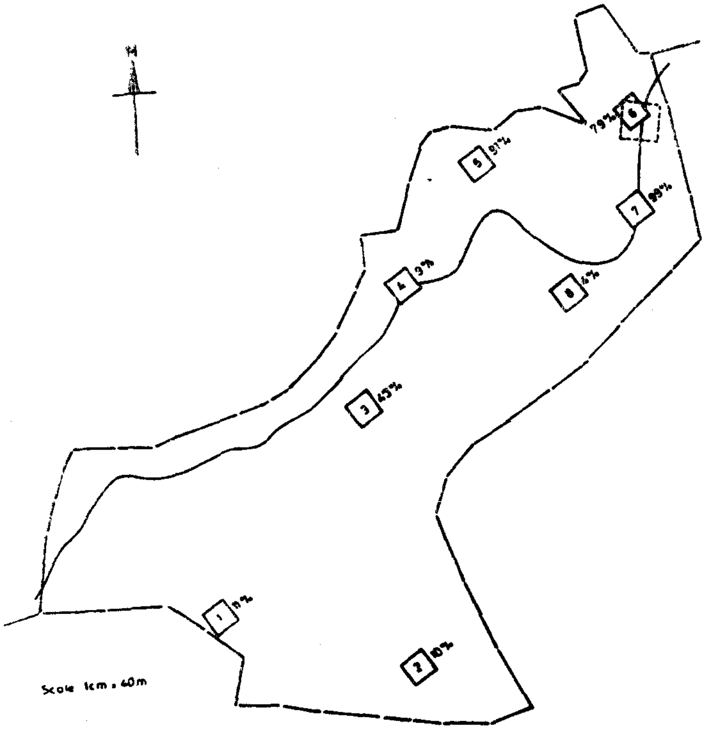

Fig. 21. **1974-teak plantation at Pullamkandam, showing plots 1 to 8 in which leading shoot damage (LSD) was enumerated in 1977. Percentage incidence of LSD in each plot is also given. The site sampled in 1985 to enumerate forking is shown by the dotted square.**

The plantation at Aravallikavu, Nilambur was two years old when the observations were made in April 1977. All the saplings in every 20th row (5% sampling) of the 22 ha plantation was examined as above. This method of sampling was found easier than the grid-sampling employed at Pullamkandam where locating the selected grids on the ground was a laborious task.

4. 4. 1. 3 Effect of LSD on forking

The ideal method to study whether die-back of the leading shoot leads to permanent forking of the tree is to mark the affected tress and re-examine them after the lapse of a few years. Such observation was made only in a few instances where LSD occurred within the experimental plots at Karulai, Nilambur.

At Pullamkandam, where comparatively heavy incidence of terminal shoot die-back had occurred in 1976-77, a portion of the plantation was examined again about 8 years later, in 1985. For this purpose, taking the narrow plantation road near Plot 6 as the baseline (Fig. 21), 10 trees on each of 20 rows on either side of the road were examined. The site was chosen because it fell within the area where heavy incidence of die-back was recorded in 1977 and was easy to locate in the field. The height at which forking occurred was examined. Forks above 10 m were ignored as the trees were all below 10 m when die-back occurred in 1977. A total of 348 trees were covered in place of the expectzd 420, since some rows did not have 10 trees each.

4. 4. 1. 4, Experiments to induce LSD by artificial defoliation

Two sets of experiments were conducted to examine whether artificial defoliation will lead to LSD. In the first set at Kariem-Muriem in the Nilambur Forest Division, 30 saplings, 3-year-old, were defoliated on 19 July 1979. The saplings had an average girth of 9.5 cm at breast height and a height of about 3.5 m. The terminal bud of the leading shoot was nipped and all the leaves were plucked off. The experimental saplings had not been under observation before the start of the experiment, but based on observations elsewhere it was presumed that a natural defoliation caused by *H. puera,* had already taken place earlier. Follow-up observations were made at fortnightly or monthly intervals for the next 4 months. The leaf size of normal and artifically defoliated saplings was compared on I December 1979 by measuring 10 saplings from each group. The normal saplings were taken from the immediate surroundings of the defoliated saplings. Six fully formed leaves were collected from each selected sapling — 2 each-from the bottom, middle and top levels of the canopy. The area of each leaf was measured by tracing its outline on graph paper.

In the second set of experiinents carried out in 1980 at Aravallikavu in the Nilambur Forest Division, the experimental trees were protected from natural defoliation by insecticidal sprays and artificial defoliations were carried out without damaging the terminal bud. To examine the effect of season on the trees’ response, the cxperiment was repeated in June, July and August in different sets of 10 saplings each.

4.4.1.5. Experiments to study possible role of microorganisms in LSD

Some experiments were conducted to determine the possible role of a fungus, *Colletotrichuum gleosporiodes* which was isolated from dead terminal shoots. With the help of the Pathology Division of KFRI, the fungus was cultured in the laboratory and viable spores were sprayed onto the saplings. Twelve healthy saplings, 3-yr-old, were selected from a plantation at Aruvacode, Nilambur, divided into two groups of 6 each and one group was subjected to total defoliation. The defoliation was carried out by pulling off the leaf blades with fingers, leaving the petiole and the main ribs. In both the normal and defoliated groups, half the number of saplings were treated and the other half served as control. Except in the controls, a spore suspension was sprayed onto 5 terminal branches of each tree and the treated portion covered with a polythene bag held in position by rubber bands. Control saplings received the same treatment except that water instead of spore suspension was sprayed. The polythene bags were removed after 48 hours and the saplings were kept under observation for 45 days.

4.4.2. Results

Die-back of leading shoot was observed in some young plantations on some occasions, but was not a regular annual feature like defoliation. It was noticed mostly in 2- to 4-year-old plantations. During a period of 7 years from 1977 to 1984, (when general observations were made in young plantations at Nilambur), LSD was noticed only in two years. Specific observations at two sites, viz., Pullamkandam in Trichur Forest Division and Aravallikavu in Nilambur Forest Division are given below.

4.4.2.1. Observations at Pullamkandam

A heavy incidence of LSD was noticed in a 3-year-old plantation at Pullamkandam in early 1977. In the third week of September 1976, a moderately heavy infestation of ***H. puera*** occurred in this plantation. Small numbers of ***E. machaeralis*** larvae were also present at that time. Subsequently, a heavy epidemic of ***E. machaeralis*** occurred in November 1976. When examined again Ion 6 January 1977, a large percentage of the saplings showed die-back of the leading shoot (Figs. 22, 23,). In many saplings, upto 4 or 5 terminal internodes of the leading shoot had dried up and epicormic branches had already appeared below the dead portion.

The eight plots sampled showed an overall mean of 43% LSD but there was large variation among the plots (Table 17). The incidence was high (79 - 99%) in 3 plots, low (4 - 11%) in 4 plots and medium (43%) in one plot. The clustering of the high LSD plots (Fig. 21) showed that high incidence was concentrated in a patch within the plantation.

4.4.2.2. Observations at Aravallikavu

LSD was recorded in a 2-year-old plantation at Aravallikkavu in the same year when LSD was noticed at Pullamkandam. Enumeration done in April 1977 showed that 33% of the 2900 saplings sampled from the 22 ha plantation were affected. The spatial distribution of the affected saplings was not studied. As at Pullamkandam, it was clear that LSD was the result of defoliations that had taken place in the previous year, but no information was available on the sequence of defoliations preceding LSD, except that a heavy wave of defoliation by ***E. machaeralis*** occurred all over Nilambur in November 1976.

In the same plantation, LSD was again noticed in the year 1980, when the saplings were 5 years old. The sequence of defoliations preceding LSD was as follows. A partial defoliation was caused by ***H. puera*** in late May 1980. An additional complete defoliation, again caused by the same insect, occurred about a month later, on 25 June. Another defoliation of partly developed leaves is suspected to have occurred around 7 July,. but accurate records are not available. There were heavy rains during late June and July. When examined on 10 July the leading shoot of many saplings were dead. In addition, the terminal portions of many side branches were dead (Fig. **7,** Section 4.1.2). The dead shoot portion was soft and black. From these shoots, two fungi, viz., ***Colletotrichum gleosporiodes*** and ***Fusarium*** sp., and an unidentified bacterium were isolated by the Pathology Division of KFRI (J. K. Sharma, personal communication).

4.4.2.3. Effect of artificial defoliation

In the first set of experiments, among the 30 saplings that were artificially defoliated on 19 July 1979 (including nipping of the terminal bud), two saplings dried up completely about 2 months after the defoliation (after they had put forth small new leaves). Among the rest, in all except 8 saplings, the new flush of leaves were smaller, the mean leaf area being 65 cm2 compared to 238 cm2 of the normal leaves. Such leaves persisted until the end November when observations were discontinued. Die-back of leading shoot was not observed.

In the second set of experiments, no LSD occurred in 20 saplings defoliated in June 1980 (1 June) and all of them developed two pairs of new, nearly full-sized leaves in about 25days. When the same saplings were defoliated again in the first week of July, 3 of them (15%) showed LSD. Leaves developing after the second defoliation also attained near normal size. When defoliation was carried out once in July (llth), 4 out of 20 saplings (20%) showed LSD in about a month's time and when it was carried out in August (16th), 1 out of 10 saplings developed LSD.

In summary, in the first experiment, no LSD occurred when one artificial defoliation including nipping of terminal bud was carried out in July, following a natural defoliation. In the second set of experiments also one defoliation in June did not cause LSD, but one defoliation in July, whether for the first or second time caused LSD in a small percentage (15 to 20) of saplings. A small percentage of LSD also occurred following single defoliation in August.

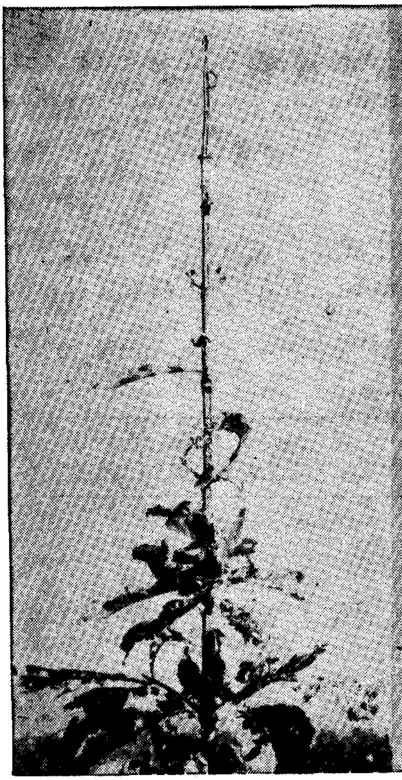

Fig. 22. Leading shoot damage (LSD) of a sapling in the Pullamkandam plantation.

Fig. 23. Same as Fig. 22, a general view.

Table 17. Incidence of terminal shoot die-back in a 3-year-old teak plantation at Pullamkandam

Sample plot No.	Total No, of saplings per plot	No. of saplings showing LSD	% of saplings showing LSD[1]
1	201	21	11
2	293	28	10
3	329	141	43
4	325	30	9
5	267	242	91
6	305	242	79
7	333	329	99
8	384	16	4
Total	2437	1049	43

[1] Rounded off to the nearest integer

4.4.2.4. *Effect of the fungus,* Colletotrichum gleosporiodes

There was no sign of damage following inoculation of ***C. gleosporiodes*** spores. in defoliated or normal saplings. The defoliated saplings reflushed normally and no LSD occurred.

4.4.2.5 LSD and forking

In the resurvey at Pullamkandam in 1985, 53 of the 348 trees examined showed forking (Fig. 24) below 10 m. The height distribution of forking (Table 18) shows that forking was less prevalent below 5 m and above 9 m. Since the height of most saplings ranged between 5 and 8 m in 1977, it is inferred that the forking recorded between these heights (39 out 348, i.e., 11%) resulted from the LSD in 1977. Considering that the area sampled in 1985 was close to plot 6 (Fig. 21) which registered 79% LSD in 1977, it may be expected that if all LSD led to forking, about 79%; of the trees should have been forked. However, only 11% of the trees showed forking. Thus, at Pullamkandam, permanent forking occurred only in 11 out of 79 trees which sufferred LSD, which works out to 14%

Table 18. Frequency distribution of forking height below 10 m, in the 1974 teak plantation at Pullamkandam

Height of fork (m)	No. of trees forked (out of 348)
2.1 - 3.0	1
3.1 - 4.0	3
4.1 - 5.0	1
5.1 - 6.0	13
6.1 7.0	16
7.1 - 8.0	10
8.1 - 9.0	7
9.1 - 10.0	2
2.1 - 10.0	53

More specific information was available for 15 trees in the experimental plots 1 to 8 at Karulai which suffered LSD in 1977. When examined in 1985, only one of these 15 trees (about 7%) showed permanent forking at the height at which LSD occurred in 1977.

Based on the above information it can be concluded that only in a small proportion of saplings, (about l0%, on an average) does die-back of terminal shoot result in permanent forking.

Fig. 24. **1974-teak plantation at Pullamkandam, photographed in 1985 showing forked trees.**

4. 4. 3. Discussion

In our observation, the average incidence of LSD was 43% at Pullamkandam and 33% at Aravallikavu. Khan and Chatterjee (1944) reported an incidence of 52% at Tithimatty, Karnataka. Although Dawkins (1921) reported it in “nearly all saplings”, it was not based on actual enumeration. Based on these observations we may generalise that upto 50% of the seedlings in the affected young plantations may suffer LSD. This figure refers to the extent of LSD when it occurs. The frequency of such occurrences has not been studied earlier. In young plantations at Nilambur although defoliation occurred every year, LSD occurred only in 2 out of 7 years showing that defoliation does not necessarily lead to LSD. This has naturally posed the question whether defoliation *per se* could cause LSD. Earlier, Laurie and Griffith (1942) wrote that the connection between leading shoot damage and defoliation has not been definitely established. According to Beeson (1941; p. 474) "if destruction of buds is coupled with injury to the epidermis of shoot and delay in reflushing, it is likely the shoot will die back." He further wrote, "complete defoliation alone does not cause dying-back or death except in saplings that are otherwise unhealthy and weakened". There are other suggestions in the literature that an attack commencing later in the year and of longer duration may cause LSD (Mackenzie, 1921), but most of these ideas lack experimental or observational proof.

Our artificial defoliation experiments at Kariem-Muriem showed that destruction of the terminal bud coupled with complete defoliation did not lead to LSD. In cantrast to this result, other experiments at Aravallikavu, showed that one complete defoliation in July or August was sufficient to cause LSD at least in a small percentage of saplings, although when the defoliation was carried out in June, no LSD occurred. The results of these experiments at Aravallikavu, must be interpreted with some caution, because although the saplings were protected from natural defoliation during the experimental period, defoliation and natural LSD were prevalent in the surrounding area. Tests with one of the microorganisms isolated from the affected shoots did not indicate its involvement, but other organisms have not bekn tested. It is quite likely that microorganisms are not involved in the die-back of terminal shoots and that it is a physiological response to repeated severe defoliation. In our observations under natural conditions, LSD has been noticed as early as 10 July (in 1980) and as late as after the third week of September (in 1977). Khan and Chatterjee (1944) observed it in October and Dawkins (1921), in November. We suspect that LSD occurs under a unique combination of conditions, namely, occurrence of repeated waves of defoliation in the same locality at short intervals (see Section 4.1.2), causing repeated destruction of buds and new flushes of leaves even before they are fully formed. Loss of buds and new foliage can affect the production of growth regulators which may lead to LSD. Further experiments are necessary to draw unequivocal conclusions.

The economic significance of LSD is not as great as suspected earlier, due to, three reasons — (1) it does not occur every year, (2) when it occurs, generally less than 50% of the saplings in a plantation suffer damage, and (3) it does not necessarily lead to forking. Our study has shown that permanent forking ocurred only in about

10% of the saplings which suffered LSD which itself was limited to less than 50% of the saplings in a plantation. In the others, one of the shoots may take over as the leader shoot and the other epicormics may become suppressed as small side branches. LSD, however, will seriously affect the height growth of saplings, but this impact is considered to be less serious than forking of the bole.

All the recorded incidences of LSD have occurred in 2- to 5-year-old saplings. Although Khan and Chatterjee (1944) observed that saplings upto I0-yr-old may be affected, those in the 2- to 5-yr age group appear to be the most susceptible.

5. CONCLUSIONS: THE PRACTICAL SIGNIFICANCE OF DEFOLIATION AND OUTLOOK FOR FUTURE

The main purpose of this study was quantification of the impact of insect-caused defoliation on growth of teak. This, in turn, was expected to facilitate decision on whether or not to control the defoliators in teak plantations. We shall now examine this practical aspect of the study.

The impact of defoliators is summarised in Fig. 25. ***E. machaeralis,*** popularly known as the skeletonizer. had little impact on growth due to the three reasons specified in the figure (see also Section 4.3). This conclusion was based on a 5-year study on 4- to 9-yr-old saplings at Nilambur and the question now arises whether it will hold good (1) for all ages, and (2) throughout India. It has been suggested in the literature (Beeson, 1941: pp. 472-473) that the incidence of defoliation is not uniform throughout the period of rotation. Some such conclusions drawn for ***H. puera (vide infra)*** have also been claimed to be applicable to ***E. machaeralis*** (Beeson, 1941: p. 521). As discussed later, we believe that no consistent relationship has been established between crop age and susceptibility to defoliation. For ***E. machaeralis,*** Patil and Thontadarya (1983) found that crops of different ages were attacked at different times but there were no differences in the intensity of attack. At present, there is no evidence to suggest that in older plantations the intensity of defoliation by ***E. machaeralis*** will be greater than was observed in this study. We think therefore that the conclusion that ***E. machaeralis*** has little impact on growth will hold good for all ages. Now, let us consider the second question of applicability throughout India. Under natural conditions, ***E. machaeralis*** appears to thrive best on old, physiologically stressed (senescent) foliage (Section 4.1.3.)

Therefore the possibility of more severe defoliations in drier regions cannot be ruled out. Because of the occurrence of two monsoons, the situation in Nilambur and other similar areas in the Western Ghats region may be unique. In the absence of systematically recorded data for northern India, no broad generalization can be made. The present findings should, however, be generally applicable throughout the high rainfall areas of southern India and it can be safely concluded that no control operations are necessary against ***E. machaeralis*** in this region. This conclusion has high practical significance since an insecticidal spray has been considered necessary in September-October, against ***E. machaeralis*** (Sen-Sarma and Thapa, 1981).

In contrast to ***E. machaeralis, H. puera,*** popularly known as the defoliator and active during the early part of the growth season, caused significant loss of increment. It also affected the quality of timber by inducing forking of the main bole in a small proportion of saplings (Fig. 24). Although the depreciation due to forking has been earlier considered “the most serious aspect of the defoliation loss” (Champion, 1934), our study shows that only rarely does defoliation lead to permanent forking (Section 4.4). Loss of volume increment is thus the most serious impact of defoliation.

For convenience of the discussson that follows, we define ‘normal increment’ as that increment which occurs under conditions of natural defoliation and ‘potential increment’ as that which occurs when defoliation is prevented. As noted earlier (Section 4.3), the impact of defoliation on volume increment can be expressed in two ways — as loss of a certain proportion of the potential increment, due to defoliation, which works out to 44%, or as gain of a certain proportion of the normal increment, due to protection, which works out to 80%. We used the first method of calculation to compare our results with previous estimates expressed in a similar way. The second method of calculation is more useful for interpretation of the practical significance of defoliation, for the following reason. We need to know either the potential increment or the normal increment throughout the rotation period in order to calculate the absolute volume lost due to defoliation or the absolute volume gained due to protection. Since defoliation is a regular feature in all teak plantations throughout India, an estimate of the normal increment can be obtained from the yield table. In other words, the increment values taken from the yield table are comparable to the increment that occurred in our unprotected plots and not the potential increment. When defoliation is prevented, this yield may be expected (subject to restrictions discussed below) to increase by 80% i.e., we may expect an additional increment equivalent to 80% of the yield table values. To

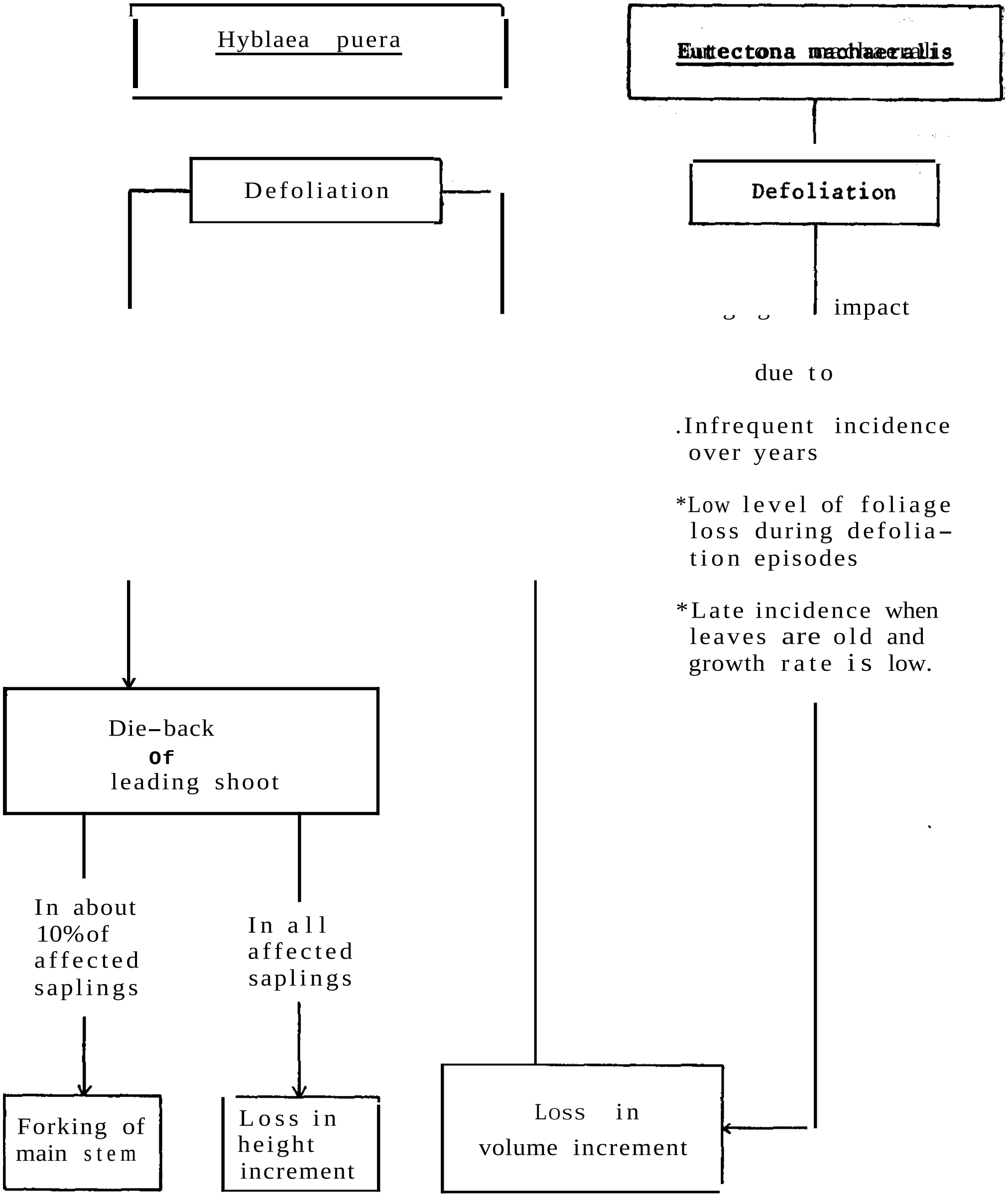

Fig. 25. Impacts of teak defoliators.

calculate the absolute gain, we shall use the yield table for site Quality 11, to which quality class our experimental area belonged.

We must now consider whether the rate of 80% additional increment we estimated from 4- to 9-year-old plantations can be applied to the entire rotation period of 60 years. Although the absolute volume of additional increment will decrease with age due to decreasing values of normal increment, there is no reason to suppose that the estimated 'rate of additional increment due to protection's will change with age. It can change with age only if the rate of destruction of foliage (i.e., annual defoliation intensity) itself gets altered as a function of age. It has been claimed that the frequency of severe defoliations (which can be mostly attributed to ***H. puera)*** is higher in the age class 11 to 45 years, with maximum in the age class 21 to 30 (Beeson, 1941: p 473). A "general falling off in the intensity of defoliation from the age of 30 years, which becomes still more marked from the age of 50 years", "largely due to improvement in control through natural enemies" has also been suggested. We think that these conclusions are based on scanty field data and are not consistent with another statement that under epidemic conditions "stands of all ages are equally clean-stripped". Our general observations did not indicate differences between age groups, except that during the first two years, when the saplings are short, they often escaped defoliation, possibly because the migrant moths preferred taller trees for egg laying (Section 4.1.2). We need more data on the relation between crop age and susceptibility to severe defoliation as well as between crop age and the seasonal growth trend. We consider that for rough calculations, use of the present estimate of 80% additional increment throughout the rotation period is acceptable. As a matter of fact, as we shall see below, we will run into more serious problems in calculating the actual gain due to protection, so that the problem of fixing a reliable rate of additional increment need not cause much concern at this stage.

Curve A in Fig. 26 shows the total yield of volume at progressive intervals in an unprotected stand (Site Quality 11, data from All India Yield Table: Anonymous, 1959). Curve B shows an artificial trend when the increment is increased by 80%. In this curve, the volume attained by the normal stand in 60 years is reached in 26

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1 The site quality of the experimental area was determined using the height of 10 highest trees from each plot (i. **e., 10 trees per 400 m^2, which is equivalent to the standard recommendation of 250 trees per ha). Both the treated and untreated plots belonged to site quality 11 (upper half), based on measurements at the end of the 9th year, although the treated plots were slightly better than the untreated.**

a This rate must not be confused with the rate of **normal increment which will be influenced by age because it would be expressed as a function of the initial volume which increases with age. We are not using the rate of normal increment in any of our calculations because we are using the values of absolute increment given in the yield table.**

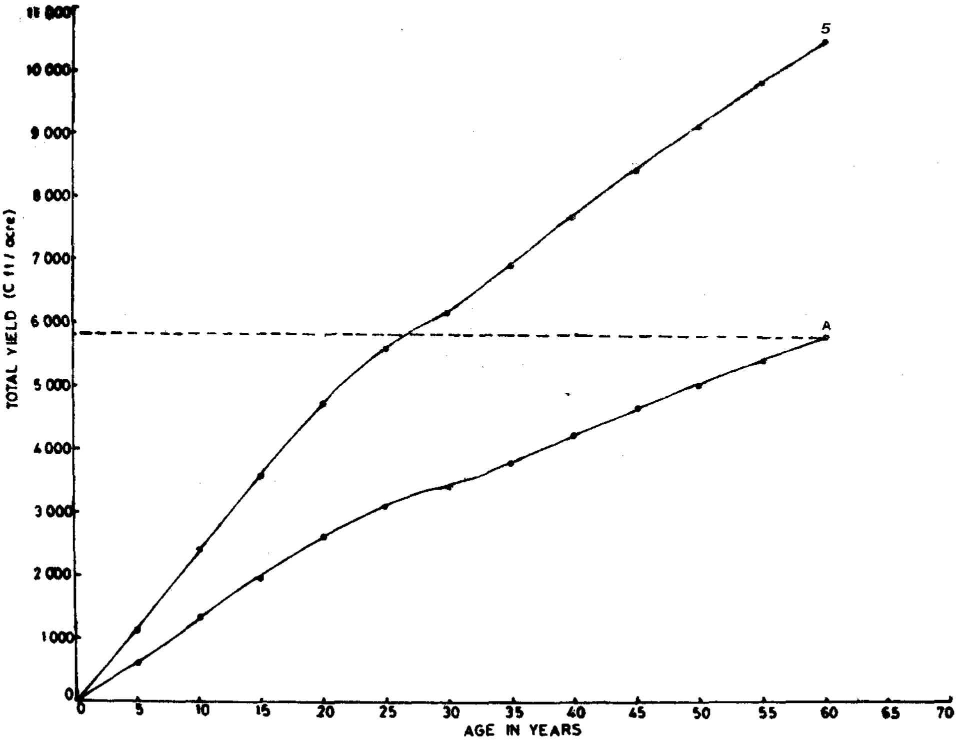

Fig. 26. Curve A shows volume increment of **a teak stand** of **Site Quality 11. An artificial trend when the increment is increased by 80% is shown in Curve B.**

years. This trend is untenable because density-dependant limiting factors will begin to operate as soon as the normal increment is exceeded, particularly since silvicultural operations like thinning have been standardised on the basis of the normal increment pattern. Without adequate experimental data, it is not possible to predict what effects an increased increment will have on stand dynamics. All existing interrelationships among foliage mass, crown structure, light penetration, partitioning of nutrient elements between biomass and soil, physiology of the tree, etc. will undergo stress and readjustments and a new state of dynamic equilibrium will result. But if we carry out thinning as in the case of a regular unprotected stand (that is, at times when the standing volume reaches the same level at which thinning is carried out in an unprotected stand) so as to compensate for the crowding effect, we can expect the same rate of increment as that obtained in the unprotected stand having the same standing volume, plus 80% of that increment. However, the conditions and assumptions involved in such prediction of the long-term effects of protection make the results unreliable. We are not therefore attempting it here. But it can be safely concluded that by protecting the plantation from defoliation and by developing an appropriate thinning schedule and implementing it, the yield can be increased substantially. With more detailed knowledge of the parameters determining volume increment, it will become possible to develop adequate models to simulate the stand dynamics. The present estimate of the 'rate of additional increment due to protection' could then be used to predict the long-term gain in volume. Unfortunately, we must await further developments in stand modelling for teak to describe the practical significance of defoliation in adequate quantitative terms.

In the strict sense, application of protective measures is worthwhile only if the benefit arising out of it is greater than the cost incurred- ideally this must be determined by benefit-cost analysis, which is an investment analysis procedure in which the benefits and costs are compared in monetary terms. We cannot attempt it here because neither the benefit nor the cost has been quantified. As discussed above, quantification of the benefit is not feasible in the present state of our knowledge of stand dynamics. And, before we can attempt to quantify the cost, we must explore the ways in which control could be effected. Although aerial spraying of insecticides has been tested against the teak defoliators in the past, *we do not recommend use of insecticides in teak plantations for control of pests*, for several obvious reasons. We used an insecticide in our experiment only to ensure adequate protection in a limited area, for a limited period, under expert supervision. Large-scale, routine use of insecticides in teak plantations will have wide-ranging consequences which will offset the large gain in wood increment, We must therefore develop pest management techniques which will be effective and environmentally acceptable. The purpose of this project was limited to finding out whether control of the defoliators is worthwhile. We conclude that control of ***H. puera*** is worthwhile, but control of ***E. machaeralis*** is not. Protection during the early years will be more beneficial because of the higher absolute increment and insurance against damage to leading shoot.

With a view to develop appropriate pest management techniques, two new projects were initiated recently, (1) to study the role of natural enemies in regulating the pests and (2) to search for natural resistance in teak against defoliators. The new knowledge gained during the present study, on the population dynamics of ***H. puera,*** the major pest, suggests that it may be possible to prevent large-scale build-up by controlling the insect in small patches where initial build-ups may occur. But more detailed knowledge of the population dynamics of the insect is necessary. Since it is clear that large benefits can accrue from prevention of defoliation, the priority in future research efforts should be development of suitable methods of protection rather than more precise estimation of the gain.

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