ECOLOGICAL STUDIES ON THE TROPICAL WAREHOUSE MOTH *EPHESTIA CAUTELLA* (WALKER) (LEPIDOPTERA : PYRALIDAE) AND ITS PREDATOR MITE *BLATTISOCIUS TARSALIS* (BERLESE) (ACARI : ASCIDAE) IN RELATION TO EFFECTIVE WAREHOUSE INTEGRATED PEST MANAGEMENT PROGRAMMES"

BY

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DECLARATION BY CANDIDATE

This is my original work and has not been presented for a degree in any other University

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ABSTRACT

The abundance and economic importance of the moth Ephestia cautella (Walker) on maize grain was established through field surveys in central storage depots and detailed evaluations carried out in selected warehouses. Through regular grain sampling on maize stacks, it was found that moth population and damage were well correlated and that damage reached 15.26 percent after 8 months of storage. It was found too, that this pest is common throughout the country wherever maize is stored and that control was a problem even with sustained use of chemicals.

Population studies were carried out both in the field and in the laboratory on the moth and its mite predator Blattisocius tarsalis (Berlese) in a continuous interaction for 33 weeks. Through life-table analysis, mortality factors regulating the moth's population were identified where density dependence was demonstrated on some especially in the first larval instar.

Despite this marked effect of the mite on the moth's population, and particularly, demonstrated density dependence, mite predator alone was determined to be of limited value in the control of E. cautella. This was considered to be partly due to the continuous availability of alternative hosts especially Tribolium castaneum, Corcyra cephalonica and Plodia interpunctella which occurred simultaneously and in abundant numbers in the storage facilities studied, and partly due to other unknown factors including the architectural design of the facilities which exposed maize to the environment. This encouraged re-infestation by the moth and thus interrupted on-going regulatory effect of the mite. The alternative hosts also comprised storage pests themselves whose thresholds could

not be ignored if economic damage was to be avoided. Negative effects of these alternative hosts otherwise negated their advantage of providing sustenance to the mite when the moth's eggs were in low numbers.

Similarly, through field surveys and laboratory screening, it was found that control with insecticides such as malathion, pirimiphos-methyl and fenitrothion or with recently introduced ones like pyrethroids; permethrin and deltamethrin, rarely eliminated the moth. The use of some chemicals such as malathion, led to increased populations of the moth after 3 months of application.

The combined use of selected pesticides and mite control yielded positive results by significantly suppressing the moth population below economic threshold level. This was demonstrated in the laboratory cage systems and in normally operating maize storage warehouses where moth population was monitored for 8 months with selected insecticide application. This revealed that integrated control was the most suitable strategy available to achieve effective pest management of E. cautella and other associated pests in warehouse storage systems for maize in Kenya.

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Thanks are also due to my own family, Winnie and the children for moral support and encouragement and also to Mrs. Pamela Maunda for exemplary patience in typing this work.

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CHAPTER 1

INTRODUCTION

1.1 THE ROLE OF THE TROPICAL WAREHOUSE MOTH EPHESTIA CAUTELLA IN CAUSING STORED GRAIN LOSSES IN KENYA

The tropical warehouse moth (Plate 1) or almond moth, Ephestia cautella (Walker)=(Cadra cautella) (Walker), is an important pest of a variety of grains and foodstuffs (Cox, 1978). The pest is widely distributed both in the tropical and temperate countries of the world (Benson, 1973). It has been recorded attacking nuts, dried fruits, cacao, cereals, garlic, oil palm kernels, cassava meal, cotton-seed meal, dried citrus pulp, sheep skins and peccaries (Keifer, 1931; Corbett, 1931; Passmore, 1932; Bosselli, 1933; Lal and Varma, 1975). These authors reported that the pest inflicted economically important losses on all the mentioned foodstuffs and materials.

A detailed account of the pest's biology is given by Barrer(1981). The adult moth exhibits crepuscular behaviour being most active during dusk at 5-7 p.m. and dawn at 6 a.m. Mating occurs at night and egg-laying takes place within 24 hours of mating. An adult female lays up to 300 eggs. These hatch in about 3 days into larvae which undergo 5-6 instars before pupation. Pupation lasts 5 days before adult emergence. Adults live for less than 14 days. Thus, development from egg to adult takes about 25 days. The developmental period depends on many factors including temperature, relative humidity and population density.

In Kenya, E. cautella is an important pest particularly on maize, the chief staple food for the majority of the population (Graham, 1970a). The pest is equally important on other cereal grains such as wheat, rice, sorghums and millets as observed in studies by McFarlane (1970). He reported that infestation by this pest was found practically in all storage

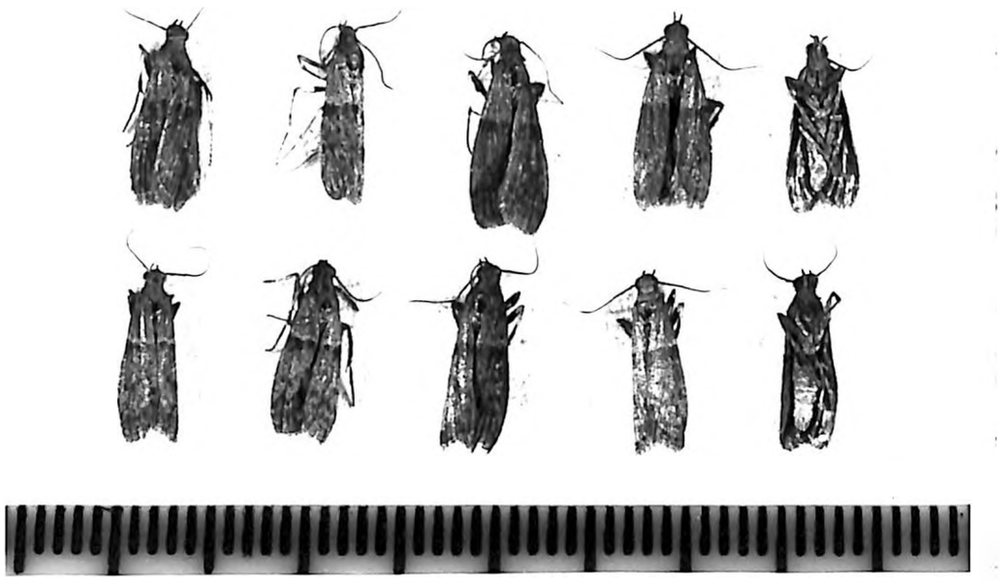

Plate 1. Tropical warehouse moth, Ephestia cautella adults. The straight line demarcation of the front one-third and the rear two-thirds of the first pair of wings distinguishes this moth from others found in the warehouses. Magnification X 2.

facilities in the country where these grains are stored. Grain storage losses both in quantity and quality are caused by this pest on the grains and foodstuffs. In addition, the profuse webbing that is characteristic of the presence of the pest, particularly when it occurs in large numbers, causes soiling of the store fabric surfaces. In this way, the presence of the pest precludes maintenance of storage facilities in a sanitary state.

Problems associated with storage insect pests on maize in Kenya have existed ever since the crop was first introduced. This is because of the high temperatures and relative humidities in most regions of the country that strongly favour the development of these pests (Ashman, 1966). Attempts to control the pests according to McFarlane (1969), have often relied heavily on the use of chemicals such as DDT, gamma - BHC, pyrethrins and malathion but such attempts have achieved limited success. At present, dichlorvos, pirimiphos-methyl, permethrin and bromophos are in use but still complete control is yet to be realised and losses through these pests continue to be incurred as shown in this study. It is therefore recognised by the grain producers, consumers and the economic community that without an organised pest control strategy for E. cautella and other storage pests, there is never any hope of gainful use of the harvested crop either for marketing or for food.

About 80 percent of the maize produced in Kenya is either marketed locally in rural trading centres or remains on the farm to cater for subsistence requirements. The rest 20 percent is offered as surplus for sale by the Government through a grain parastatal, National Cereals and Produce Board (NCPB). This is according to the National Food Policy Paper of 1981. NCPB carries out its operations of storage, distribution and marketing of grain throughout the country. The storage structures in these centres were observed, in these studies, to be of three types; silos constructed from cement or metal,

hermetic ("Cyprus") bins and conventional warehouses. Over 80 percent maize stocks were observed to be stored in conventional warehouses; making this form of storage to be the most prevalent in the country.

Since grain stocks maintained centrally by the government serve as buffer stocks which may remain stored for a long time, sound preservation techniques are called for to minimise quantity and quality losses against storage pests which include insects, rodents and birds. Among these pest problems, insect damage is the most acute and the most prominent as measures for control are rarely as discrete as those of the other pests and weather related problems (De Lima, 1978).

Infestation trend of the harvested crop can be broken into three phases depending on the important species attacking the crop and the storage environment. The first phase occurs when the grain is maturing in the field and is characterised by infestations by primary pests such as, Sitophilus zeamais (Motsch) and Sitotroga cerealella Olivier(Ayertey, 1978; Floyd, 1971) these being those which attack whole grain. During this phase, Ephestia cautella is absent on grain. Once grain is shelled and placed in warehouses, E. cautella becomes important in close association with other secondary pests particularly, Tribolium castaneum, Corcyra cephalonica and Oryzeaphilus spp. (De Lima, 1972) Secondary pests are those that feed on grain already damaged by primary pests and also fragments of grain. The third phase in which E. cautella is less important, occurs when control operations are less than optimal and comprises infestations by Rhizopertha dominica, Cryptolestes spp and Tenebroides mauritanicus (Graham, 1970a). Table 1 lists the pests which have been observed to be associated with E. cautella infestations.

Control of storage pests in Kenya has, since the beginning of organised agriculture, been based largely on the use of

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Table 1. List of storage insect species occurring in association with Ephestia cautella in warehouses.

FAMILY	SPECIFIC NAME	COMMON NAME
COLEOPTERA		
Anobiidae	Lasioderma serricorne	Cigarette beetle
Anthribidae	Araecerus fasciculatus	Coffee bean weavil
Bostrichidae	Rhizopertha dominica	Lesser grain borer
	Dinoderus sp	Bamboo borer
	Prostephanus truncatus	Larger grain borer
Cleridae	Carthartus quadricollis	Square-necked grain beetle
Curculionidae	Sitophilus oryzae	Rice weavil
	S. zeamais	Maize weavil
Dermestidae	Attagenus piceus	Black carpet beetle
	Dermestes maculatus	Hide larder beetle
Mycetophagidae	Typhaea stercorea	Hairy fungus beetle
Nitidulidae	Carpophilus dimidiatus	Corn sap beetle
Trogositidae	Lophocateres pusillus	Siamese grain beetle
	Tenebroides mauritanicus	Cadelle
Silvanidae	Oryzaephilus surinamensis	Saw-toothed grain bettle
Tenebrionidae	Alphitobius diaperinus	Lesser mealworm beetle
	A. laevigatus	Black fungus beetle
	Gnathocerus maxillosus	Slender-horned flour beetle
	Palorus ratzeburgii	Small-eyed flour beetle
	*Tribolium castaneum	Rust-red flour beetle
	T. confusum	Confused flour beetle

LEPIDOPTERA		
Galeriidae	*Corcyra cephalonica	Rice moth
Gelechiidae	Sitotroga cerealella	Angoumois grain moth
Pyralidae	*Ephestia elutella	Tobacco moth
	Plodia interpunctella	Indian meal moth

* Major pests occurring in association with E. cautella in warehouses.

recommended pesticides (De Lima, 1973, Hall, 1970;McFarlane, 1969). Control of these pests on farm stored grain has been achieved through residual chemical sprays on storage structures and insecticidal dusting on cob maize (Anon, 1974). In central storage, on the other hand, the main emphasis has been on fumigation accompanied by spraying on store fabric and on commodity surfaces (McFarlane, 1969). Spraying is carried out to achieve immediate control of surface and spatial infestation and thereafter to provide residual protection on surfaces.

Since the chemicals are broad-spectrum in their action they would control all species present. However, some species, including E. cautella have persisted following spray operations (Graham, 1966). Occasionally, upsurges of E. cautella have been observed following treatment with chemicals indicating a possibility of its resistance to commonly used chemicals (Graham, 1970a). Therefore, detailed quantitive studies on its biology and ecology are necessary in order to design effective control measures against the pest.

Apart from Sitophilus spp, the pest under study has the greatest impact on warehouse stored maize and in conditions where initial fumigations are completely successful, the pest is more predominant than Sitophilus spp in subsequent infestations (McFarlane, 1970). It is for this reason that the pest has been studied under warehouse conditions of maize storage in Kenya. Like most storage insect pests, it is the larval stage of E. cautella that feeds on and destroys grain. The adult is mainly reproductive in function and does not destroy grain. Adult population, however, is a measure of the pest's infestation intensity in a store.

E. cautella is preyed upon by a mite Blattisocius tarsalis (Berlese) (Plate 2) which feeds on the moth's eggs and is phoretic on the adult, being transported from place to place

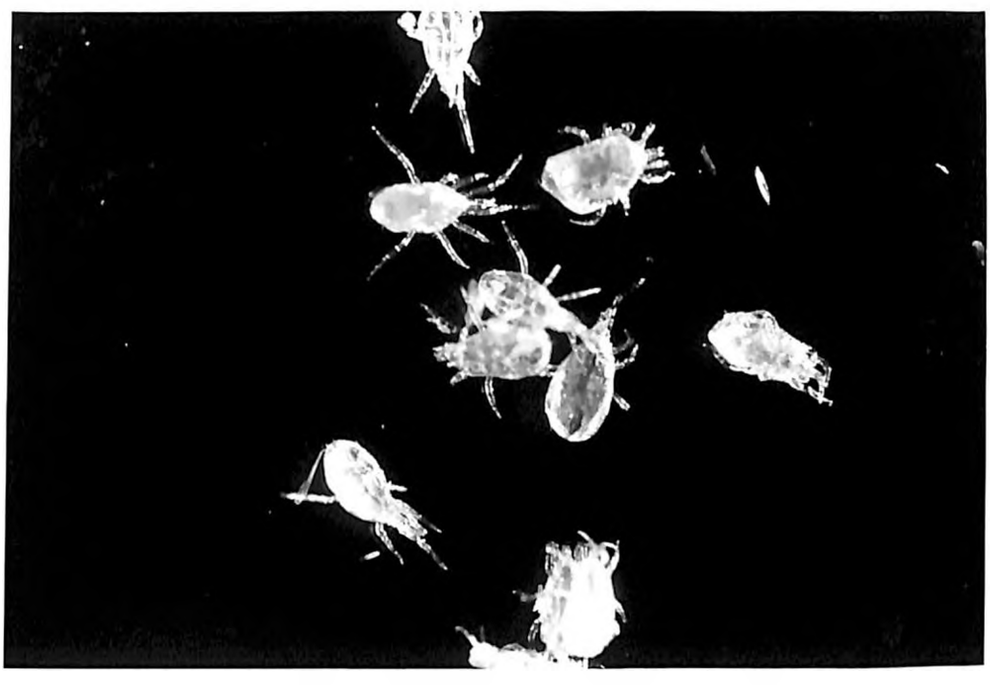

Plate 2. The mite, Blattisocius tarsalis Berlese. Magnification x 202

underneath the wings. Previous studies have shown that this predator is always present in a population of E. cautella upon which it has a marked influence (Graham, 1970b; Haines, 1981). Thus, these studies include the population dynamics of the moth under the influence of the mite. It was hoped that this would give an insight into the role of the mite as a possible biological control agent. Since the activity of the mite was likely to be influenced by other insect species always present in stores, these investigations were extended to determine the interactions of these other pests with the mite vis-a-vis its predation on E. cautella. The data obtained would provide a sound basis for planning storage strategies that would reduce heavy losses.

1.2 LITERATURE REVIEW

1.2.1 Economic importance of E. cautella

Keifer (1931) was the first person to notice that E. cautella was an economically important pest which caused damage on stored foods and other materials. Corbett (1931); Edwards (1932) and Passmore (1932) also reported this moth as being a pest of copra, oil-palm and cocoa. Furthermore, Bosselli (1933) and Myers (1928) observed E. cautella's damage on dried figs and Lal and Varma (1975) and Bhattacharya et al (1976) found it attacking soya beans and onion bulbs respectively causing serious economic damage on all these commodities.

In Kenya, E. cautella has been observed causing losses on various stored food grains and products including maize, wheat, sorghum and other cereals (McFarlane, 1969; Graham, 1970a, b and c). Sharma (1976) demonstrated that maize was only second to sorghum in preference by this pest.

1.2.2 Biology and ecology of E. cautella

Several authors have dealt with the general biology of the common insect pests of stored products including E. cautella (Burgess and Haskins, 1965; Munro, 1966; Graham, 1970b; Benson 1973; Barrer, 1981 and Wallace, 1981). Most of these studies covered in detail the life cycles, flight behaviours and distributions. In particular, Graham (1970a) demonstrated that E. cautella was crepuscular in its flight habits, while Benson (1973) was concerned with its distribution which he noted was world-wide with a capacity to hibernate to overcome the harsh winter conditions in the temperate regions.

Studies on the behaviour of this pest mainly covered two aspects; flight and sexual activities in pheromone production (Dickins, 1936; Haines, 1976). Steele (1970) found that peak sexual activity occurred just after dusk suggesting that

copulation usually took place at night. The moth, according to Barrer and Jay (1980) responded to grain odour and a high carbon dioxide concentration that stimulated egg-laying. Steele (1970) observed that eggs were laid soon after mating and that oviposition was completed within 2 - 5 days of the moth's emergence from the pupal cocoon. Takahashi, (1956c) found that the number of eggs laid ranged from 104 to 270 when the moths had no water to drink while Steele (1970) found that 400 eggs were laid if water was provided. Graham (1970a) found that egg laying took 2 - 3 weeks and that eggs hatched within one week.

In larval studies, Takahashi (1955) and Benson (1973) found that the number of larval instars varied between 3 and 7 depending on food availability and that if the larvae were too numerous, they tended to leave the food to enter a wandering stage while searching for cracks and crevices in which to pupate. During this wandering stage, large quantities of silk were spun which covered bagged maize, surfaces of walls and ceilings of warehouses. Burges and Haskins (1964) and Graham (1970a) observed that adult moths were found amongst the grains or resting on bags and store fabric surfaces. Three generations were produced in a year (Graham, 1970a) under natural warehouse conditions but up to 6 generations were produced under higher temperatures. Bosselli (1933) and Takahashi (1978) also found that the developmental period depended on temperature and relative humidity levels and also on the nutritional value of the food available to the moth.

1.2.3 Population Ecology of *E. cautella* in relation to other Pests of stored products.

Munro (1966) and Benson (1973) stated that the need for profound understanding of the population dynamics of storage insect pests was fundamental to devising effective control strategies, particularly for integrated management. These findings were highlighted in various host-parasite

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interrelationship studies by authors such as Ayertey (1978), De Lima (1973), Flanders and Hall(1965), Hassell (1971) Kentack(1959), White and Huffaker (1969) and Whiting (1961). Predation and disease occurrence on storage pests were also reported by Fulton (1933) and Williams and Floyd (1971) and possibilities for their use in biological control were mentioned.

Among the studies reported on factors causing changes in the population of E. cautella, Takahashi (1981) observed that population density had a marked effect on the speed of development, mortality and reproduction. High density resulted in prolonged developmental periods, high mortality and consequently reduced reproduction rates. Similar effects were produced through temperatures lower than or higher than 30 degrees centigrade which appeared to be the optimum temperature for the development of this pest (Burges and Haskins, 1964). Another negative effect of high density and sub-optimal temperatures was the production of sex-ratios at variance with 1:1 leading to higher female or male components which was accompanied by malfunctioning of the copulatory organs (Benson, 1973). Also, it was shown by Bell (1976) that E. cautella is very sensitive to crowding and as such is best reared on shallow food in cultures of greater surface area. Bell had earlier in 1975 found that development of this moth was most successful at 30 degrees centigrade and 70% R.H. He showed too, that pupal development was prolonged if temperatures were lowered leading to an overall longer developmental period.

The effects of over-crowding were further elaborated by Navarro and Calderon (1974) who showed that high carbon dioxide concentration directly resulting from overcrowding was lethal to the moth and led to reduced weight of adults. Similar effects were demonstrated when moths were bred at relative humility levels below 70%.In the above trials by Navarro and Calderon, concentrations of carbon dioxide higher

than 29 percent and relative humidities of 20 - 22 percent were also shown to have similar effects. In other trials, Imura (1981) found that relative humidity ranges between zero and one hundred percent affected neither the percentage of eggs hatching nor the pupal mortality in E. cautella, these being the hardiest stages.

1.2.4 Parasites and predators of E. cautella

Champ and Wallace (1981) reported on the parasites of the moth E. cautella and observed that the moth was subject to parasitism and predation in its various developmental stages by other arthropods found in Orders; Hemiptera, Hymenoptera, Diptera and Acariforma. They also indicated that some of these natural enemies had influenced the moth population under natural warehouse conditions.

Myers (1929 and Boselli (1933) had reported the wasp **Microbracon hebetor** as a parasite on the larvae of **E. cautella**. Also **Nemeritis canescens** another wasp and ants **Iridomyrmex defectus** and **I. rufoniger** Lorne were found by Graham (1970b) to be predators on the eggs of the moth. In studies of the mite **B. tarsalis** and the moth **E. cautella**, Graham (1970b) and Haines (1977) recorded heavy predation on the moth's eggs. A scenopinid fly was also observed to attack the eggs of the moth in maize storage warehouses by De Lima (1978) while Hagstrum (1983) reported parasitism of **E. cautella** by **Bracon hebetor** Say, a braconid wasp which suppressed the moth population dramatically within only two generations. However, in the laboratory , experiments failed to show this, making the author to conclude that there were possibilities of other unknown key factors that were operating.

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of E. cautella through fumigation with either carbon disulphide or carbon tetrachloride. Later, Harris (1945) working in Tanzania found that for general control of storage pests, diatomite applied at 0.5% by volume gave some control in shelled maize.

Lindane at 1.0 percent was also recommended for control of general pests in farm-stored cob maize (Kockum, 1953, 1958). Kockum obtained complete protection from pest-infestation for 13 months on maize dusted with 0.06% gamma BHC plus 4 g coumarone in one litre of kerosene per 100 sq. ft. Later, Lloyd and Hewlett (1958) tested other pesticides and found that 0.3 percent pyrethrins in 3.0 percent Shell Risella Oil 17, controlled E. cautella adults. Their experiments demonstrated that in the more effective and moderate cases, 98% and 56% mortality, respectively, were obtained within 6 days of treatment.

Green and Kane (1960) found that pyrethrins (0.3%) synergized with 3.0% piperonyl butoxide led to control of the pest when applied on the outside of stacks on cocoa at 1 gal. per 500 sq. ft. at monthly intervals. Later, McFarlane (1966) reported in Jamaica that synergized pyrethrum in technical white oil at 1.3% pyrethrins equivalent applied at 1 gal. per 2000 sq. ft. appeared to give effective control of E. cautella among other pests on bagged copra for 8 - 10 days in a closed warehouse. In further trials in Kenya, MacFarlane (1963) found that while fogging treatment with pyrethrins synergised with piperonyl butoxide reduced adult E. cautella populations in warehouses in Nairobi, it had negligible effect on the larval population. Therefore, these findings showed that pyrethrins, synergized or not gave limited control of this pest.

Other insecticides such as lindane and malathion were later shown not to offer reliable protection to maize when admixed into shelled maize or when cobs were dusted (Parkin and Forster, 1963; Ashman 1964) even when followed by fumigation

with methyl bromide. Ashman 1964 had also found malathion wettable powder sprays or Lindane and DDT admixture unsatisfactory against E. cautella infestations, thus necessitating further fumigations every 3 - 4 months, particularly, against T. castaneum, commonly associated with the moth's infestations. Ashman later in 1966, observed that 1.0 percent malathion even applied at 4 oz. per bag of 90 kg was not effective for control of E. cautella but that 0.2% pyrethrins synergized with 1.0% piperonyl butoxide was effective for 6 to 8 months if an additional synergist saffroxan was added. Thus, insecticidal dust admixtures and sprays with either malathion or lindane were not giving optimal control of the pest and further work was required to impart stability on pyrethrins.

Later work by Dyte and Rowlands (1968), Longoni and Micheli (1969), McFarlane and Sylvester (1969) and Ardley and Sticka (1977) confirmed this instability of pyrethrins and other insecticides known by then including malathion, fenitrothion and bromophos. Further screening of other chemicals was carried out by Strong (1969, 1970) whereby direct application of spray solution to the moth showed that among 12 organophosphorous insecticides, dichlorvos was the most effective agreeing with earlier findings by Tyler and Greene (1968) who found that rapid reinfestation by this pest occurred on bagged maize in conventional warehouses following the use of malathion and lindane as protective sprays. Other tests comprised dichlorvos in slow release strips and automatic dispenser units (McFarlane, 1963; McFarlane and Sylvester, 1969; Bengston, 1976). These special techniques were tested mainly towards reducing the then considered excessive reliance on spraying which required the use of rather expensive equipment. the slow release strips were found useful in warehouses with still air arising from limited ventilation while the automatic dispenser technique was suitable since by its correct timing of sprays the crepuscular

behaviour of the moth could be used beneficially to automatically apply the spray when the moth is most abundant. In later trials with other organophosphates, Weaving (1981) demonstrated that fenitrothion, iodofenphos and tetrachlorvinphos were more effective than pyrethrins while malathion was intermediate in the control of this moth. Fenitrothion and pirimiphos-methyl gave protection for over 12 months at 2 and 4 ppm. These trials were carried out on insecticide admixed grain in traditional grain bins. In 1982, Zettler found that there was no resistance to dichlorvos and pirimiphos-methyl in malathion resistant E. cautella while Greening (1983) found that barley was protected for 10 months from E. cautella when treated with fenitrothion. Wool and Belsky (1983) also found that older moths were more susceptible to malathion mainly due to exhaustion from flight activity and mating.

More recent trials employ organophosphates in combination with pyrethrins and pyrethroids (Ardley, 1976). Bengston et al (1983) showed that organophosphorothioates and synergised pyrethroids were effective in the control of E. cautella. They also found that malathion resistant strains of E. cautella were sensitive to fenitrothion plus bioresmethrin and pirimiphos-methyl plus carbaryl mixtures. Chlorpyrifos-methyl plus piperonyl butoxide and fenitrothion plus (IR)-phenothrin mixtures also controlled this pest. Yadav and Jha (1985) tested deltamethrin, cypermethrin and permethrin for persistence on glass, polythene, filter and jute fabric, and showed that deltamethrin at 20 mg/sq m and 3 ppm as dust treatment on wheat was most effective followed by cypermethrin and pyrethrins.

1.2.6 Biological Control

Graham (1966) found that after fumigation with methyl bromide, E. cautella population attained its third generation peak in

140 days and during this period about 3,000 adults were being caught in flight traps each day. Thereafter, a decline was recorded in the moth population which was caused by the mite B. tarsalis to a level where 1-10 moths per day were being counted. He also found that T. castaneum eggs served as an alternative host which the mite reverted to when E. cautella eggs were in short supply. Graham (1966) also noted that in the absence of chemical sprays and the mite, E. cautella populations were very large and occurred often in combination with T. castaneum. Apart from the apparent control by B. tarsalis, he also found that disease caused by Bacillus thuringienesis, predation by the coffee ant Pheidole megacephale (Crowe) and spiders played a role in the reduction of E. cautella population.

Haines (1974, 1981) reported that the mite B. tarsalis had a worldwide distribution in its feeding on the eggs of E. cautella on which it seemed to impart natural control particularly on maize in bag storage warehouses. Graham (1970b) postulated that:(1) B. tarsalis was able to control infestations of E. cautella to an economic level, especially in concert with an alternate host; (2) that where an insecticide was necessary to be combined with mite control, some chemicals appeared to be more toxic to the mite than to the moth and; (3) that the continued use of such an insecticide led to the increased importance of E. cautella as a pest in maize stores.

Other biological control agents on E. cautella were recorded by Myers (1929) who observed Microbracon hebetor and Nemeritis canescens as parasites and ants, Iridomyrmex defectus and I. rufoniger Lorne as predators on the moth. In detailed studies, Benson (1974) found that in a relationship between E. cautella and Bracon hebetor, the key factor causing population change in the moth was the egg and early larval mortality caused either by mite predation and larval competition for food and

space or by variation in fecundity due to changes in emerging adult numbers. In 1982, Press et al tested two parasitoids B. hebetor and Venturia canescens and a predator Xylocoris flavipes in suppressing the population of the moth whereby they found that the parasitoids exerted greater control than the predator.

1.3 SCOPE, AIMS AND OBJECTIVES OF THE STUDY

In previous studies, relevant ecological factors in the biology of E. cautella have been identified. Some of these have been studied in detail while others have yet to be explored. Except for the ecological work by Graham (1970a, b and c) most of the studies in Kenya have dwelt on insecticide screening both in the laboratory and in the field trials. The purpose of the present study was, therefore:-

(1) To understand key biological and ecological aspects of this pest in laboratory and field trials in order to obtain an improved basis for control of the pest in maize storage warehouses in Kenya.

(2) To gain some understanding of the pest species composition in storage warehouses and their relative rates of abundance on maize.

(3) To develop an improved strategy for overall control of major warehouse pests that is based on sound ecological understanding of the moth and its associated pests.

The objectives of the study are:

(1) To determine the performance of the mite B. tarsalis in regulating E. cautella populations under defined field and laboratory conditions.

(2) To identify any other mortality factors which may contribute to regulation of E. cautella populations in Kenyan warehouses.

(3) To test the efficacy of the commercially used chemicals for the control of E. cautella in warehouses and compare

the effects of these chemicals against other potentially useful ones on both the moth and its mite predator.

(4) To elucidate the factors that encourage the development of E. cautella into a serious pest in warehouses in Kenya.

(5) To determine the timing for insecticidal or biological application in order to achieve maximum control of E. cautella before serious economic loss or damage of maize is incurred.

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CHAPTER 2

THE PREVALENCE AND IMPORTANCE OF E. CAUTELLA IN KENYAN GRAIN STORES

2.1 Introduction

Storage systems in Kenya vary from the simple traditional granaries used on the farm to modern bulk storage silos used in central storage. Between these extremes are conventional warehouses ranging in size from small transit sheds with a capacity of less than 5000 bags to large stores which were able to carry over 100,000 bags. Protection of grain in all these structures is beset with serious problems arising from insect pests attack which cause considerable losses. This survey was undertaken to determine the occurrence and the role of E. cautella as one of the insect pests in such storage facilities for maize grain. Infestation levels of this pest and its timing would be important in determining the moth's role in causing maize grain losses during storage.

Furthermore, since after harvest the maize is distributed from the surplus regions of the country to the high consumption and deficit ones, this survey would show how the moth has been dispersed through grain movement to all parts of the country where storage facilities exist. The survey would therefore highlight the role of the pest against other species occurring in storage warehouses.

2.2 Survey of E. cautella in maize storage warehouses in Kenya.

The survey was carried out to establish the role of E. cautella as a maize pest in Kenya. Initial investigations were carried out between 1978 and 1984 and covered most of the storage warehouses operated by National Cereals and Produce Board countrywide. The intention was to provide comparative

data on this pest against others commonly occurring alongside it under various agroclimatic zones. The resultant information was intended to form a basis for later, more detailed studies on this pest.

2.2.1 Materials and methods

Samples of 500g maize grain were extracted from stacked bags of 90 kg using a spear probe (Golob, 1976). This probe is capable of extracting 30g at each insertion. To obtain a representative sample of the full contents of a bag, the probe was applied with the open end facing downwards, then turned through 180 degrees after which the probe was withdrawn. The samples so collected were bulked then sieved to free the insects. The grain was thereafter incubated in Kilner jars inside a room whose temperature and relative humidity were controlled at 25 degrees centigrade and 70% R.H. for 4 weeks to obtain the F1 generation. This ensured that immature stages not apparent during initial sieving and examination were obtained and counted. During incubation, the jars were covered with filter paper to prevent entry of other insects.

2.2.2 Results

The locations of the various central stores in Kenya where the moth E. cautella was found to be a major pest are shown in Figure 1. These locations are shown against the main maize growing areas of the country. In this figure, those central stores in which E. cautella was found to be a major pest are indicated. Since in some stores other commodities were stored together with maize, only insects identified from spear probe samples could be correctly associated with maize. Many adults and larvae in some cases escaped sampling with a spear probe since they tended to wander away from the commodity. It was observed that E. cautella populations were higher in the outermost layers of maize grain stacks than in the internal regions. Out of the total 94 storage centres operated by NCPB,

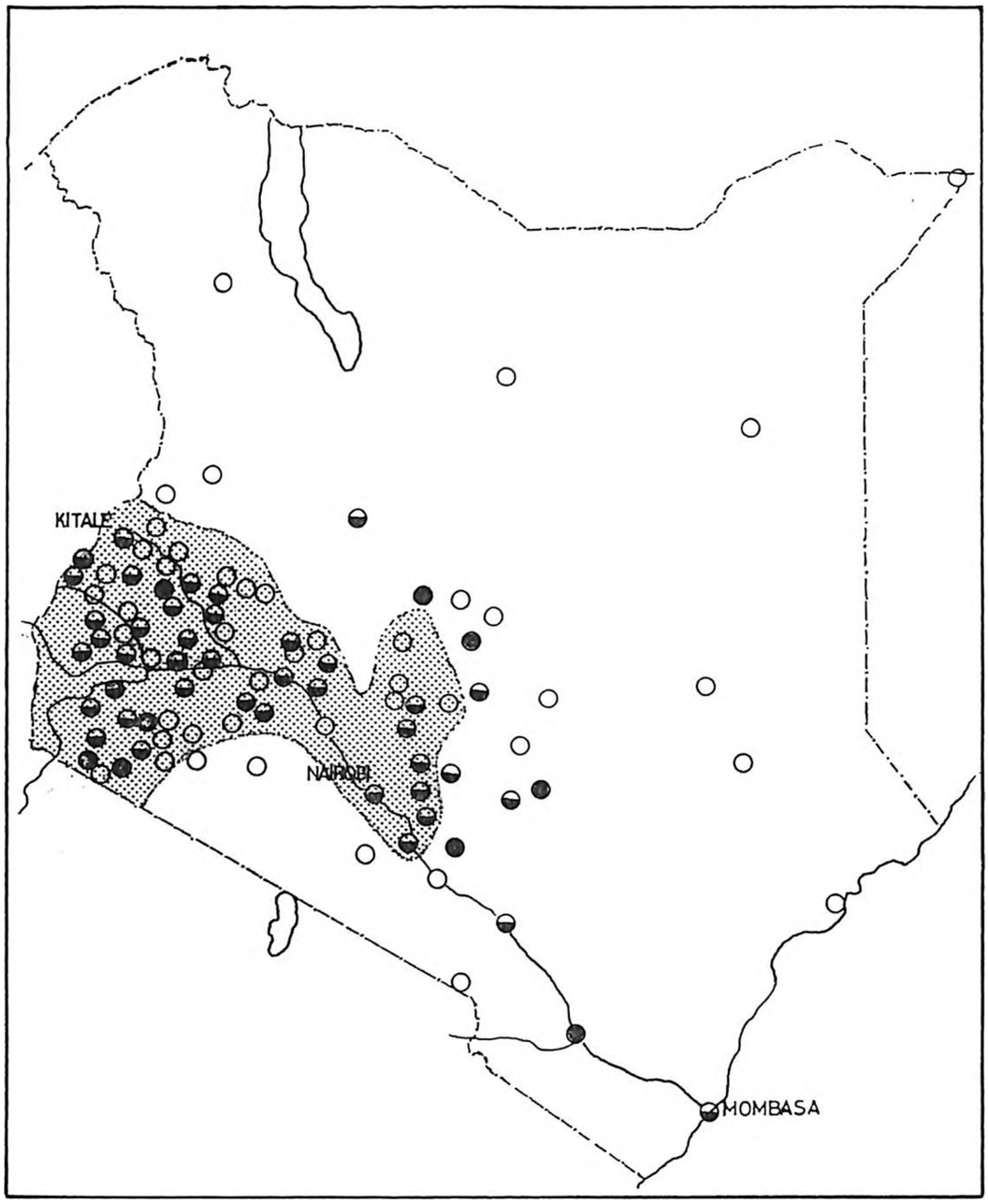

Fig 1. Map of Kenya showing National Cereals and Produce Board maize storage centres. E. cautella was identified as a prominent pest in centres with partially open (◒) circles. In the centres with closed (●) circles, E. cautella was not a prominent pest. Centres represented by open circles were not visited. The shaded area represents the main maize growing zone.

only 55 were sampled and 41 of these were shown to have E. cautella as a major pest of storage through the presence in high numbers in the samples obtained while six of these centres were in deficit areas.

The pest was also observed to prevail not only in depots located in the maize surplus areas in the country but also in the deficit areas and in high consumption areas located in cities and townships such as Mombasa, Nairobi and Nakuru.

2.2.3 Discussion and conclusions

E. cautella was the major insect pest recorded on maize being most abundant in the 41 out of the 55 storage sites visited. All the centres in the maize growing areas are susceptible to the occurrence of this pest. In all cases grain is fumigated on first entry into warehouses but this fumigation does not confer any residual protection on grain which rapidly becomes reinfested by E. cautella and T. castaneum. Infestation by E. cautella diminishes after approximately 4 generations to be followed by other secondary pests, these being those that browse on the outside of the grain or grain fragments (Barrer,1981). E. cautella was also found to attack wheat, sorghum and rice, both in milled and in paddy form, bulrush millet and finger millet.

From these surveys, it was observed that in many situations, E. cautella does not occur in isolation but rather in association with other pests simultaneously. Thus, control measures of practical value must of necessity take into consideration these other insect pests that are resident on the grain since they must also be controlled. These other pests are particularly secondary pests controlled through initial fumigation. The main pests associated with E. cautella were found to be T. castaneum, C. cephalonica and Plodia interpunctella. These are the pests which cannot be ignored in arriving at suitable measures to control E. cautella and whose

relationships with the key pest need to be understood to form a background to sound control strategies.

2.3 A STUDY OF E. CAUTELLA POPULATIONS IN CENTRAL AND EASTERN PROVINCES IN KENYA

2.3.1 Introduction

The use of chemical insecticides alone cannot eradicate E. cautella. The general practice has been to apply these chemicals regularly whenever the pest populations increase to such levels as to cause economic loss. Thus, numbers of this pest continue to fluctuate in a storage warehouse throughout the entire period that the commodity remains in storage. Since the pest is present all the time, aggregated damage continues to be incurred despite control measures. This survey therefore sought to trace the populations of the moth and its associated damage on maize in the stores.

2.3.2 Materials and methods

A survey of E. cautella in Central and Eastern Provinces was undertaken for 8 months from February to August, 1989 to explore the trend in population increase of the pest on maize. Thika depot was used as the representative sampling point for Central Province while Machakos and Konza depots were used for Eastern Province. Most of the maize stored in Thika and Konza depots had originated from Rift Valley, Nyanza and Western Provinces while about two-thirds of the maize in Machakos was locally produced.

Insects were collected from three sources:

(1) From spear probe samples drawn from the outermost layers of bags in stacks of maize ranging in size from 5,000 bags to 40,000 bags,
(2) From one square metre sampling areas marked on the stacks; and
(3) From similarly marked areas on adjacent wall surfaces.

The method of sampling from one square metre marked areas was considered suitable in estimating the moth population both on the wall and on the stack surfaces in these maize stores. Each spear probe sample consisted of 30.5±1.2g of maize grain. Insects were brushed off from both the wall and stack surfaces or picked using a "sucking" tube. Seventeen spear probe samples comprising approximately 500g of maize were collected. The maize was sieved off to free the insects and then incubated in a controlled temperature and relative humidity room at 27°C and 70% R.H to bring forth the first generation emergence. In both cases, live and dead insects were counted and recorded separately. It was ensured that marked areas on walls were made on similarly marked areas on the maize stack surface to ensure that infestations were as much as possible to those resident on maize since other commodities were also stacked in the same stores.

Damage by E. cautella larvae on grain was assessed by counting kernels excavated by the moth larvae since this kind of damage is distinct from that caused by primary pests, these being those that eat into the grain (Barrer, 1981). The 500g samples were subdivided through a Boerner divider to obtain a working sample of approximately 100g. E. cautella damaged grains were then weighed and their percentage of the total number in the 100g. sample calculated.

2.3.3 Results

Monthly adult counts for a period of 7 months from February to August, 1989 are shown in Table 2 for numbers obtained from probe samples while those swept from marked areas are shown in Table 3. Table 2 also shows the increasing damage obtained through the moth for this period and a high correlation of moth damage and the increase in moth numbers with time in all the three sites. The highest rate of increase of the moth which ranged from 60.42 to 256.23 was observed in Machakos while that of Thika which ranged from 38.97 to 170.38 was the lowest. The highest number of moths per 500 g observed was in

Table 2. Live and dead adult *E. cautella* obtained from 500g samples collected from maize stack outer layers of bags for 7 months from February to August, 1989 in stores in Thika, Machakos and Konza.

	Months (x)	2	3	4	5	6	7	8
Thika	Mean cumulative No. of insects (y)	4.24	32.43	34.80	78.33	117.70	119.89	143.52
	S.E.	±0.37	±2.10	±2.13	±5.22	±1.00	±1.64	±2.00
	Mean grain Damage %(z)	0.32	2.63	3.06	5.65	9.50	9.91	12.54
	Regression		y = 24.03x - 44.35					
	S.E. of slope		= 27.5*					
	Correlation co-efficient (y and z)		r = 0.99					
Machakos	Mean cumulative No. of insects (y)	12.56	57.41	73.11	151.98	158.25	192.36	208.07
	S.E.	±1.35	±1.30	±2.97	±1.33	±10.51	±12.58	±6.63
	Mean grain damage %(z)	0.82	4.12	5.36	11.15	12.65	14.04	15.26
	Regression		y = 34.60x - 51.04					
	S.E. of slope		= 54.92 ns					
	Correlation co-efficient (y and z)		r = 0.98					
Konza	Mean cumulative No. of insects (y)	6.12	34.29	44.69	45.14	45.78	73.81	76.35
	S.E.	±0.54	±2.77	±3.31	±3.14	±2.28	±6.53	±6.31
	Mean grain damage %(z)	0.77	4.98	5.17	5.25	5.33	9.57	8.98
	Regression		y = 10.37x - 6.25					
	S.E. of slope		= 9.0**					
	Correlation co-efficient (y and z)		r = 0.94					

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	Mean grain Damage %(z)	0.32	2.63	3.06	5.65	9.50	9.91	12.54
	Regression	y = 24.03x - 44.35						
	S.E. of slope	= 27.5*						
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	Regression	y = 34.60x - 51.04						
	S.E. of slope	= 54.92 ns						
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	Mean grain damage %(z)	0.77	4.98	5.17	5.25	5.33	9.57	8.98
	Regression	y = 10.37x - 6.25						
	S.E. of slope	= 9.0**						
	Correlation co-efficient (y and z)	r = 0.94						

Table 3. Live and dead adult *E. cautella* obtained from stack and wall surfaces of a maize filled store for 7 months from February, 1989 to August, 1989 in Thika, Machakos and Konza depots.

	Months (x)	2	3	4	5	6	7	8
Thika	Mean cumulative No. of insects	38.97	39.13	49.87	108.95	142.72	157.52	170.38
	S.E.	±2.57	±2.60	±0.95	±12.62	±9.18	±6.27	±15.21
	Regression equation	y = 23.8x - 25.09						
	S.E of slope	= 17.5**						
	Correlation coefficient	r = 0.96						
Machakos	Mean No. of insects	60.42	214.22	218.51	224.83	234.36	236.63	256.23
	S.E.	±2.16	±3.43	±25.25	±16.17	±12.63	±7.50	±6.46
	Regression equation	y = 23.2x + 89.96						
	S.E of slope	= 37.2**						
	Correlation coefficient	r = 0.76						
Konza	Mean No. of insects	66.50	182.64	184.39	188.98	198.82	222.73	242.89
	S.E.	±5.01	±1.98	±10.11	±8.74	±6.55	±18.45	±14.22
	Regression	y = 22.5x - 72.55						
	S.E of slope	= 31.91**						
	Correlation coefficient	r = 0.86						

Machakos during the eighth month. A similar trend was observed in moth period numbers collected from the walls as shown in Table 3 although the rates of increase of moth numbers were not significantly different.

Some other insect species were found in association with E. cautella, mainly T. castaneum, Liposcelis entomophilus, Xylocoris flavipes, Bracon hebetor, B. tarsalis and a scenopinid species, probably Scenopinus fenestralis, all of which except for T. castaneum and L. entomophilus are either predators or parasites. Figures of these species were however, not presented as the species do not form the subject of this study. T. castaneum occurred in such low numbers that the observed damage on grain was entirely attributable to E. cautella. Liposcelis entomophilus feeds on fine grain dust while the scenopinid species is a larval predator on both coleopteran and lepidopteran hosts. It was noted that the numbers of E. cautella were highest in Machakos where the mean maximum temperature was 24.7°C. The mean maximum temperature for Thika was 21°C but Konza which has the same order of mean annual temperature as Machakos had the lowest numbers counted over the period. It appeared, therefore, that population levels could not be simply related to mean annual temperatures since other factors such as variation in store management and other climatic factors possibly affected the moth development and multiplication.

2.3.4 Discussion and conclusions

The observed prevalence of E. cautella in large numbers corresponds with the prolonged storage period of maize which had been kept since the 1986/87 season. This trend was also

confirmed by the presence of Rhizopertha dominica and Cryptolestes spp, since these secondary pests occur much later in the pest succession pattern. It was also noted that despite the varied behaviour in grain damage by the species, there was continued co-existence, with none of the species being phased out indicating low competition and niche specificity.

During the survey period, fumigations with either phosphine or methyl bromide were carried out in March and June while sprays were done monthly with either dichlorvos or pirimiphos-methyl alternately. Dichlorvos is targeted at lepidopterous pests while pirimiphos-methyl is aimed at coleopteran species. Despite this pest control scheme, low levels of infestation of these pests persisted. Of particular note, was the continued presence of S. zeamais otherwise normally controlled during the first fumigation upon grain intake. With prolonged storage, the aggregate levels of infestation leads to intolerable quality and weight losses.

Actual sampling was carried out between 10.00 a.m. and 5.00 p.m. during which times the flight activity of E. cautella is lowest. This, in effect, gave a better estimate of the numbers because most of the insects would either be within the sacks or resting on stack and wall surfaces. Moreover, moth adults do not penetrate deep into grain layers, and therefore grain samples from spear probes could not yield large numbers of moths. Furthermore, a large number of moths tends to escape during collection and as a result, the numbers caught are usually lower than those actually present.

These observations show that in spite of an elaborate pest control programme such as that in use in these premises, it is

points that provide harbourages to insects such as cracks and crevices. Such inaccessible areas cannot be cleaned thoroughly or sprayed effectively since the spray drift often does not reach them. Therefore, regular and frequent use of chemicals in such premises is necessary if grain stacks are to be preserved in a sound state.

CHAPTER 3
POPULATION DYNAMICS OF E. CAUTELLA IN MAIZE STORAGE WAREHOUSES UNDER CHEMICAL CONTROL PROGRAMMES

3.1 Introduction

In the previous chapter it was observed that despite the existence of elaborate pest control programmes, storage insects are not in practice normally eliminated but instead their numbers continued to fluctuate. Past studies by Graham (1966) and personal observations indicate that the levels of insect numbers are low following a fumigation or spray operation but thereafter, they rise again until it becomes necessary to re-fumigate or re-spray. The purpose of this investigation was, therefore, to outline the role of E. cautella in relation to other pests occurring at the same time in storage warehouses.

This re-infestation was related to the specific periods of fumigation or spray and to the types of fumigant or spray used. It would bring out the frequency of fumigations or spray required as a result of this re-infestation. From experience, it has been observed that the first fumigation following loading a store with maize controls primary infestation by Sitotroga cerealella and Sitophilus spp. (Ashman, 1964, McFarlane, 1969). In this investigation this observation would be confirmed or refuted. Furthermore, fumigations and sprays are only carried out when light infestation is present (Ashman, 1970) since economic rationale dictates that it would be wasteful to undertake pest control measures when pests are absent. This "light infestation" cannot in practice be determined with precision (Thomas,

1981). The present investigation would establish the infestation at which pest control measure would be undertaken.

3.2 Materials and methods

Using a paint brush, all insects were swept monthly from eight one metre square marked areas on maize stacks and wall

surfaces and then pooled together. The sampling areas on the wall surfaces were marked directly opposite those on the stack surfaces. A hand aspirator was used to collect adult moths resting on the walls and stack surfaces. The insects collected were examined and identified using Freeman's (1980) key.

Sampling was sustained for 12 months from September, 1988 to August 1989. During this period some stacks were disposed of and others erected. Hence, some marked areas were abandoned while new ones were made. When full, each of these stores has a capacity of 50,000 bags or about 4,500 tonnes of maize. Such a store would have 8 sampling locations distributed 12 metres apart. Insects were collected between 10.00 a.m. and 5.00 p.m. since outside these limits most of them, particularly the lepidopterous species would be in flight rather than resting on store and stack surfaces and would escape being captured.

3.3 Results

The changes in the insect numbers collected are shown in Figures 2, a, b, c, and d, standing for Stores 4,5, 9 and 10

STORE 4

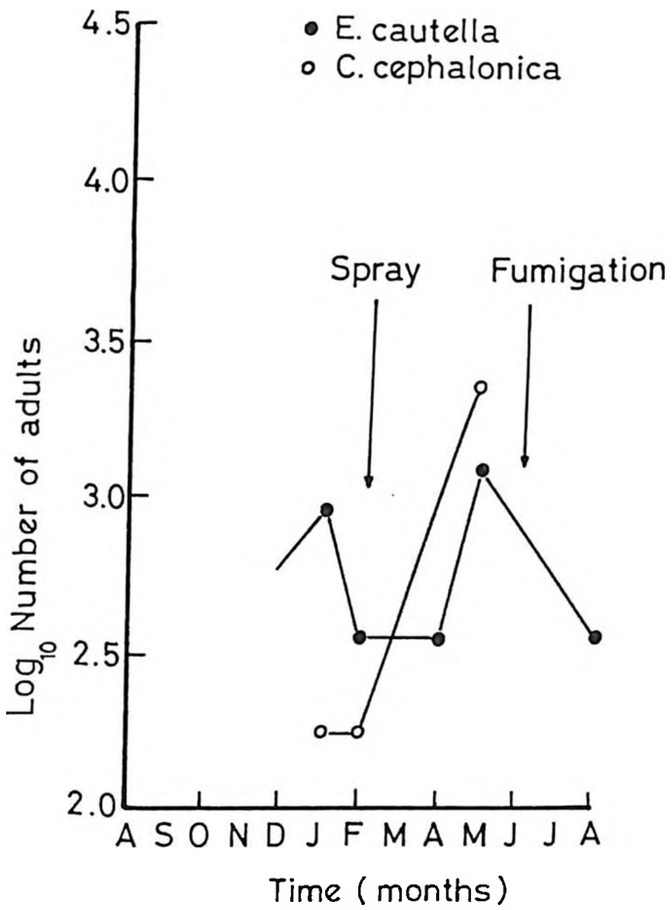


Fig 2. Population trends of important species of stored maize over a 12 months storage period in 4 Nairobi stores.
(a) Store 4.

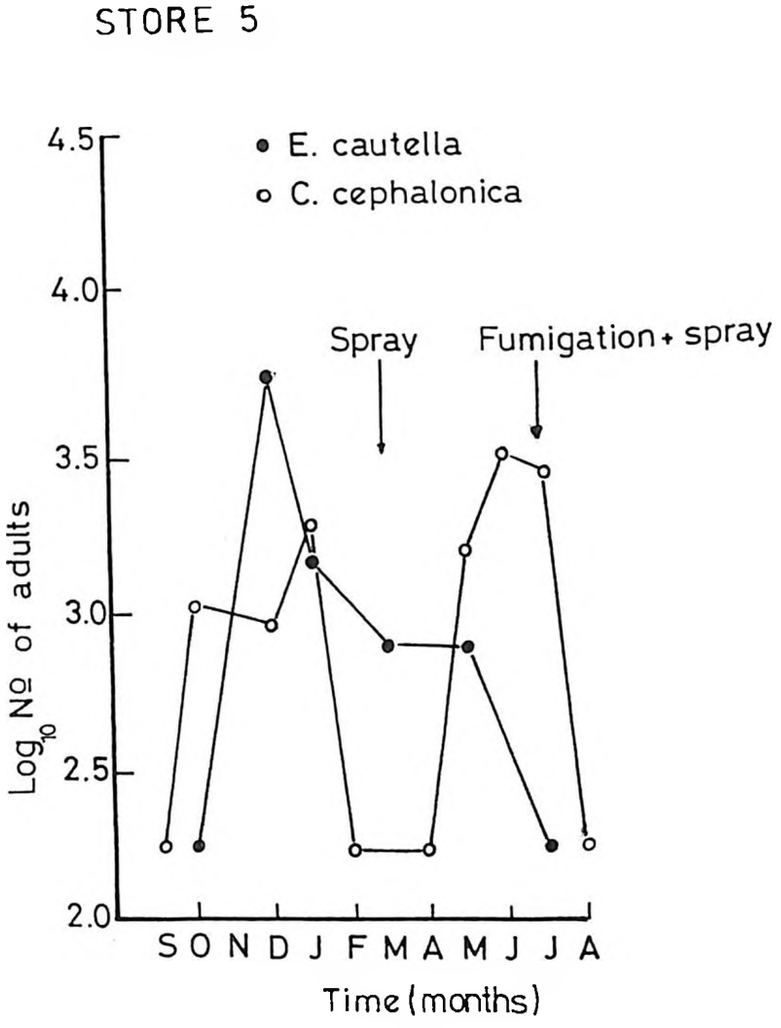


Fig 2. Population trends of important species of stored maize over a 12 months storage period in 4 Nairobi stores.
(b) Store 5.

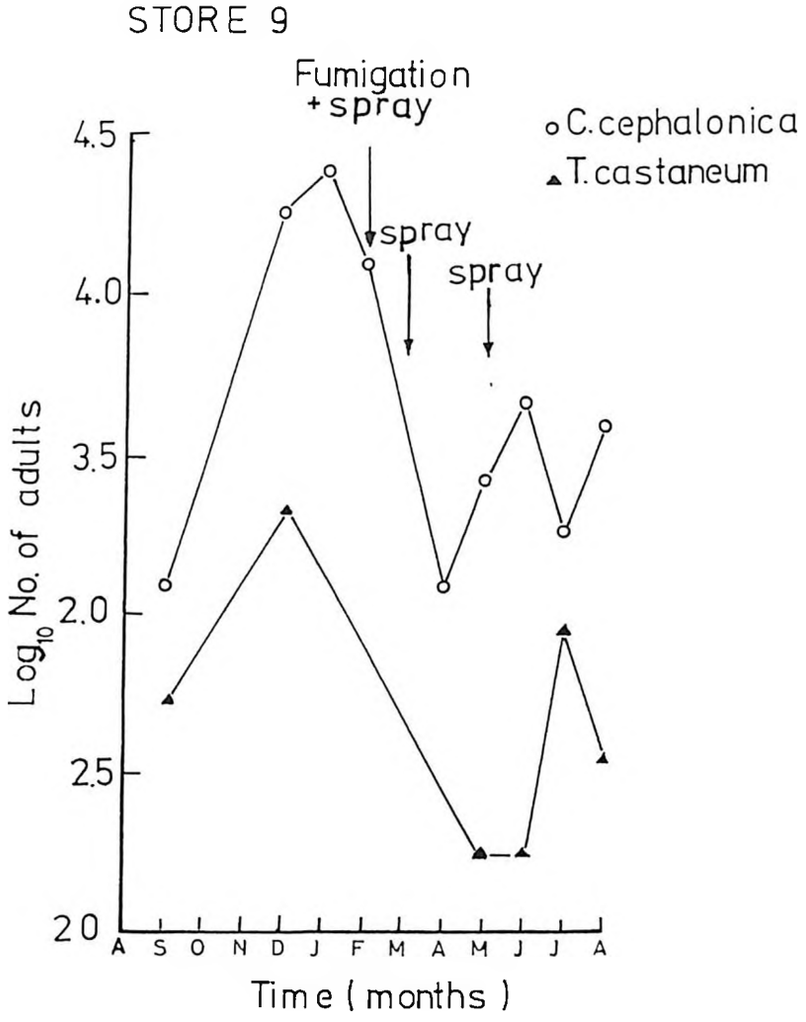


Fig 2. Population trends of important species of stored maize over a 12 months storage period in 4 Nairobi stores.
(c) Store 9.

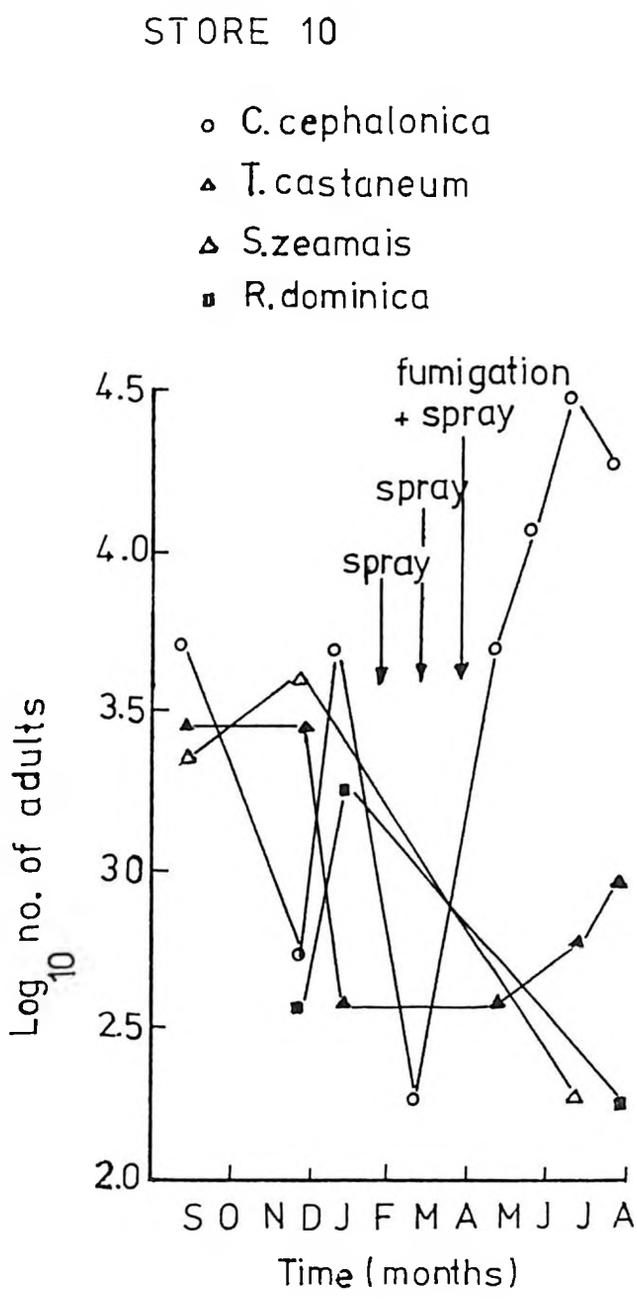


Fig 2. Population trends of important species of stored maize over a 12 months storage period in 4 Nairobi stores.
(d) Store 10.

respectively. In Stores 4 and 5, only E. cautella and C. cephalonica were found. In Store 5 (Fig.2b) Sitophilus zeamais and R. dominica were also prominent apart from C. cephalonica and T. castaeum. The absence of E. cautella can be explained as being a result of the rapid turn-over of maize stocks arriving and being disposed off which inhibited normal succession of storage insect infestations. Population trends are shown in logarithms in order to damp the wide fluctuations in numbers thus making the changes clearer. The presence of S. zeamais and R. dominica in Store 10 can be explained by the introduction of new previously unfumigated maize into this store. In Stores 9 and 10, E. cautella was recorded in very low numbers and, although observed in other locations within the same stores, was not caught in the marked areas. Also these, stores were located approximately 100 metres from Stores 4 and 5 which implied that cross-infestation was minimal.

3.4 Discussion and conclusions

In the results of insect counts as shown in Fig. 2, wide variations both in species diversity and abundance of individual species were a common feature. The wide fluctuations in insect numbers in these stores can partially be explained by the frequent movement of maize in and out since these stores were under normal continuous operation. It was evident too, that the longest stored maize had been in storage for a maximum of only 8 months. This frequent movement itself caused considerable disturbance to the insect populations. Furthermore, some stores contained other commodities at some stage which even if they may not share the same pests, caused variations in patterns and trends of

temperatures and relative humidities. These physical parameters in turn would affect the insect populations associated with maize.

During the 12 months period, maize in these stores was sprayed at least twice and fumigated at least once. The spray chemicals were either dichlorvos or pirimiphos-methyl which were used alternately while the fumigant used was either phosphine or methyl bromide. Dichlorvos has no residual effect and normally gives a better kill of moths while pirimiphos-methyl is more effective against coleopterous infestations. The fumigants have no known residual effects and both give close to total kill when properly applied. Fumigations are always accompanied by sprays with one or other of the two types of insecticides.

Apart from Store 10 in which grain which had received no prior fumigation was stored, the other stores did not carry primary infestations. The population of S. zeamais in Store 10 also declined after the fumigation in April. This, in effect, confirmed that primary infestation ceases to be a problem with the first fumigation and thereafter, other pests, mainly E. cautella, C. cephalonica and T. castaneum persist in storage in varying numbers. It is observed that although sprays are considered to be effective in that they substantially reduce pest numbers, complete eradication is not possible. One of the reasons which has been given as an explanation for this by Graham (1970b) and Haines (1981) is the suppression of the predator B. tarsalis by these chemicals and incomplete control by the chemical spray thus negates possible control of the pest by the predator during the intervals between succeeding sprays. This incomplete control of the moth has also been

temperatures and relative humidities. These physical parameters in turn would affect the insect populations associated with maize.

During the 12 months period, maize in these stores was sprayed at least twice and fumigated at least once. The spray chemicals were either dichlorvos or pirimiphos-methyl which were used alternately while the fumigant used was either phosphine or methyl bromide. Dichlorvos has no residual effect and normally gives a better kill of moths while pirimiphos-methyl is more effective against coleopterous infestations. The fumigants have no known residual effects and both give close to total kill when properly applied. Fumigations are always accompanied by sprays with one or other of the two types of insecticides.

Apart from Store 10 in which grain which had received no prior fumigation was stored, the other stores did not carry primary infestations. The population of S. zeamais in Store 10 also declined after the fumigation in April. This, in effect, confirmed that primary infestation ceases to be a problem with the first fumigation and thereafter, other pests, mainly E. cautella, C. cephalonica and T. castaneum persist in storage in varying numbers. It is observed that although sprays are considered to be effective in that they substantially reduce pest numbers, complete eradication is not possible. One of the reasons which has been given as an explanation for this by Graham (1970b) and Haines (1981) is the suppression of the predator B. tarsalis by these chemicals and incomplete control by the chemical spray thus negates possible control of the pest by the predator during the intervals between succeeding sprays. This incomplete control of the moth has also been

observed by Graham (1961, 1970b) in situations where malathion, one of the longest used storage chemicals, has been applied.

In order to improve control of these pests, it is therefore important to investigate certain biological features about them, their reactions to the chemicals and the role of the predators especially B. tarsalis in the control of the pests before and after a spray operation. The key pests in this relationship are E. cautella, C. cephalonica and T. castaneum. C. cephalonica is more prevalent in stores in Nairobi, Thika, Sagana, Machakos and Konza than in the rest of the country. C. cephalonica was previously a minor pest until it was accidentally introduced in large numbers with imported yellow maize from Thailand and the United States of America in 1984/85. Numbers of the pest have been decreasing since then and it is expected that the pest's frequency will eventually drop to the previous low level since yellow maize storage is nearly over. R. dominica, on the other hand, can be associated with the wheat stored in the same warehouses adjacent to the maize. Wheat is known to be very susceptible to R. dominica.

CHAPTER 4

THE PREDATION ON E. CAUTELLA BY THE MITE B. TARSALIS UNDER WAREHOUSE STORAGE CONDITIONS

4.1 General introduction

Populations of the mite B. tarsalis and their prey moths increased correspondingly following a fumigation resulting in a rapid decline in the moth numbers by the third generation (Graham 1970b). This was followed by very large numbers of B. tarsalis which reduced the numbers of E. cautella. This decline of the prey was attributed to predation of the moth's eggs by B. tarsalis. Graham also emphasized the choice of chemicals that should be used in this treatment since some, such as malathion, lindane and piperonyl butoxide used for synergising pyrethrins did not appear to be effective. The role of the mite on the moth in this context had not been previously studied. This investigation was an attempt to evaluate the mite's role on E. cautella population under natural maize storage conditions in Kenya.

It is hoped that the findings could form a sound basis for formulating strategies using biological control techniques for stored products protection. Furthermore, the rate of feeding of the mite on moth's eggs was evaluated in an attempt to obtain the impact of the mite in reducing moth populations. Lastly, the analysis of one generation life-table data was necessary to determine the multiplication rate as compared to that of the mite under simulated warehouse conditions.

4.2 Studies of *E. cautella* populations under *B. tarsalis* predation in four warehouses in Nairobi between chemical spray intervals

4.2.1 Introduction

Pest control practices in maize storage warehouses incorporate fumigations and sprays. The influence of these chemical applications not only on the mite population itself but also specifically on the numbers of mites per moth was not known. This sampling survey, therefore, sought to determine the trend in the *E. cautella* predation by *B. tarsalis* during intervals

from their prey moths by shaking all those collected in ethyl acetate and then counted under a dissecting microscope. Moths for this estimation were collected once a week for 22 weeks, this being the period that the maize stacks lasted in these warehouses before being disposed off through sale or transfers.

4.2.3 Results

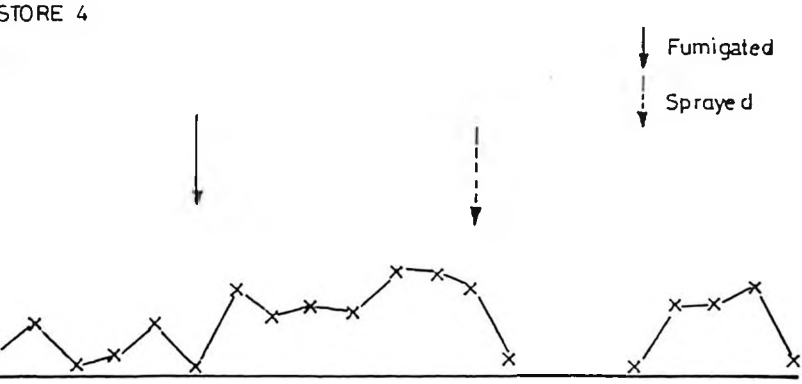
Fig. 3 shows the trend in the number of mites found on each individual adult E. cautella for the 22 weeks in the 4 warehouses whereby the maximum peak number was 2.94 mites per moth. There were no moths collected after 9th week period in Store 9 and between 6th week and 16th weeks in Store 10. In Store 4, during the period between the fumigation at the 6th week and spray at the 12th week there was an increase in mite numbers per moth of up to 2.2. A similar trend was observed in Store 5 between the 6th week and 12th week. At each spray operation, however, the number of mites per moth was seen to decline but did not reach zero. Also, in all cases, all the moths sieved contained mites and the lapse following each spray was short-lived lasting less than 2 weeks.

In Fig. 4 the relationship between the number of mites/moth against time in weeks for the periods between the 5th and 12th week is shown whereby linearity is observed with a significant correlation in Store 5. There were no visible differences in the levels of phoresy of mites on adult moths regarding whether spray was with pirimiphos-methyl or dichlorvos although this was not systematically evaluated. Other pests which were observed to occur in small numbers in association with E. cautella were T. castaneum, C. cephalonica, and Plodia interpunctella.

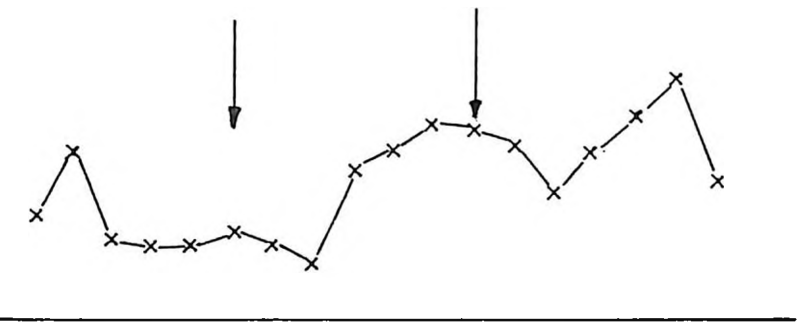
with =

interpunctella.

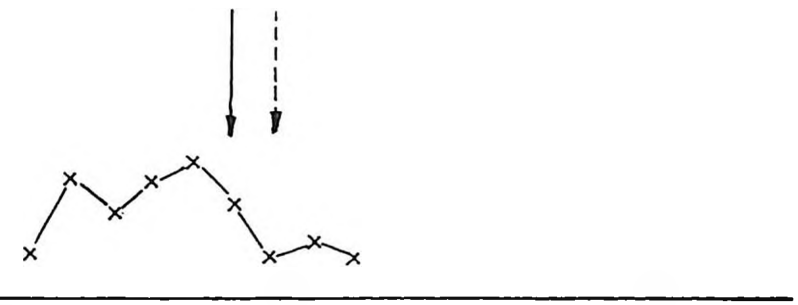
STORE 4



STORE 5



TORE 9



TORE 10

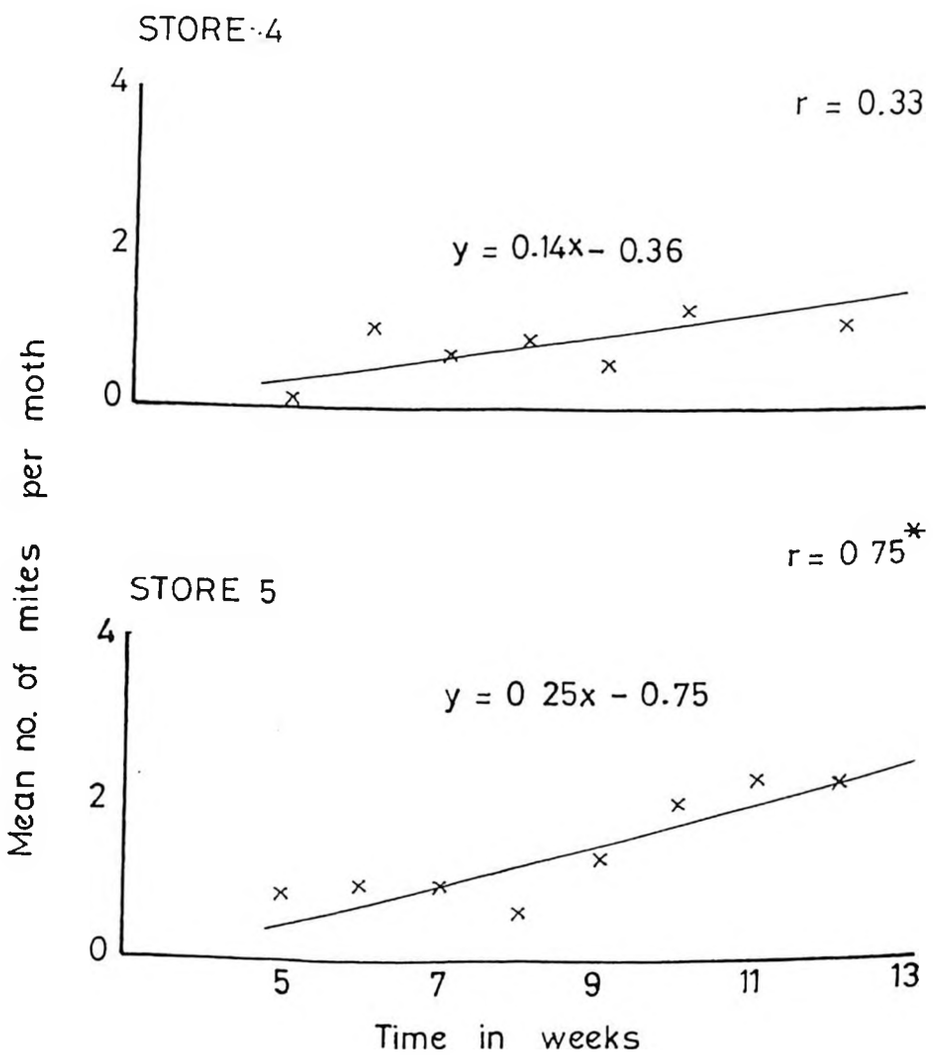


Fig 4. Relationship between time and number of mites per moth in the intervals between successive insecticide treatments in Stores 4 and 5 in Nairobi GCP depot (see also Fig 3.)

4.2.4 Discussion

Since fumigants have no residual effect, any residual control was due to these chemical sprays that is, either dichlorvos or pirimiphos-methyl. Infestation by moths signified the end of such effects. Their numbers beyond a given level meant that treatment was again necessary.

T. castaneum eggs and those of the other two moths, C. cephalonica and P. interpunctella have been recorded by Benson (1973b) as providing alternate hosts to B. tarsalis. Hence, their presence would appear to be beneficial especially when they occur in small numbers but this apparently positive factor is negated by the fact that these species are also pests in their own right. The observed relationship between the increase of the numbers of mites counted per moth with time following a spray is seen as initiating the interaction between mites and moths where the moth populations increased with time and later fell as a result of the predatory influence of the mite (Graham, 1970a, b and c). Furthermore, mites were not confined to adult moths but also abounded on other surfaces in the warehouses such as on walls, floors and bag surfaces and for this reason could not be counted. Mites were also found among the grains within the bags and although no attempt was made to enumerate these, it was recognized that a large reservoir existed for phoresy on the moths. Mites were also found among the grains within the bags. Moreover, individuals concealed in the deep layers of the grain in the bags were not accessible by sprays and survived when spraying was carried out separately without accompanying fumigation. As shown in Fig. 3, there were also no distinct differences in predation rates within the four warehouses despite variations

in the frequency of sprays and fumigations. Although comparisons of mite populations on bag surfaces, on wall and floor surfaces were not made, it was observed that the effective population of mites was that within the stacks or amongst the grains, since this is the region where the moths laid their eggs. Hence, mite populations on walls, floors and on doors became important as a reservoir for phoresy on the adult moths during their wandering while in flight in these areas.

Apparently, the role of the mite in the control of the moth population can only be realised in situations where E. cautella is prominent as a pest of maize but this role becomes limited if other pests such as T. castaneum and C. cephalonica are important as well. Although eggs of these other pests have been shown to provide alternative hosts to B. tarsalis (Haines, 1981) they are themselves pests in their own right and cannot therefore be tolerated in storage.

4.3 Determination of phoresy preferences by B. tarsalis for sexes of E. cautella moths.

4.3.1 Introduction

In the previous studies of E. cautella and B. tarsalis the level of predation on the different sexes has not been established. An understanding of differential sex preferences of this mite is necessary especially as this factor influences the searching efficiency of the mite and ultimately the performance in the control of the moth. Also, it was not clear if predation levels varied from place to place for each of the sexes of the moth and on both sexes combined. A trial was, therefore set up in three storage sites, namely; Thika,

Machakos and Konza to elaborate on these aspects as a further attempt to obtain an improved understanding of the mite, the moth and their interrelationships.

4.3.2 Materials and methods

Moths were collected from three stores located at Machakos, Thika and Konza. In each store, fifty moths each of males and females were obtained from the collected number through subdivision in a sorting tray. Individual adult moths were sexed and placed in a 7.5cm x 2.5 cm specimen tube with ethyl acetate and shaken vigorously to release the mites which according to Graham (1970) would normally be tucked underneath the wings. **E. cautella** males and females were easily identified using size, wing and labial palp characteristics (Freeman, 1980; Collier, 1981). Mites were then counted on a filter paper under a dissecting microscope.

4.3.3 Results

The numbers of **B. tarsalis** mites counted from male and female **E. cautella** moths collected from stores in Thika, Machakos and Konza are shown in Table 4 and a statistical analysis of the data is given in Table 5. The rate of predation on eggs in individual females as compared to that on males as determined through the number of mites extracted from adult moths was significantly higher in Thika than either in Machakos or Konza. This indicated that females tended to have higher numbers of mites in phoresy than males.

There was also a significant difference observed between the number of mites counted on females between Thika and Machakos, and Machakos and Konza but as regards phoresy on the males

Table 4. Number of *B. tarsalis* mites found in phoresy on 50 male and female *E. cautella* adult moths collected from Thika, Machakos and Konza.

Sample at 1 month intervals	Sampling Site											
	Thika				Machakos				Konza			
	m	f	m+f	f/m	m	f	m+f	f/m	m	f	m+f	f/m
	26	71	97	2.73	75	94	169	1.25	15	23	38	1.53
2	122	336	458	2.75	74	95	169	1.28	24	35	59	1.45
3	98	268	366	2.73	86	106	192	1.23	58	98	156	1.68
4	253	645	898	2.54	128	188	316	1.47	77	108	185	1.40
5	254	509	763	2.00	140	185	325	1.32	79	124	203	1.56
6	310	902	1212	2.90	156	200	356	1.28	90	137	227	1.52
7	124	272	396	2.19	92	186	278	2.02	83	96	179	1.16
8	81	252	336	3.08	76	77	153	1.01	101	155	256	1.53
Mean	158.50	406.88	565.75	2.62	103.38	141.38	244.75	1.36	65.88	97.00	162.88	1.48
S.D.	100.53	265.00	362.49	0.36	32.88	52.50	82.53	0.30	31.19	45.50	77.07	0.15

Key: m = males, f = females, f/m = ratio of females to males, m+f = sum of males and females.

Table 5. Testing of B. tarsalis mite infestation on E. cautella in Thika, Machakos and Konza sites.

A. ANOVA tables.

	Source of variation	Degrees of freedom	Sum of squares	Variance	F
Male + female infestation	Total	17	1497452	88091	
	Replication	5	329045	65809	
	Sites	2	885610	442805	15.7**
	Error	10	282887	28288	
Female infestation	Total	17	857688		
	Replication	5	158855	31771	
	Sites	2	525966	262983	1.52ns
	Error	10	172867		
Male infestation	Total	17	96494		
	Replication	5	32248	6450	
	Sites	2	48220	24110	15.04**
	Error	10	16026	1603	

B. Comparison of moth infestation of B. tarsalis in the 3 sites

Site	Male + female	Female	Male
Thika	682	489	194
Machakos	272	160	113
Konza	168	100	69
$LSD_{.05}$	342.05		81.5

** Significant at 1% level
ns not significant

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only Thika and Konza were significantly different. In relation to the combined number of mites on both female and male moths again only Thika was significantly different from Konza.

These results demonstrated variations in phoresy between different sites for females and males and a general preference for females. The presence of large numbers of mites on male moths though non-egg-laying was noticeable with up to 5.1 mites per male moth in Thika and a mean of 2.2 moths per mite. The maximum number of mites per female moth on the other hand was 18.0 and the average female moth phoresy was 4.1 in the three places.

4.3.4 Discussion

The observed presence of mites on male moths is considered to be purely for the purpose of phoresy as the mites are not known to feed on other materials apart from eggs laid by the female moth. Nevertheless, this is beneficial in enhancing searching efficiency as it enables wider distribution of the mite amongst the female population. The higher incidence of the mites on females meant that the mite is able to distinguish between the sexes. This however would not be necessary for the purpose of feeding which occurs away from the moths body where the eggs are deposited.

The variation in the levels of phoresy of both male and female moths in the three places also indicated that the regimes in control which may be expected of the mite will vary from place to place. This was likely to be dependent on the mode of activity of the spray chemicals (dichlorvos and pirimiphos-methyl) applied, or on actual intrinsic intensity of mite predation on the moth eggs and actual adult moth

susceptibility to phoresy in these places. Graham (1970b) observed the variation of moth numbers in a stack of maize to be dependent on temperatures, and moth population has been shown to be interrelated with the mite population. Other factors that are considered to have influenced the levels of predation are the alternate host populations of T. castaneum and C. cephalonica but only mildly so since numbers of these pests were very low in these places.

4.4. Trend of the attack of E. cautella eggs by B. tarsalis.

4.4.1 Introduction

B. tarsalis mites like all predaceous arthropods constitute one of the factors which may be used most advantageously in biological control. A sound knowledge in the feeding behaviour of B. tarsalis on the eggs of E. cautella would facilitate planning biological control measures for storage insect pests. It is for this reason that this experiment was carried out to determine the feeding method of this mite on the moth's eggs.

4.4.2 Materials and methods

The mites, B. tarsalis were obtained from adult moths by shaking the infected moths in glass vials. They were then sorted out into adults and nymphs. Adult mites have all the 8 legs, a characteristic of arachnids. Nymphs have four pairs of legs while larvae have three pairs. The pattern on the dorsum of idiosoma in the larvae is also distinctly different from that of the nymph (Haines, 1978). Sorting was done under a binocular microscope in a petri-dish. A camel hair brush was used to pick up the adult mites which were then transferred to a petri-dish containing eggs of E. cautella. Eggs of E.

cautella were obtained by confining newly emerged female moths in a Kilner jar inverted onto a wire-mesh screen through which eggs fell and were collected in a petri-dish below. The eggs ranging in number from 10 - 80 were placed into petri-dishes, a pair of mites being introduced onto 10, 20, 40 and 80 eggs and each treatment being replicated 4 times. Each tray was taped at the sides to contain the mites and prevent escape. The petri-dishes were placed on supports on paraffin oil to prevent entry of other factors such as other insects. The experiment was carried out in a controlled temperature and relative humidity room at 27± 2 degrees centigrade and 70± 5% R.H.

4.4.3 Results

The numbers of destroyed and whole eggs after exposure for 24 and 48 hours are shown in Table 6. Destroyed eggs include all those which had been punctured and which could therefore not hatch and those which had been wholly consumed. The number of eggs destroyed in 24 and 48 hours did not appear to vary markedly probably indicating that satiation had been attained with initial feeding. Furthermore, those destroyed appeared to increase in relation to the number of eggs presented ranging from 0.5 to 2.0 eggs per mite after 24 hours and 1.25 to 8.0 eggs per mite after 48 hours.

4.4.4 Discussion

Haines (1981) observed that the number of eggs eaten per mite was 3.75 per day. In this trial the number of eggs consumed was up to 4 per day which shows a high potential of this mite to destroy the moth's eggs. After the 48 hours exposure, it was observed that most of the affected eggs were only

Table 6. Mean number of destroyed and intact eggs of *E. cautella* following exposure to *B. tarsalis* for different periods.

Initial No. of eggs	After 24 hours		After 48 hours	
	Destroyed eggs	Intact eggs	Destroyed eggs	Intact eggs
10	1.0 ±0.2 (0.5)	9.0	2.5 ±0.3(1.25)	7.5
20	1.3 ±0.1 (0.65)	18.7	3.3 ±0.4(1.65)	16.7
40	3.6 ±0.4 (1.8)	36.4	8.0 ±1.3(4.0)	32.0
80	4.0 ±0.8 (2.0)	76.0	16.0 ±2.1(8.0)	64.0

Figures in brackets represent mean number of eggs consumed per mite.

partially destroyed.

These figures demonstrated that the mite is a wasteful feeder particularly when E. cautella eggs are plentiful. This is an advantage in the effectiveness of the mite in regulating moth numbers since greater number than would actually be needed for satisfaction are destroyed. Furthermore, this high rate of destruction with increase in the number of moth eggs available implies potential for positive response by the mite to the moth's density.

4.5 E. cautella population growth under controlled temperature and relative humidity.

4.5.1 Introduction

Fluctuations in physical conditions such as temperature and relative humidity within a warehouse could affect the rates of population growth and also, warehouses in different parts of the country would differ in physical conditions. Knowledge of population development of an insect pest is important as it would determine its potential for increase relative to its predators and parasites for biological control. It is for this reason that this trial was carried out to determine the rate of increase of E. cautella under simulated average warehouse temperatures and relative humidities prevailing in Kenya.

4.5.2 Materials and methods

Moth eggs were obtained from gravid females collected by the methods already described above in warehouses in Nairobi. Such females were kept inside inverted kilner jars which rested on fine wire-mesh covering the petri-dish. When moths laid their

eggs, the latter dropped into petri-dishes through the wire-mesh. Thereafter, 200 eggs less than 48 hours old were introduced into culturing jars each containing 200 gm food medium. A fine camel-hair brush was used to lift the eggs from the petri-dish into the food medium which consisted of wheat feed, yeast and glycerol in the ratio of 10:1:3. The cultures were then incubated in a controlled temperature and relative humidity room set at 27± 5% R.H. as monitored on a thermohygrograph tracing paper. These conditions were considered to be similar to those pertaining in normal warehouses throughout the country. Thereafter, numbers of larvae, pupae and adults were counted every three days with the instar number being determined in the case of larvae. This was continued until adult emergence had ceased in order to complete assessment of a full moth generation.

4.5.3 Results

Numbers of larvae, pupae and adults emerging in the development of the moth from egg to adult area shown in Table 7. These were used to construct an age-specific life-table for the moth as shown. Actual numbers counted are indicated in column 2 while column 3 shows the logarithm to the base ten of these numbers. The k-values shown in column 4 are the differences in the logarithms of the figure in the preceding stage and that in the succeeding stage. The k-values represent the mortalities between two successive developmental stages. Seven mortalities were distinguished including k_6 in the adult, representing the failure to reach the maximum natality of 200 eggs per adult. The total mortality from egg to adult is represented by K which is a summation of individual mortalities occurring within the various stages k_0 to k_7. It stands for the total mortality in the 200 eggs laid by the

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Table 7. k-factor analysis of the life data for E. cautella

Stage	Number	Log. Number	k-value
Maximum potential Natality	403	2.605	
			0.304 $-k_e$
Eggs laid	200	2.301	
			0.102 $-k_1$
Larva I and II	158	2.199	
			0.135 $-k_2$
Larva III	116	2.064	
			0.099 $-k_3$
Larva IV	92	1.965	
			0.062 $-k_4$
Larva V	80	1.903	
			0.040 $-k_5$
Pupa	73	1.863	
			0.386 $-k_6$
Adult	30	1.477	
Total mortality			1.128 -K

indicated number of moths introduced and the eventual adult emergence. Since, it was found that the mean number of eggs laid per female moth was 64.5±3.2, the 200 eggs introduced represented 3.1 adult females. However, the maximum potential number of eggs laid by a female E. cautella at these physical conditions is 130 (Graham 1970b). Hence, the maximum potential number of eggs that 3.1 adult females were expected to lay was 403. This is therefore, the number of eggs used as a starting cohort to the life-table. The developmental period from egg to the adult was 31 days and the proportion of eggs reaching adult stage was 0.15 or 30 out of the original 200.

Furthermore, the population of the original egg cohort of 200 in terms of adult females was used to determine the net reproductive rate R_0 of the moth. This was derived from the numbers of adults counted from first emergence after one week up to the 6th and 7th week as shown in Table 8. The net reproductive rate R_0, that is, the amount by which the population increases each generation can be calculated using the method described by Longstaff (1981) to analyse life-table data for population increase characteristics. This net productive rate is used to calculate the rate of population growth of the moth, at the prevailing environmental conditions.

Thus, $l_x m_x = 4.837$

Where l_x = Population of original cohort of eggs surviving and m_x = mean number of female eggs laid per female adult within time interval. Generation time in weeks, T is estimated

Table 8. Calculation of the rate of increase of *E. cautella* from life-table data at 27± 2°C and 70±5% R.H.

Average age in weeks	Population of original egg cohort surviving	Mean number of eggs laid per female adult within time interval	Effective fertility
x	l_x	m_x	$l_x m_x$
4.5	0.140	32.25	4.515
5.5	0.007	32.10	0.225
6.5	0.003	32.20	0.097
		R_0 =	4.837

by calculating the weighted mean of the $l_x m_x$ distribution,

$$T = \frac{\sum x l_x m_x}{\sum l_x m_x} = \frac{22.1855}{4.837} = 4.587$$

Thus, since R_0 = 4.837, the rate of increase is 4.837 individuals per generation of 4.59 weeks which is 1.055 individuals per week.

4.5.3 Discussion

When cultured at 27°C and 73% r.h. Haines (1981) found that the developmental period of B. tarsalis was 5.9 days when cultured on E. cautella eggs while the adult life-span was 55 days. He (Haines, 1981) found that the mite consumed 3.8 eggs per day. In the present study, the mite was found to consume a maximum of 4 eggs per day which corresponds with Haine's findings. The rate of increase for the mite was found to be 6.8 per month while for the moth in the present study the rate was found to be 1.0 per week or 4.5 per month. The developmental period of the moth was also found to be 31 days while the adult life-span was 2 weeks. This higher multiplication rate, longer life-span and voraciousness gives a potentially high capacity for the mite to prevail and reduce populations of the moth. The ability of the mite to survive on alternate hosts like T. castaneum, C. cephalonica and P. interpunctella eggs is also an added advantage in ensuring continued survival of the mite when the population of E. cautella is reduced.

Haines (1981) reports, that the eggs of C. cephalonica and P. interpunctella provide alternative hosts to E. cautella eggs for predation by B. tarsalis. T. castaneum eggs have also been found by Graham (1970) and Haines (1981) to be another important alternative host. All these pests re-emerge following fumigations and sprays in warehouses storing maize; of these E. cautella and T. castaneum are the most important, the former being more prominent. Since both the populations of E. cautella and B. tarsalis increase after a fumigation or spray, the moth eggs provide food for the mite during these periods when the moth population is low.

The other factor that tended to favour the potential capacity of the mite to reduce E. cautella moth populations was the widespread occurrence of the mite in several areas of a warehouse where the moth is also found. The mite's small size also meant that it had greater mobility into most parts of a grain stack and therefore escaped contact with sprays when hidden in inaccessible spots in the warehouse. The mite's preference for the female in its phoretic behavior further ensured that food was available when eggs were laid as searching effort was minimal. Phoresy on the male also ensured a wide distribution of the mite to facilitate attack on the eggs when laid by the females. In addition, the voracity of the mite in its capacity to consume large numbers of moth eggs and to destroy many others in the process was a further advantage.

All these considerations point to the capability of the mite to effectively control E. cautella populations in maize storage warehouses and the applicability of an integrated pest management strategy. However, even if the mites were able to

CHAPTER 5

POPULATION STUDIES OF E. CAUTELLA UNDER THE INFLUENCE OF THE MITE B. TARSALIS AS A PREDATOR AND OTHER ASSOCIATED STORAGE INSECT PESTS.

5.1 Introduction

Apart from the outlined predation of E. cautella eggs by B. tarsalis it has also been recorded in previous studies by Graham (1970b) and Haines (1981) that the eggs of T. castaneum and those of other phycitid moths namely; C. cephalonica and P. interpunctella that also occur in storage warehouses at the same time, are also susceptible to the mite B. tarsalis and constitute alternative hosts to moth's eggs. It has also been observed that secondary pests such as Rhizopertha dominica, Oryzaephilus spp. and Cryptolestes spp. also occur in these warehouses although in smaller numbers and causing less damage. Occasionally too, primary pests like S. zeamais may also be found. These considerations were therefore made in the attempt to understand the interaction of the mite and the moth. Thus, apart from the relationship between the moth and the mite, the influences of T . castaneum on the interaction and that of other warehouse pests were also studied. Such studies could not be successfully carried out in warehouses in normal use since environmental factors such as temperature and relative humidity would be too variable and thus distort results. Hence, they were carried out in cage ecosystems under controlled temperature and relative humidity conditions. Advantages of controlled experiments where temperature, relative humidity, light and other climatic factors are held constant have been highlighted by other workers (Benson, 1973). Basically, in the laboratory, it is possible to study

control the moth, it is seen that other pests also occur in association with E. cautella even if these are less important. These other pests have not been observed to be under the control of B. tarsalis and yet their presence is also undesirable. Their usefulness as alternative hosts for B. tarsalis has to be set against their undesirability. It would appear, therefore, that reliance entirely on the mite for control of the moth is fraught with problems. The stable level of all these pests when control is being exerted by the mite may also be too high to be tolerated.

After these considerations, an alternative strategy is identified as the use of chemicals that control the moth but which facilitate the occurrence of the mite when the moth re-infestation emerges. Hence, it was necessary to screen both the present and new chemicals not only for their capacity for control of E. cautella and other associated pests but also for their effects on the mite itself. This would be feasible particularly if the levels of the pests associated with E. cautella when this is under the control of the mite cannot be tolerated. Lastly, to form a sound basis for this control, it is necessary to investigate the population dynamics of E. cautella in combination with other associated pests and the mite both with, and without pesticidal influence, especially in a set-up where wide variations of temperatures and relative humidities as occurs in natural environment are minimised.

the detailed consequences of the changes in the density of E. cautella and the biology and behaviour of the predator B. tarsalis and other related species, whereas under field conditions the underlying relationships may be obscured when several factors are varying simultaneously.

The main objective in carrying out these studies was to determine the role of B. tarsalis in regulating population change in E. cautella through the influence of the mite on the egg stage of the moth. This was necessary because accurate estimation of the mite numbers through counting individuals was impossible in practice as the mites are found not only on the moths but also in large numbers in the food medium and in all internal surfaces of the cage. Should the studies show that B. tarsalis is a key factor, this would confirm its importance in the regulation of the moth population and its potential for control of E. cautella on the magnitude of this regulatory effect. The results would show if the control obtained is sufficient for a decision to be made to dispense with the use of chemical control or to scale down the use of the latter in combination with mite control.

5.2 Materials and methods

Population studies of E. cautella were carried out under varied conditions established in the laboratory cages. Each cage had a rectangular framework of which three sides were covered with clear polythene sheeting. The other three sides were covered with plywood. The front side with plywood had an access window 12 cm diameter consisting of a folded muslin cloth sleeve. This access window also provided ventilation. The cage had inside dimensions of 40.5 cm x 37.0 cm x 30 cm (Plate 3). Care was taken to ensure that all the joints were

well-sealed to prevent escape or entry of other insects and mites. The entire floor of the cage was completely covered with 81 shallow paper trays with dimensions of 4cm x 4cm x 2cm. These trays were filled to a depth of 1.75cm with a culturing medium which in cages A, B, C and D consisted of maize meal, yeast and glycerol in ratios of 10:1:3 and weighed 20g for each tray. The moth had been shown in previous studies by Takahashi (1978) to develop most satisfactorily on a shallow food medium less than 2cm deep. Maize meal was used in preference to wheat meal normally used in standard culturing media for E. cautella in order that the results so obtained would be more relevant to practical situations of maize storage. In the case of cage E, whole maize drawn from a stack in a normally maintained warehouse was used for setting up the experiment. In all cages water was not provided in order to enhance discrete moth generations since in earlier studies Benson (1973b) had shown that egg laying was prolonged for up to 2 weeks when water was provided. Egg-laying was completed in about 2 days when water was excluded from the diet.

The adult moths used in these investigations were cultured from adults collected from warehouses in Nairobi and with maize in storage. After emerging the adult moths were 48 hours old when introduced into the cages. Mites used for the experiment were collected from the moth adults drawn from the same warehouses using the method already described in Chapter 4.

In cage A, E. cautella was bred together with B. tarsalis. Fifty moths were introduced into the cage. Since the moths were drawn from naturally occurring populations in maize storage warehouses described above, they were expected to be infested with an average of 2.94 mites in phoresy per moth as

Plate 3. Type of cage used to set up laboratory ecosystems for a study of population dynamics of E. cautella to which the mite predators were introduced.

demonstrated in Chapter 4.

In cage B, where the interaction comprised E. cautella, B. tarsalis and T. castaneum, 50 adult beetles of T. castaneum were introduced at the same time as the moths which had been shown to have mites in phoresy on their bodies. The culturing medium was not varied since under natural conditions both pests thrive on similar food materials.

In cage C, where E. cautella and T. castaneum interaction in the absence of mite predation was studied, the mite was excluded by starting off the cultures using laboratory-bred moths where mite contamination was avoided through isolating the cultures by placing them on paraffin oil baths in a tray.

In cage D, the growth of E. cautella population as a single species was studied whereby 50 newly emerged adult moths less than 48 hours old were introduced into the cage and all other insects and the mite excluded.

Lastly, in cage E, E. cautella population growth under the influence of other associated warehouse pests was studied. The maize used in this trial carried a low level of infestation not only of E. cautella but also of T. castaneum, S. zeamais, R. dominica, Crytolestes spp and O. surinamensis apart from the mite B. tarsalis. This maize was used to fill the trays in the cage to start off the trial as in the rest of the cages with an artificial culturing medium.

All the cages were placed in a controlled temperature and relative humidity room at 27±2°C and 70±5% R.H respectively in which normal 12 hour daylight and darkness conditions were maintained. The set temperature was maintained by using a

thermostatically controlled electric fan heater while the required relative humidity was maintained through the use of shallow water evaporation trays. By varying the number of trays and the fan speed, the relative humidity level could be adjusted. Each week, nine trays in one row were carefully removed from the cage while avoiding dislodging the insects and these trays were replaced with new ones containing fresh medium. Care was also taken to avoid the escape of insects through the access sleeve while sampling and replacing the food medium. Thus, since there were nine rows of trays, all the food in the cage was replaced once every 9 weeks. All the cages were maintained for 31 weeks.

In estimating the population of E. cautella, eggs were not counted directly but rather, the number of adults were multiplied by their expected fecundity (Takahashi, 1956a; Benson, 1973b). First and second instar larvae were difficult to distinguish and were, therefore combined into small larvae while 3rd and 4th instars were similarly treated for the same reason into large larvae. Since numbers in successive stages of both larvae and pupae tended to overlap, the number at each stage was estimated as the peak count of that stage plus later stages present and counted at the same time. The amount of work involved in population census precluded replication of these cage ecosystems while the monospecific treatment where E. cautella was bred alone provided a reference with which the other 4 systems were compared. Lack of replication in mortality analysis studies of this kind has been determined not to invalidate the analysis and consequent results (Benson, 1973). Varley and Gradwell's method (1960) was used in the analysis of life-tables. The method describes how to determine the value of contributions of previous mortality factors to the fluctuations of the population of an animal. In this

particular case, the method was used not only to evaluate the role of the various mortality factors but also to identify the key mortality factor in the moth's population. Consequently, seven mortalities, k_1 to k_7 were distinguished, each designating mortality between successive developmental stages or groups of stages as small larvae and large larvae. The sum of these individual mortalities comprised the generation mortality K in each case.

Thus, $K = k_1 + k_2 + k_3 + k_4 + k_5 + k_6 + k_7$

where each k is calculated by subtracting each logarithm from the previous one, that is,

$k_1 = \log N_i - \log N_{(i+1)}$ where, N_i is the population before the mortality acts and $N_{(i+1)}$ is the population after the mortality.

In this way, egg mortality was identified as k_1 (log expected no. of eggs - log small larvae) and was presumed to be a result of various causes including failure of adult females to achieve maximum fecundity, infertility, disease, starvation, cannibalism and predation by the mite B. tarsalis. It included variation in adult fecundity attributed to egg or adult size variation, since it was assumed in the formulation of the life-tables, that each female moth lays 200 eggs and that the sex ratio was equity in each generation.

Mortality in the 1st and 2nd instar larval stages represented by k_2 (log small larvae-log large larvae) which comprised death due to disease, starvation and cannibalism. Diseased larvae were distinguishable as they appeared partially or wholly darkened and in various stages of decay. Cannibalism is a normal phenomenon in phycitid larvae (Benson, 1973; Flanders

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and Hall, 1965) while starvation is observed when overpopulation of moths occurs. Disease has been observed to be due to Bacillus thuringiensis, a sporozoan as the symptoms comprising black marks and eventual decay are very characteristic.

Mortality in 3rd and 4th instars was due to the same factors as in 1st and 2nd instars with the only exception being that disease incidence was higher in the former case. Disturbance caused by B. tarsalis has also been observed to cause stress and death by Benson (1973) in previous studies. Mortality occurring in 3rd and 4th instars was represented by k_3 (log large larvae - log larvae 5).

Mortality in the 5th instar was treated in two ways, k_4 due to diseases which was very prevalent in this stage (log diseased larvae) and k_5 (log larvae 5 - log pupae -log diseased larvae).

Pupal mortality which was similarly treated in two ways, k_6 due to disease where diseased pupae had similar features to diseased 5th instar larvae (log diseased pupae) and k_7 (log pupae - log adult - log diseased pupae). Other causes of death in the pupal stage were recognised as being due to developmental disorders and failure to achieve the critical size necessary for successful emergence of the adult as demonstrated by Benson (1974).

In the adult stage, possible causes of mortality were recognised as due to premature death of adults in copula and actual stress from phoresy by B. tarsalis. Small and insignificant numbers of adult moths were also deemed to have escaped through the access window during sampling. Mortality

in this stage is reflected both in the pupal stage as pupal mortality k_6 and in egg mortality k_1 as well.

5.3 Results

5.3.1 Growth of E. cautella population under B. tarsalis predation in cage A.

E. cautella generations were distinguished by plotting the number of moth pupae each week for the entire period and using the pupal peak numbers to represent successive generations as shown in Fig. 5. Seven generations were recognised during the study period of 31 weeks in the cage. There was considerable overlap from week 17 onwards and generations 4 - 7 were just noticeable.

As seen in Fig 5, there was a tendency for the population of the moth to collapse during the 8th week but it picked up again during the 9th and 10th weeks after which it remained somewhat stable until the 30th week when there was another mild decline. The lack of pupae in week 7 and 8 and again in weeks 16 and 17 indicates occurrence of initial discrete generations but later after the 4th generation pupal population tended to level off as is characteristic of overlapping generations. However, 7 generations could be inferred from the fluctuations observed in the pupal numbers. The life-tables formed from the seven generations of the moth identified are shown in Table 9 where each generation phase is calculated from adult to adult. In the 9th week, the period when the medium in the cage had undergone complete renewal, two generations of the moth were expected, hence, the number in the previous generation was reduced from the total counted

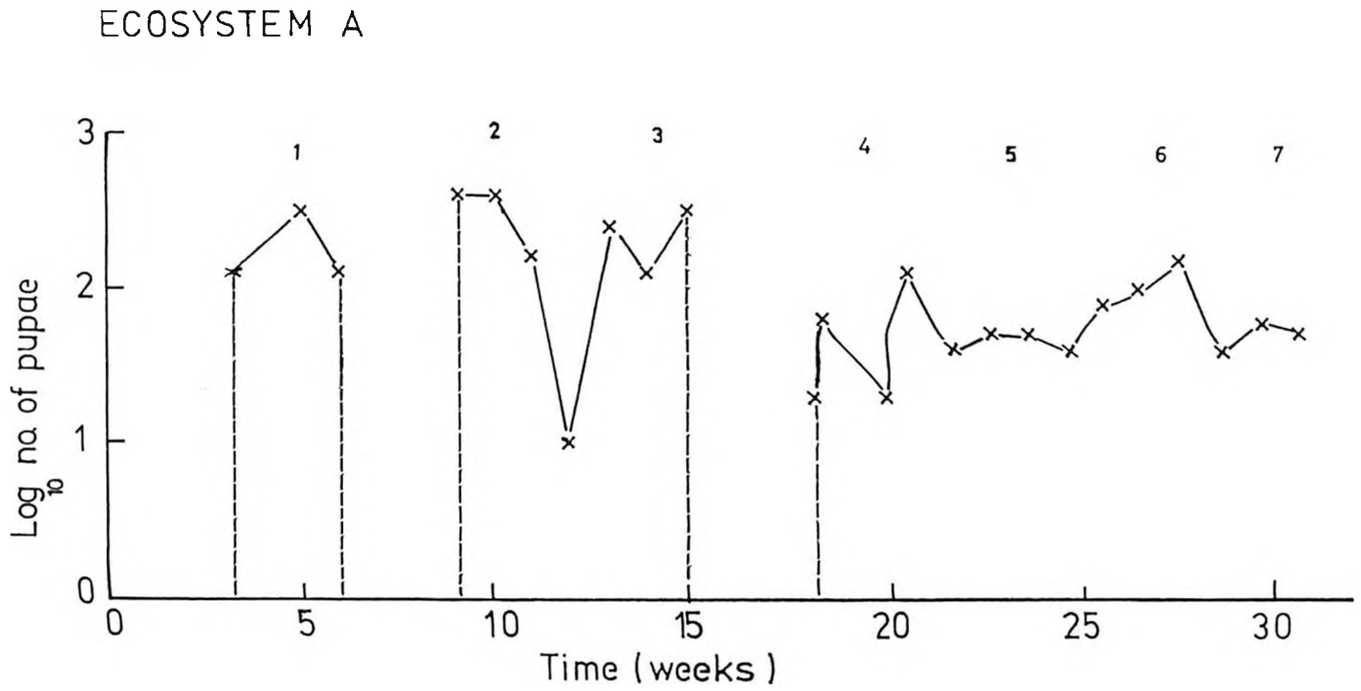

Fig 5. Population change in numbers of E. cautella pupae shown as logarithms of numbers over a period of 30 weeks to locate generations of the moth under predation by B. tarsalis in cage A.

Table 9. Life-tables of E. cautella under predation by B. tarsalis
(All figures are in logarithms)

Stages and mortality factor	Generations						
	1	2	3	4	5	6	7
Eggs	3.699	4.334	4.033	4.873	4.396	4.334	4.185
k_1	0.538	1.033	0.203	1.693	1.286	1.580	1.170
Small larvae	3.161	3.301	3.830	3.180	3.110	2.754	3.015
k_2	0.277	0.101	0.431	0.296	0.237	0.274	0.362
Large larvae	2.884	3.200	3.399	2.884	2.873	2.480	2.653
k_3	0.011	0.365	0.055	0.011	0.113	0.071	0.097
Larvae 5	2.873	2.835	3.344	2.873	2.760	2.409	2.556
k_4	0.000	0.075	0.000	0.000	0.013	0.015	0.000
k_5	0.044	0.288	0.180	0.038	0.085	0.050	0.083
Pupae	2.829	2.472	3.164	2.835	2.662	2.334	2.423
k_6	0.017	0.000	0.000	0.006	0.036	0.000	0.000
k_7	0.478	0.439	0.290	0.111	0.328	0.159	0.405
Adult	2.334	2.033	2.874	2.718	2.334	2.185	2.068
K	1.365	2.301	1.159	2.155	2.098	2.149	2.117

to give the number in the current generation since adult moths lived for only 1-2 weeks (Benson, 1973).

For the key factor identification, individual k values were plotted in successive generations and the points linked. This enabled any correlations between each k and the total K to be recognised. The key factor, if present, is that factor which is the main cause of variation in the total mortality and has the highest correlation with the total mortality K according to Varley and Gradwell (1970). Fig. 6 shows the key factor to be egg mortality k_1 which although it had no correlation with K, it was the highest amongst all the mortalities. Other mortalities had negative correlations, too small correlations or no correlation at all with the total mortality K. The k_1 values were then plotted against the logarithm of expected egg density whereby the relationship was seen to be density dependent using Varley and Gradwell's method (1970). When the points were joined together according to this method as shown in Fig. 7 there were no distinct anti-clockwise spiralling effect indicating absence of any delayed dependent component in the relationship. The positive slope of the plot (b=0.536) also indicated that the factor was under-compensating on the numbers of the expected egg density (Southwood, 1966).

5.3.2 Population growth of E. cautella while interacting with T. castaneum and B. tarsalis

Generations of E. cautella were identified by plotting the logarithms of numbers of pupae every week and noting peak numbers as shown in Fig 8. In this way seven generations of the moth were recognised where due to overlapping, the 1st, 4th, 5th and 6th generations were just distinguishable. Numbers of E. cautella and T. castaneum adults are shown in

ECOSYSTEM A

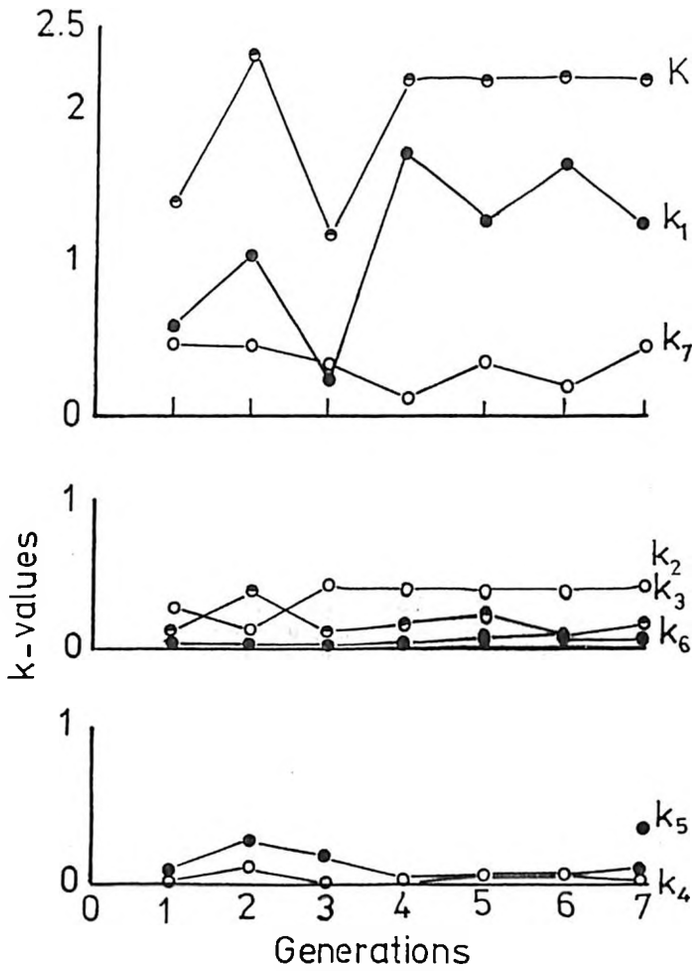

Fig. 6. Graphical key factors analysis of mortality factors acting against E. cautella in Ecosystem A where the moth was under predation by B. tarsalis.

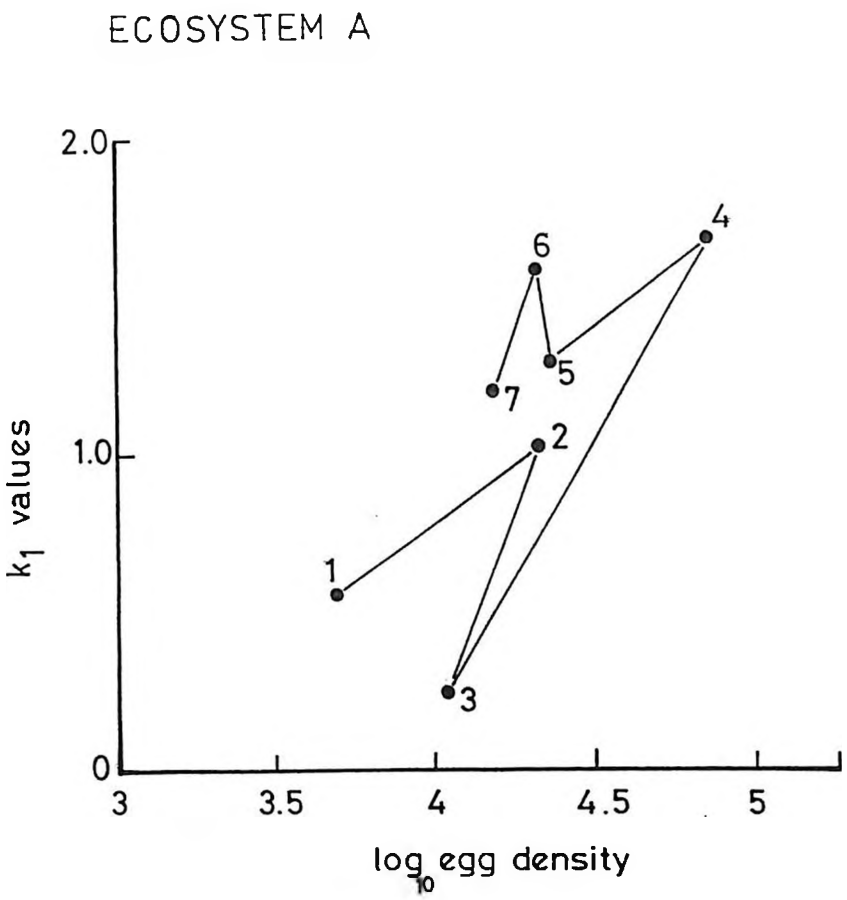

Fig 7. Relationship between mortality k_1 and the log expected egg density in Ecosystem A where the moth E. cautella was under predation by B. tarsalis. The numbers on the graph trace refer to moth generations.

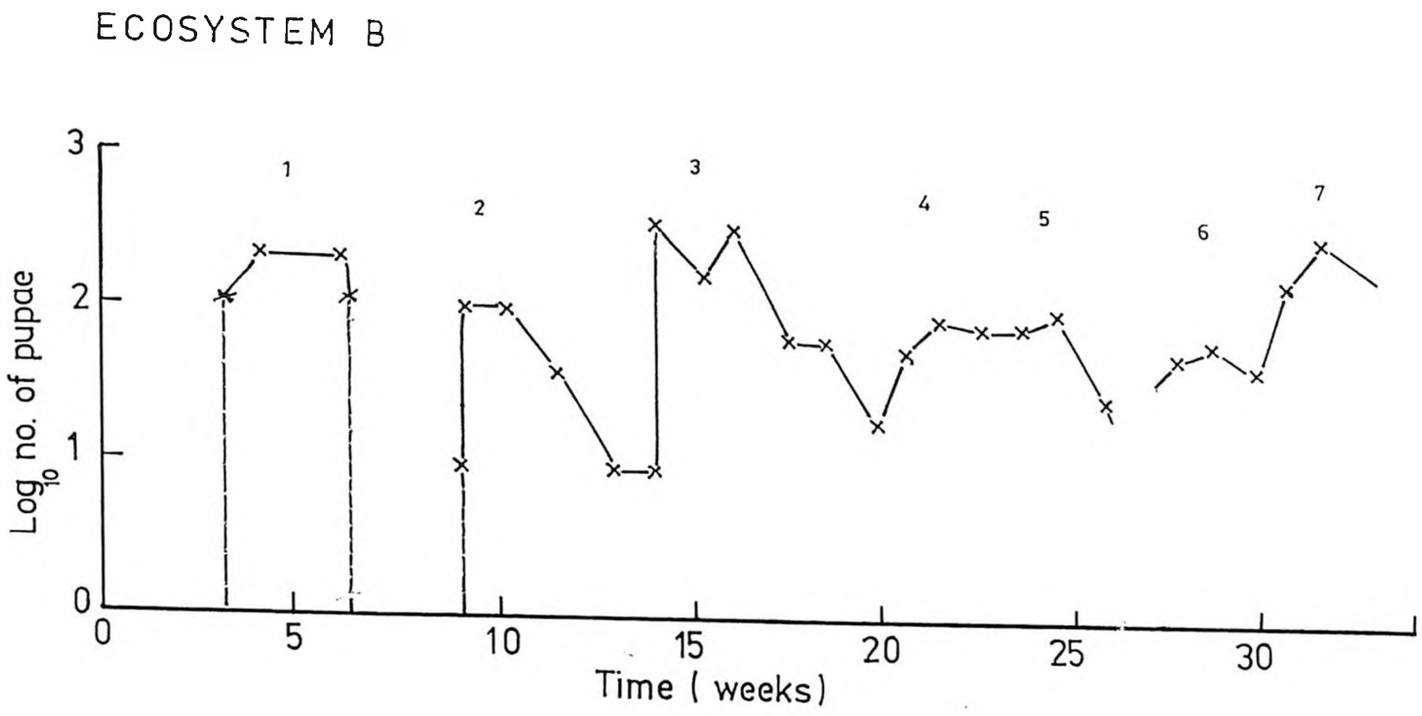

Fig 8. Population change in numbers of pupae of E. cautella through successive generations of the moth in Ecosystem B consisting of the moth interacting with B. tarsalis and T. castaneum.

Table 10. Relative size of T. castaneum populations against peak numbers of E. cautella generations (Figures are in logarithms)

	E. cautella Generations						
Species	1	2	3	4	5	6	7
E. cautella Live adult numbers	2.233	2.246	2.568	2.431	2.185	1.653	2.255
T. castaneum Live adult numbers	1.954	2.446	2.754	-	1.996	2.316	2.386

Table 10 expressed as logarithmic numbers. It is seen that the two populations co-exist throughout the 31 weeks except during the 4th generation of the moth when no T. castaneum adults were observed. Such a fluctuation in T. castaneum numbers can be caused by disease, cannibalism, competition for food from E. cautella and other mortality factors. The population of E. cautella was highest in the generation preceding this drop.

Mortality factors in E. cautella population were identified in the same way as in Ecosystem A and 6 mortality factors were identified as shown in Table 11. In order to identify the key factor in E. cautella population in this interaction, individual k-values were again plotted in successive generations as shown in Fig.9. In this interaction the key factor emerged as k_1 which was correlated with k at 1% level with a coefficient of 0.8821 as seen in Table 18. Other factors showed only minor correlation except for k_3 which had a coefficient of 0.6227 that was not significant. In investigating the presence of any density relationship, k_1 was plotted against the logarithm of the expected egg density (Fig. 10) from which a positive slope of 0.7748 was obtained and a correlation of the two factors of 0.9412 shown in Table 17. This demonstrated direct density dependance but under-compensating for density changes in the expected egg density. By joining the points in the k values against the expected egg density some anti-clockwise spiralling effect is just discernible but the points fall close to a straight line and consequently any delayed density effect is hardly obvious. From this, it is inferred that k_1, that is, mortality in the egg and early larval stage is the key factor in the moth population growth and has a direct density dependent effect on the population of the moth. However, any delayed density dependence effects by this mortality are not clearly discernible.

Table 11. Life-tables of E. cautella interacting with T. castaneum and B. tarsalis (All figures in logarithms)

	Generations						
	1	2	3	4	5	6	7
Eggs	3.699	4.083	4.246	4.569	4.431	4.185	3.653
k_1	0.772	0.081	1.127	1.548	1.604	1.411	0.461
Small larvae	2.927	3.002	3.119	3.021	2.827	2.774	3.192
k_2	0.217	0.358	0.114	0.222	0.183	0.177	0.212
Large larvae	2.710	2.644	3.005	2.799	2.644	2.597	2.980
k_3	0.075	0.122	0.066	0.039	0.088	0.151	0.013
Larva 5	2.635	2.522	2.939	2.760	2.556	2.446	2.967
k_4	0.000	0.069	0.065	0.125	0.110	0.413	0.242
Pupa	2.635	2.453	2.874	2.635	2.446	2.033	2.725
k_5	0.006	0.000	0.000	0.009	0.000	0.000	0.000
k_6	0.396	0.207	0.305	0.195	0.261	0.380	0.470
Adult	2.233	2.246	2.569	2.341	2.185	1.653	2.233
K	1.466	1.837	1.677	2.138	2.246	2.532	1.398

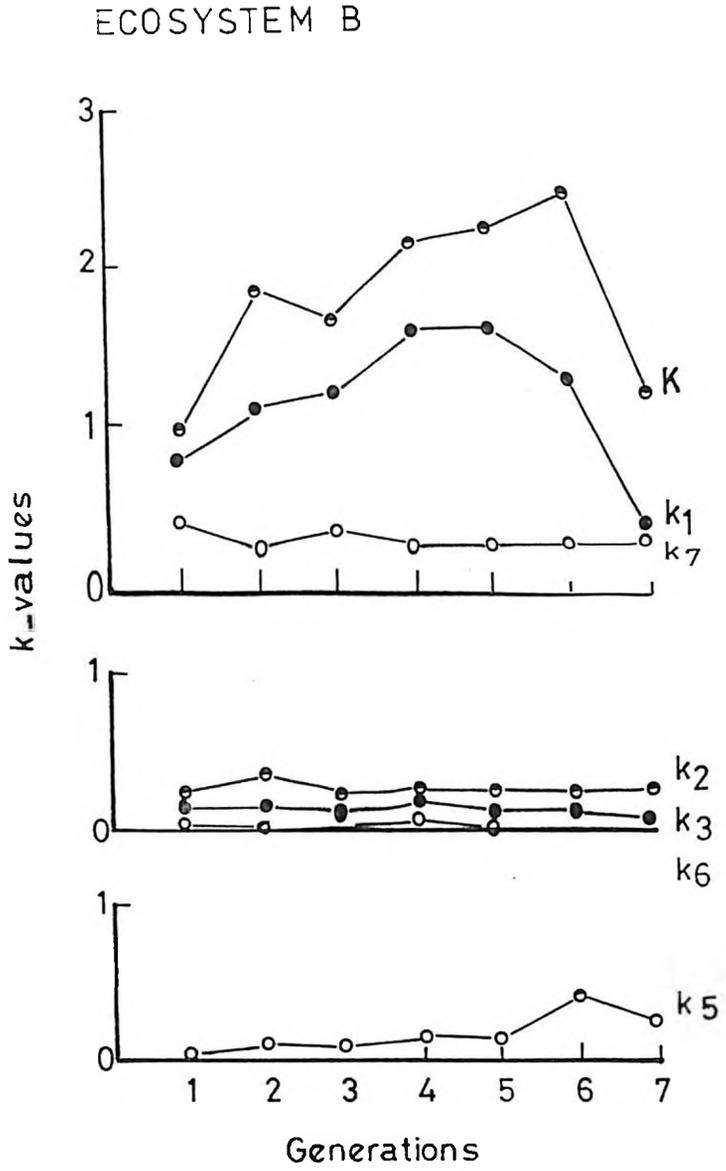

Fig 9. Graphical key factor analysis of mortality factors acting against **E. cautella** in an interaction with **T. castaneum** and **B. tarsalis**.

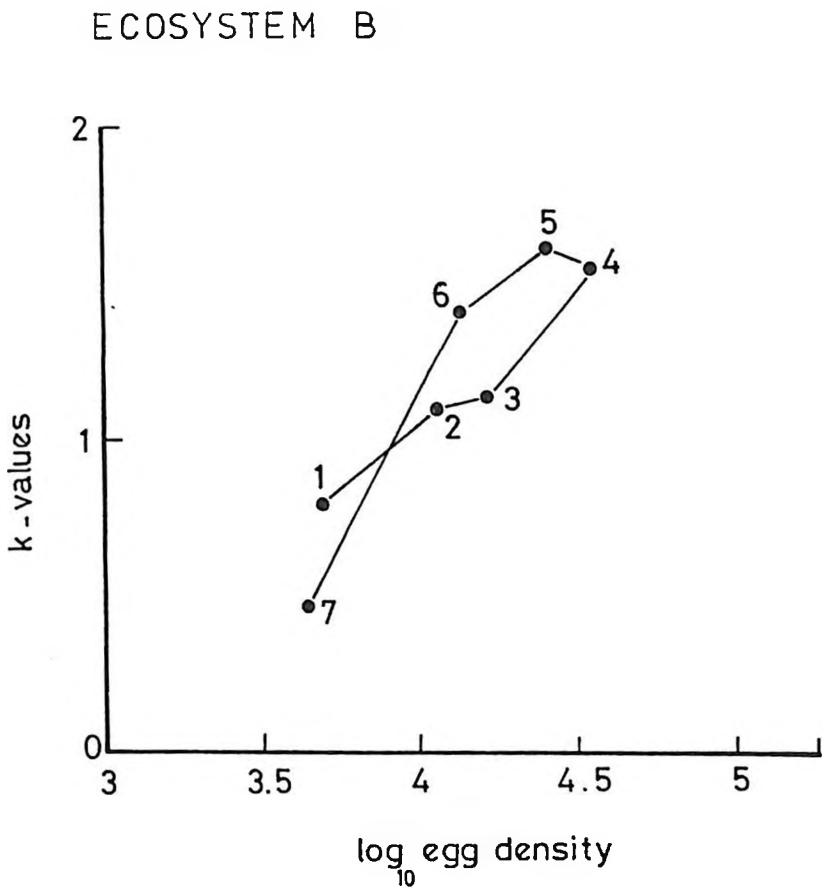

Fig 10. Density dependence relationship between mortality k_1 and log expected egg density in Ecosystem B. The numbers on the graph denote moth generations.

5.3.3 Population growth of E. cautella while interacting with T. castaneum.

Results of population counts of E. cautella developmental stages and T. castaneum adults were analysed in the same way as for the previous systems. There was overlap of generations 2 and 3 of E. cautella between weeks 11 and 19. However, six generations of the moth were identified whereby the population of the moth was seen to increase gradually through to the sixth generation (Fig. 11). Numbers of T. castaneum in relation to those in the 6th generation of the moth are also shown in Table 13 whereby the two species are seen to have co-existed with no obvious inter-species competition. The life-tables for E. cautella are shown in Table 12 and the graphical key factor analysis is shown in Fig.12. It appeared that k_1 was the key factor judging from the close relationship with the total mortality K. Upon correlation analysis however, it was found that the coefficient was insignificant, being only 0.5548. The highest coefficient of correlation was between k_5 and K but this again was not significant. Furthermore, it is seen that by joining successive k_1 values through generations in Fig 13, no cyclical trend is obtained and there is no correlation between k_1 and the expected egg density as seen in Table 17. Similarly, the relationship between k_2 and the log of small larvae as seen in Fig.14, does not show any density dependence as there was no correlation between the two factors.

In this system, it appeared that there was no prominent key factor determining the change in the population of E. cautella through the generations observed. This implied that a number of factors were acting simultaneously to bring about the variation in the moth population in the developmental stages.

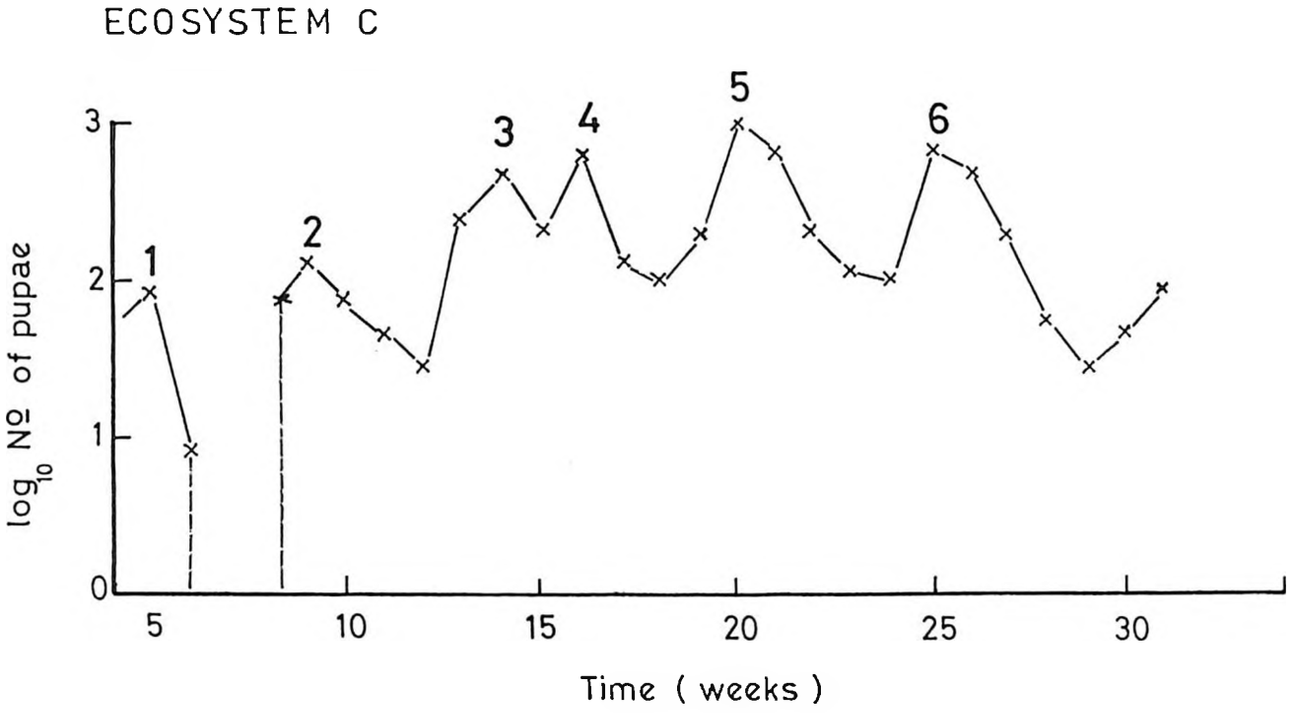

Fig 11. Population change in E. cautella pupae through successive generations of moth interacting with T. castaneum.

Table 12. Life-tables of E. cautella interacting with T. castaneum.

	Generations					
	1	2	3	4	5	6
Eggs	3.699	3.826	3.255	4.610	4.511	3.857
k_1	1.078	1.367	0.257	1.400	1.111	0.505
Small larvae	2.621	2.459	2.998	3.210	3.400	3.342
k_2	0.401	0.125	0.047	0.204	0.128	0.125
Large larvae	2.220	2.334	2.951	3.006	3.272	3.217
k_3	0.050	0.018	0.000	0.000	0.028	0.030
Larvae 5	2.170	2.316	2.951	3.006	3.244	3.187
k_4	0.000	0.000	0.000	0.000	0.000	0.005
K_5	0.000	0.158	0.000	0.037	0.205	0.145
Pupae	2.170	0.158	2.951	2.969	3.030	3.037
k_6	0.000	0.000	0.000	0.000	0.000	0.011
k_7	0.344	0.903	0.341	0.341	0.458	0.438
Adult	1.826	1.255	2.610	2.511	1.857	2.588
K	1.873	2.581	0.645	2.099	2.654	1.259

Table 13. Relative size of T. castaneum population against E. cautella without predation by B. tarsalis (All figures in logs)

	E. cautella Generations					
Species interacting	1	2	3	4	5	6
E. cautella adult numbers	1.826	1.255	2.610	2.511	1.857	2.588
T. castaneum adult numbers	2.068	2.386	2.628	2.086	2.255	2.417

ECOSYSTEM C

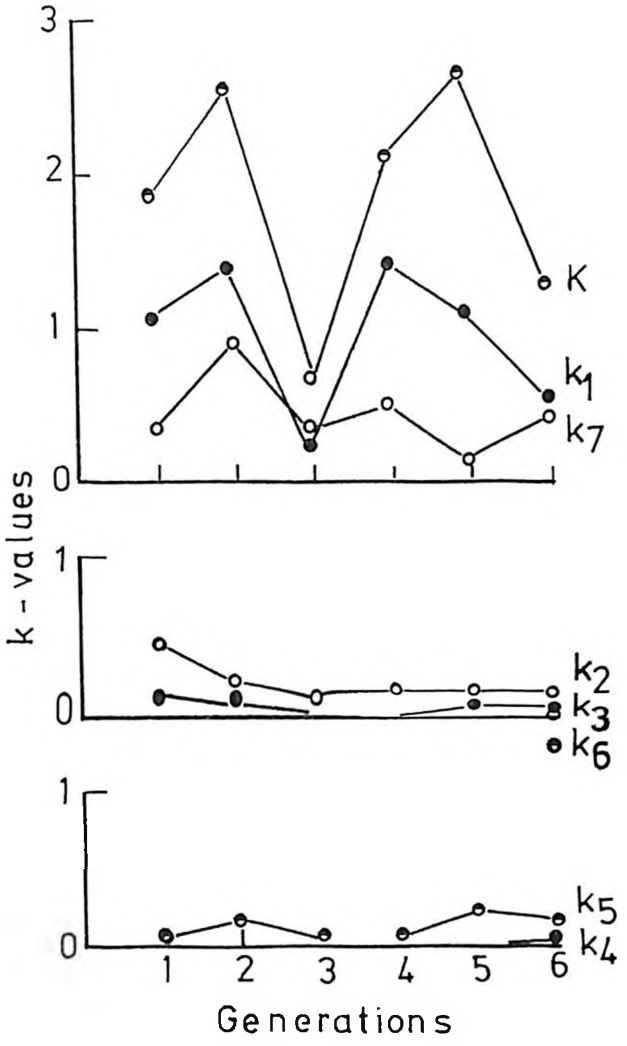

Fig 12. Graphical key factor analysis of mortality factors acting against E. cautella interacting with T. castaneum.

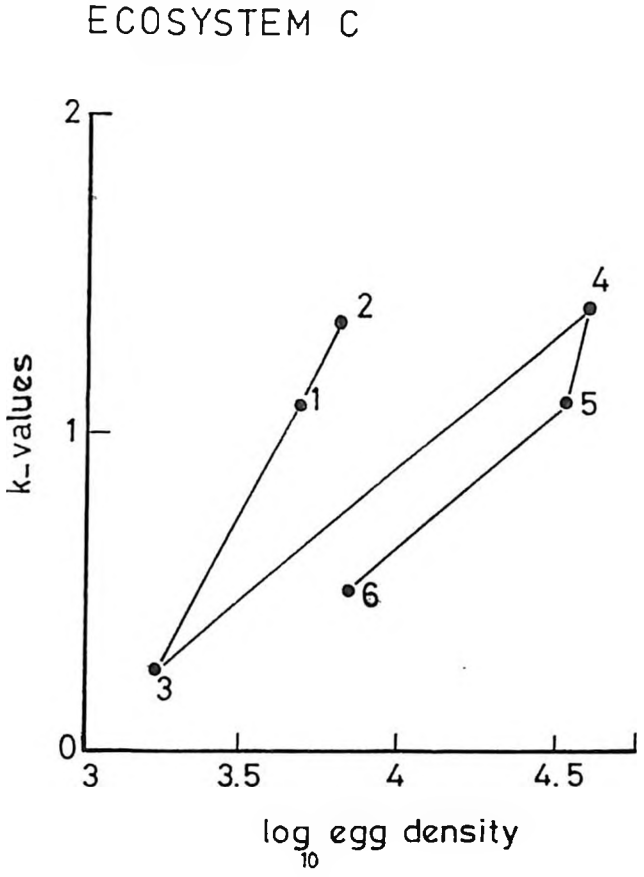

Fig 13. Relationship between mortality factor k_1 and the log of expected egg density in Ecosystem C with E. cautella interacting with T. castaneum. Numbers on the graph represent moth generations.

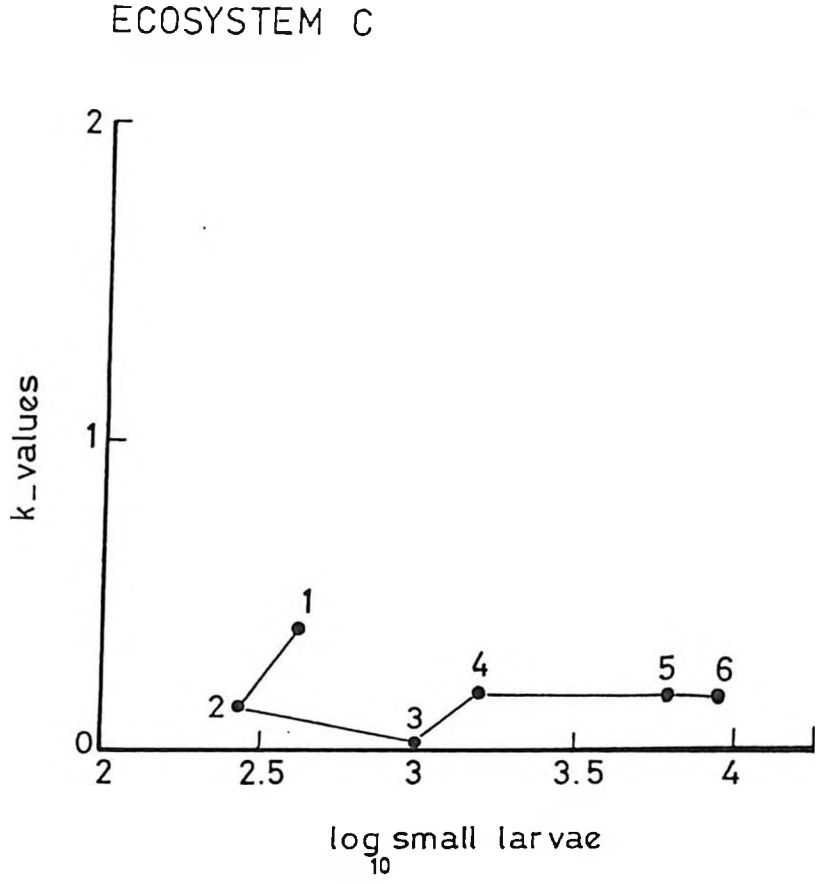

Fig 14. Relationship between mortality k_e and the log of numbers of small larvae in Ecosystem C. Numbers denote moth generations.

ECOSYSTEM D

5.3.4 Population growth of *E. cautella* under a single mono-culture system.

Using the method of constructing population budgets outlined in the previous systems, 6 generationsof the moth with 6 mortalities, k_1 to k_7 impinging on them were also recognised in this system as shown in Fig. 15, the only difference being that in k_1 the contribution by *B. tarsalis* was absent since this mite was excluded. This meant, in the first place, that possible stress normally associated with the presence of the mite carried on the body of the adult moth was absent. Such stress would normally lead to reduced fecundity of the adult female moth. In the second place, egg predation by the mite was also absent. Moreover, with regard to mortalities k_2 and k_3 (that is, mortalities occurring in small larvae and large larvae, respectively) the contribution otherwise expected from *B. tarsalis* in terms of causing stress and constituting contamination was also absent. Such effects on fifth larval instar were expected to be minimal if they occurred. Table 14 shows the mortality levels in the life tables demonstrating their magnitude.

Key mortality in the moth population was determined through plotting individual k values in successive generations as shown in Fig. 16 where it is apparent that k_1 is most closely correlated with the total mortality K, the correlation coefficient for this being 0.8701 which was significant at 1% level. The mortality k_1 was therefore identified as the key factor mainly determining the moth population changes. To investigate the density relationship of this key mortality factor k_1, its values were plotted against log expected egg density (Fig 17), where it was found that the correlation was high being 0.9560 as shown in Table 17. The slope of the regression of k_1 against egg density was 0.6959 indicating a direct density dependence but under-compensating the variation in egg density. Upon joining the k_1 values there was no

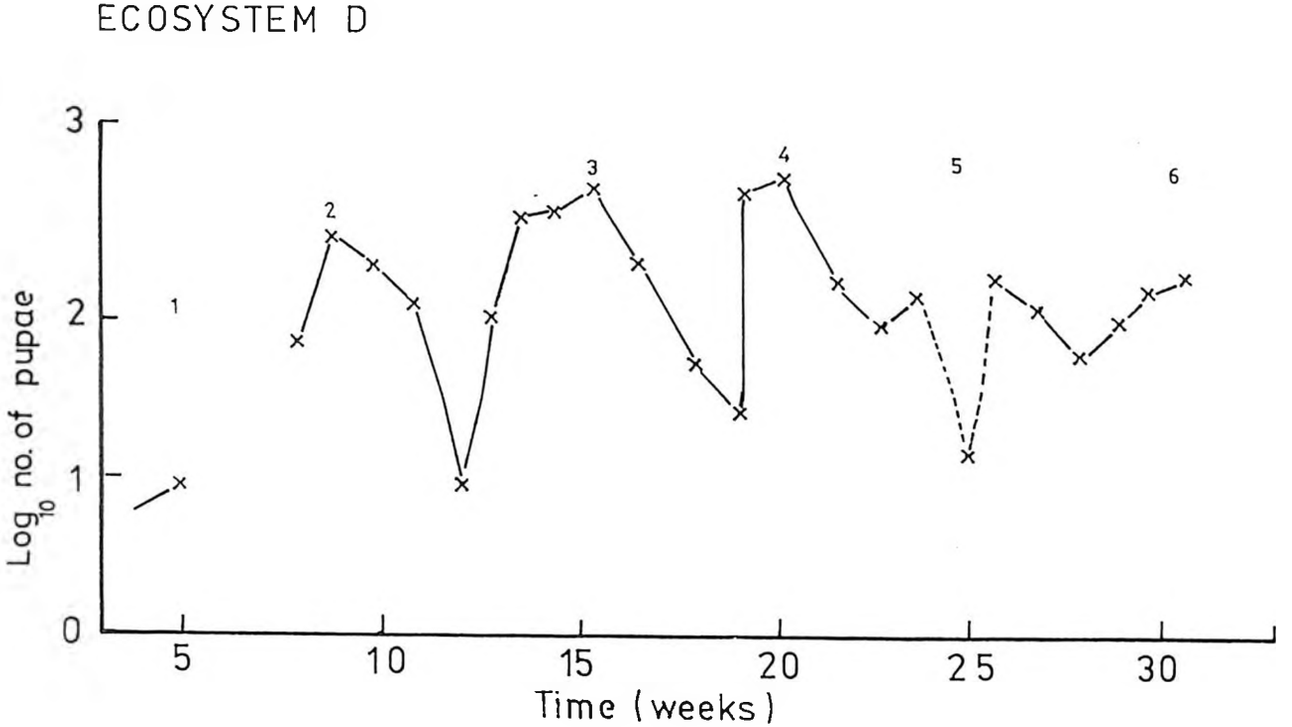

Fig 15. Population change in E. cautella pupae through time plotted to identify successive generations of the moth in Ecosystem D.

Table 14. Life-tables of E. cautella.

	Generations					
	1	2	3	4	5	6
Eggs	3.699	3.857	3.556	4.543	4.292	4.320
k_1	0.398	0.274	0.072	1.233	1.114	1.294
Small larvae	3.301	3.583	3.484	3.310	3.178	3.026
k_2	1.143	0.467	0.422	0.177	0.325	0.266
Large larvae	2.158	3.116	3.062	3.133	2.853	2.760
k_4	0.090	0.248	0.118	0.021	0.112	0.065
Larvae 5	2.068	2.868	2.944	3.112	2.741	2.695
k_5	0.160	0.301	0.088	0.147	0.204	0.237
Pupae	1.908	2.567	2.856	2.958	2.537	2.458
k_6	0.000	0.000	0.000	0.024	0.000	0.000
k_7	0.051	0.011	0.313	0.642	0.217	0.182
Adult	1.857	1.556	2.543	2.292	2.320	2.276
K	1.842	2.301	1.013	2.251	1.972	2.044

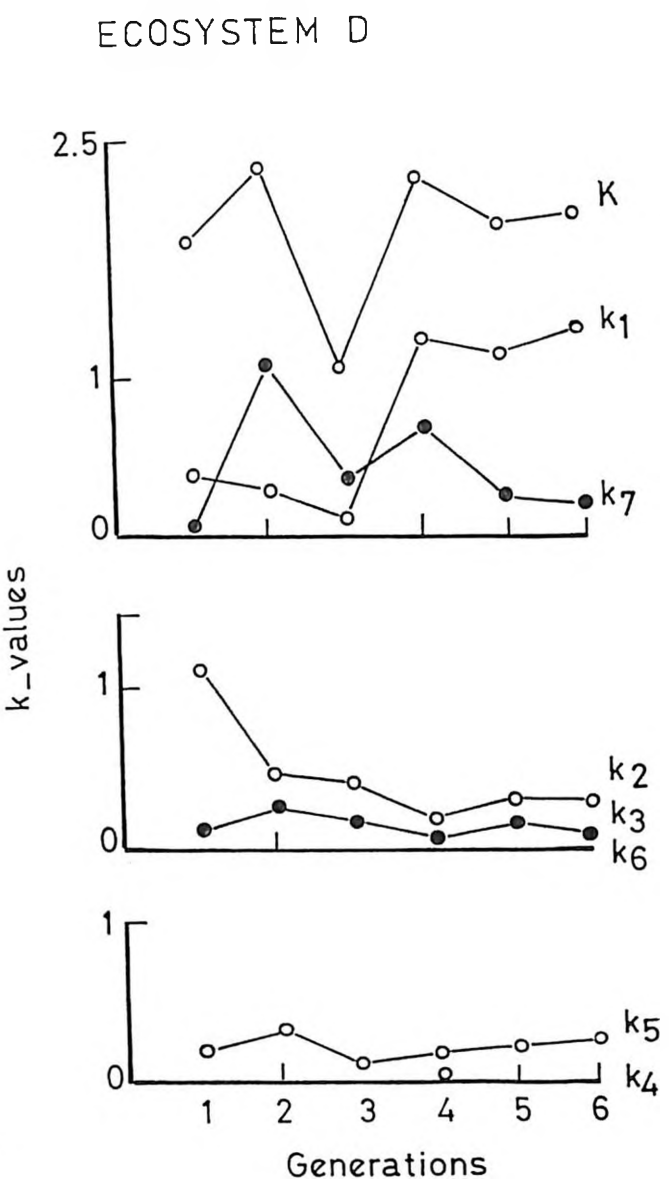

Fig 16. Graphical key factor analysis of mortality factors acting against E. cautella in the absence of predation or competing species.

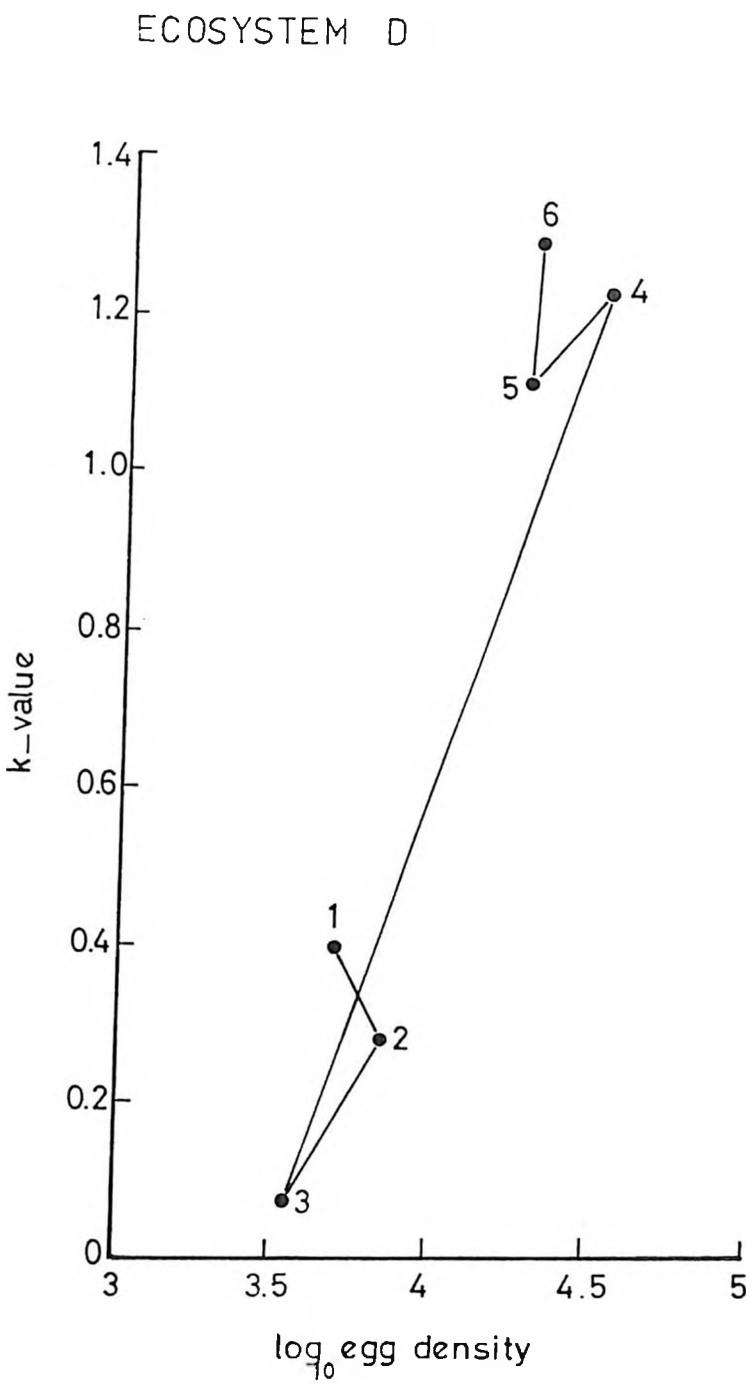

Fig 17. Relationship between mortality k_1 and the log of expected egg density in Ecosystem D. Numbers on the graph denote moth generations.

spiralling trend and the points were close tracing a more or less straight line indicative of direct density dependence. In this system, k_1 was not shown to be the key factor and the key factor was not distinct. Furthermore, although this mortality was shown to affect expected egg density in a direct density dependent way, its effect on the overall mortality in the moth population was not profound, probably due to the effects of other factors acting in an inverse density dependent or density independent way.

5.3.5 Population changes of E. cautella when interacting with other naturally occurring warehouse pests.

The analysis of mortality factors in E. cautella populations was carried out in an identical way as in the previous ecosystems studied. However, in this ecosystem, generations of the moth were recognised by plotting the logarithms of adult numbers against time of development. Moth generations could not be identified easily by using the peaks of the logarithms of the numbers of pupae as done earlier since by doing so the generations of the moth were indistinct. By using this method, 6 generations were identified during the 31 week duration of the experiment as shown in Fig. 18. The population of the moth fluctuated marginally throughout except for the 3rd generation which was most prominent. The 4th and 6th generations, in particular, were not so clearly distinguishable. In monitoring the populations of the other species present, adults were counted. Numbers of individuals of other species counted against those of E. cautella are shown in Fig. 19. The relative population sizes of these other species against the 6 generations of E. cautella are shown in Table 15 for comparison.

Apparently, the most prominent of other species were Sitophilus zeamais and T. castaneum. The observed large numbers of S. zeamais were expected since this maize had not

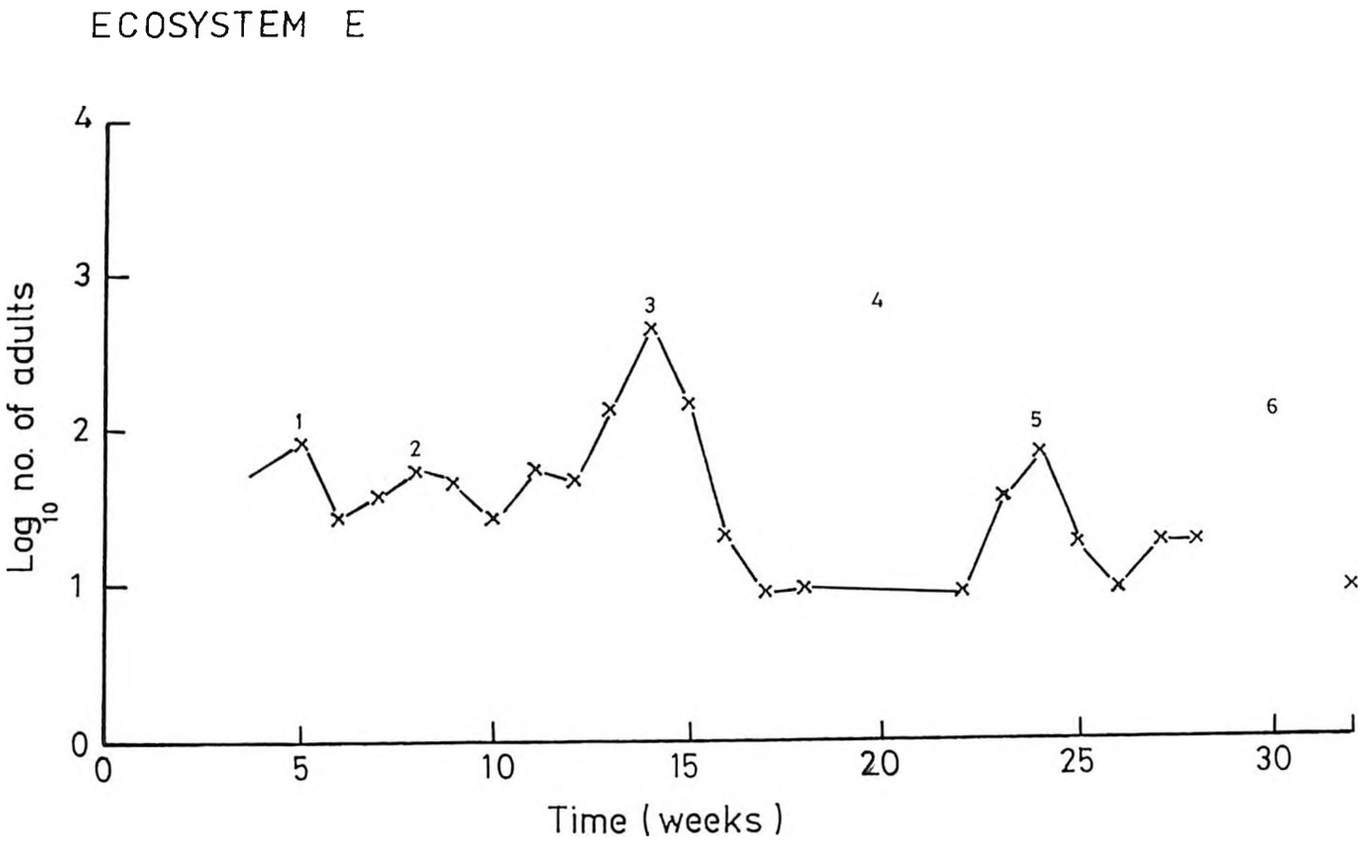

Fig 18. Population change in adult E. cautella through time to identify successive generations of the moth in Ecosystem E.

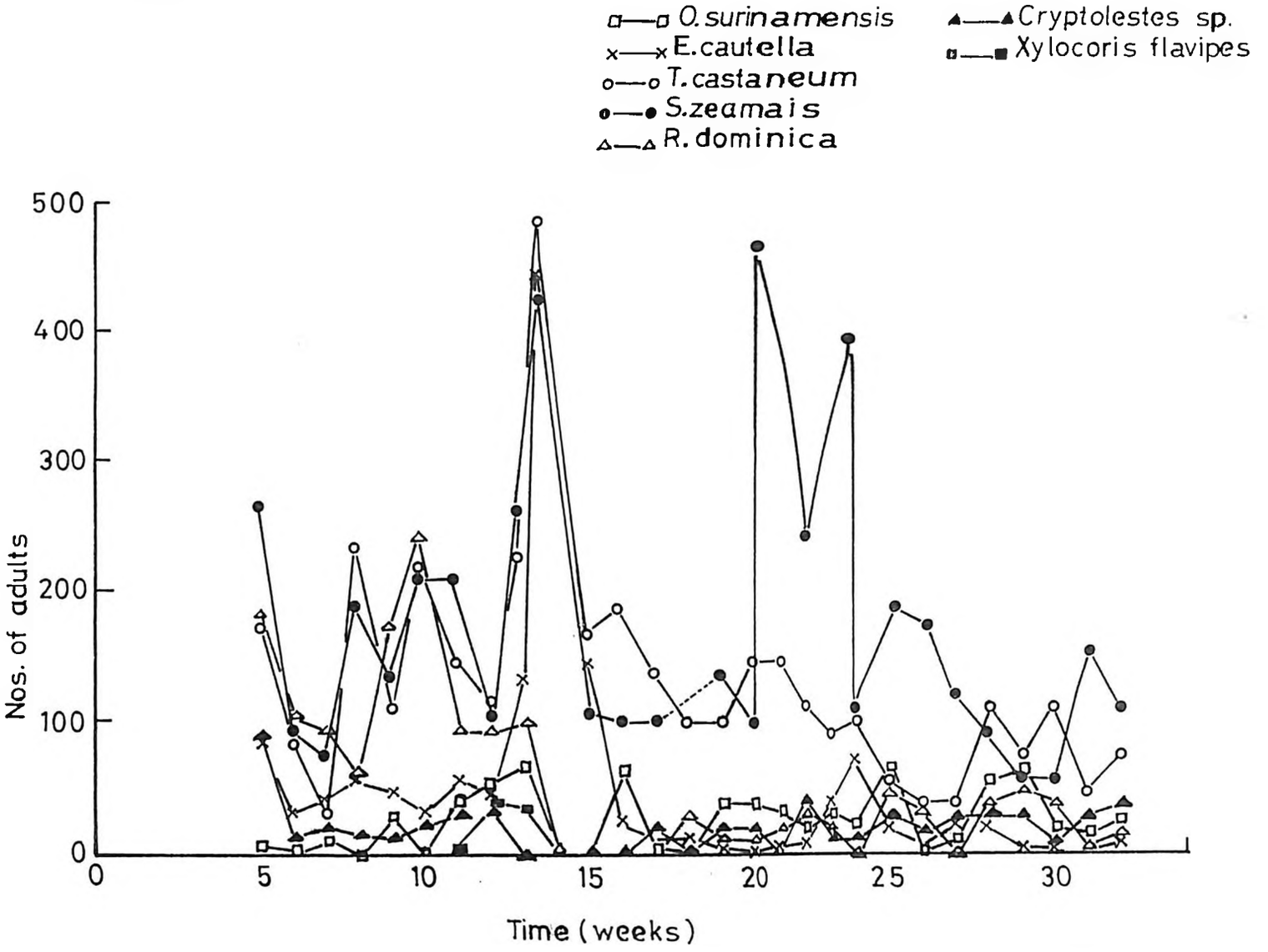

Fig 19. Relative numbers of various warehouse insect species interacting with E. cautella in Ecosystem E.

Table 15. Relative numbers of various species of storage insects interacting with E. cautella as studied in a cage ecosystem. Time periods indicate E. cautella generations (live + dead insects).

Interacting species	E. cautella generations					
	1	2	3	4	5	6
E. cautella	81	51	446	-	72	-
T. castaneum	171	134	486	144	98	108
S. zeamais	261	189	426	99	117	54
R. dominica	171	54	0	9	0	36
Cryptolestes ssp	162	9	0	18	9	9
O. surinamensis	0	0	0	36	18	18
Xylocoris flavipes	0	0	0	0	0	0

been fumigated since being procured from the farm. Numbers of Cryptolestes spp., R. dominica, E. cautella and O. surinamensis fluctuated at about the same initial level, followed by a sudden increase after which the population of E. cautella collapsed between the 12th and 16th weeks. In order to determine the influence of other contemporary storage pests and the mite on the population of E. cautella, its life-tables were constructed as shown in Table 16 and were analysed in the same way as before. It was apparent from the key factor analysis on these tables and the graphical analysis (Fig. 20) that mortality factors k_3, k_4 and k_6 were very small while the key mortality factor was again identified as k_1 having a correlation of 0.9014 as seen in Table 17 with total mortality K which was significant at 1% level. On the other hand, when k_1 values were plotted against log expected egg density (Fig 21), there was no correlation but upon joining the successive k value points, a spiralling anti- clockwise trend was obtained indicating delayed density dependence.

5.4 Discussion

Four out of the five systems studied, k_1 (that is, mortality in the expected number of eggs), was distinguishable as the key factor that determined the population change in E. cautella to the greatest extent throughout the duration of the experiments where 6-7 generations were obtained. It is only in Ecosystem C_1 where the changes in the population of the moth in an interaction with T. castaneum was studied, that k_1 did not appear prominent. However, even in Ecosystem D_1 where E. cautella population as a single species was studied, and remarkably without predation by B. tarsalis, k_1 was still prominent as the key population regulatory factor. In Ecosystem A where the moth's population while under predation by B. tarsalis was studied, the correlation of k_1 on K though not significant, was pronounced being 0.8398 as shown in Table 18.

Table 16. Life-table of E. cautella interacting with mixed insect pest species in grain warehouses.

	Generations					
	1	2	3	4	5	6
Eggs	3.699	3.491	3.362	4.626	3.653	3.431
k_1	1.623	1.066	0.316	2.398	1.937	1.632
Small larvae	2.076	2.425	3.046	2.228	1.716	1.799
k_2	0.000	0.279	0.326	0.104	0.000	0.243
Large larvae	2.076	2.146	2.720	2.124	1.716	1.556
k_3	0.585	0.029	0.000	0.000	0.083	0.000
Larvae 5	1.491	2.117	2.720	2.124	1.633	1.556
k_4	0.000	0.000	0.000	0.000	0.000	0.000
k_5	0.000	0.000	0.000	0.056	0.077	0.125
Pupae	1.491	2.053	2.720	2.068	1.556	1.431
k_6	0.000	0.000	0.000	0.000	0.000	0.000
k_7	0.000	0.691	0.094	0.415	0.125	0.000
Adult	1.491	1.362	2.626	1.653	1.431	1.431
K	2.208	2.129	1.736	2.973	2.222	2.000

ECOSYSTEM E

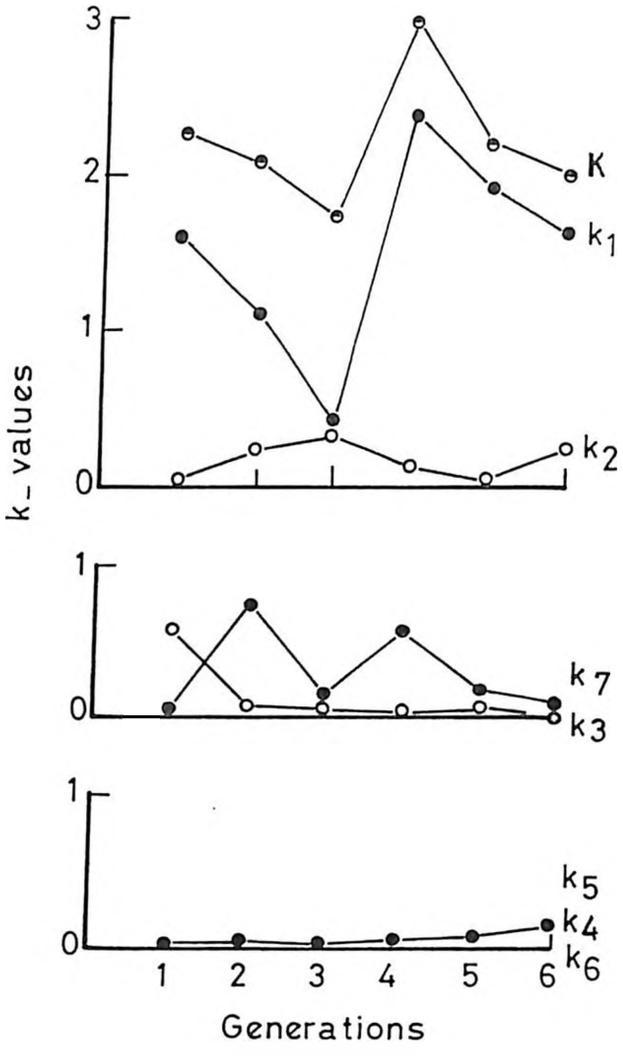

Fig 20. Graphical key factor analysis of mortality factors acting against E. cautella in an interaction with other common warehouse insect pests.

Table 17. Regressions of k_1 against expected number of eggs to analyse density dependence.

Ecosystem	Component species	Regression	Correlation
A	E. cautella B. tarsalis	y = 0.5365x + 3.6898	0.8031
B	E. cautella T. castaneum B. tarsalis	y = 0.7748x + 3.2378	0.9412
C	E. cautella T. castaneum	_	None
D	E. cautella	y = 0.6959x + 3.5359	0.9560
E	E. cautella Natural species complex	_	None

ECOSYSTEM E

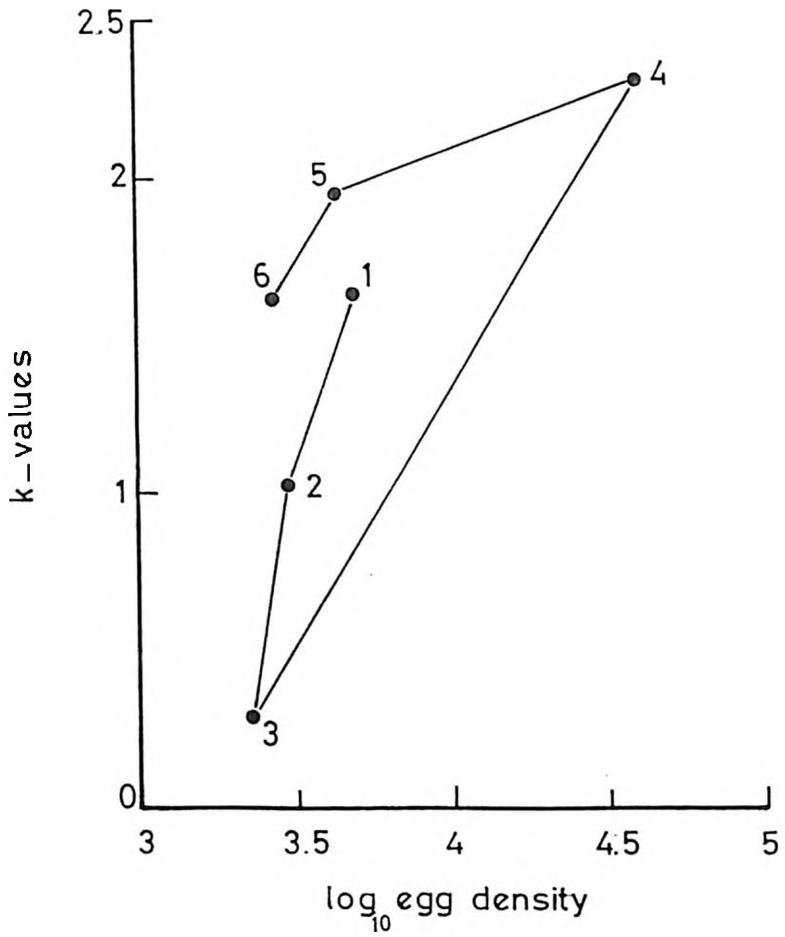

Fig 21. Density dependence relationship between mortality k_1 and the log expected egg density in Ecosystem E. Numbers on the graph denote moth generations.

Table 18. Correlation of individual mortalities with total mortality to identify key factors under various combinations of E. cautella with other storage insect species and the mite B. tarsalis

Ecosystem	Description	Correlation with K						
		k_1	k_2	k_3	k_4	k_5	k_6	k_7
A	E. cautella B. tarsalis	0.8398	-0.5051	-0.0072	-	0.1187	-	0.3773
B	E. cautella T. castaneum B. tarsalis	0.8821*	-0.1025	0.6227	-	0.5375	-0.0471	-0.4211
C	E. cautella T. castaneum	0.5548	-0.1721	-0.0658	0.3626	0.7391	0.3626	0.4554
D	E. cautella	0.8701*	-0.6138	0.4849	0.4843	0.0431	-0.0219	0.2335
E	E. cautella & other storage insect species	0.9017*	0.2544	0.2505	0.2848	0.5821	0.4303	0.7834

* Significant at 1% level
- no correlation
- behind figure = negative correlation

The key mortality k_1 is a composite of several factors, among them being:

(1) Premature death of adult female moths in copula (Brindley, 1930),

(2) Death of adults due to infestation by the mite B. tarsalis (White & Huffaker, 1969a),

(3) Predation of moth eggs by spiders in warehouses (Graham, 1970),

(4) Emigration and loss through crevices in the joints of the cages used to set up these ecosystems and through the access sleeves during sampling,

(5) Variation in the fecundity of the adults since the average figure of 200 eggs per moth was presumed to be the standard fecundity,

(6) Cannibalism among larvae of the moth, and

(7) Predation by the mite B. tarsalis.

The prominence of k_1 was observed even in the Ecosystem E where the influence of the other warehouse pests on E. cautella was also present. Direct density dependence was demonstrated through the positive slope of k_1 against the log of the expected number of eggs in three ecosystems A, B and D. The two systems in which there was no direct density dependence were those where the moth and T. castaneum were maintained and where the moth and other warehouse species were cultured together. A possible element of delayed density dependence in this relationship was observed through the spiralling trend of the plots of this mortality against the log of expected number of eggs in Ecosystems A and E. However,

in view of the fact that density dependence was also observed in Ecosystem D where E. cautella was cultured alone, no further emphasis can be laid on this trend as far as the effect of B. tarsalis is concerned.

In spite of the observed presence of direct density dependence in Ecosystem D it is still considered that predation by B. tarsalis constitutes one of the components in this mortality although the proportion of this contribution could not be determined in these investigations. This consideration is supported by the high multiplication rate of the mite arising from its short developmental period of 5.9 days (Haines, 1981) as compared to that of the moth observed to be 31 days in this study. Such a relationship is deemed to occur through increase in mite numbers corresponding with increase in moth numbers and eggs. This observation is also supported by Hassell and Huffaker's (1969b) and White and Huffaker's (1969a, b) findings in studies of interactions between B. tarsalis and Anagasta kuhniella, another pyralid moth. They showed that there was a strongly pronounced pattern of repeating population cycles of the mite accompanied by development of distinct generations of the moth. In the present study it seems that even if density dependence in the mortality of the eggs may have been caused by the mite this is clouded by other mortality factors in this stage as outlined above. A complete detailed study would establish the relative importance of each of these components not only towards the expected number of eggs but also towards the total mortality. In this study it has been established that egg mortality is the key factor and that it causes direct density dependence in the expected number of eggs and on the total mortality.

In an attempt to further understand this density dependence in the egg mortality, each of the seven components of this mortality is examined in turn. Premature death of adults in

copula (Brindley, 1930) was possible but death due to predation by spiders (Graham, 1970) was not demonstrated here. There was minimal loss, if any, of adults through crevices or gaps in the access sleeves in the cages during sampling. Also cannibalism was expected to be rare in conditions where severe overcrowding is absent. Moreover, with the uniform diet and controlled environmental conditions provided, the size of adults and consequently egg output, is expected to have varied a little. The other factor is mite predation on the eggs and death of adults from stress by mite phoresy but the prominence of this component is questionable for the demonstrated density dependence of egg mortality in the key mortality when the moth was cultured alone.

The observed density dependence in the key factor k_1 on the egg mortality does not therefore appear to be exclusively due to the mite since even the slope (b = 0.6959) in the system where the moth was cultured alone was higher than in that where the moth was cultured with the mite (b = 0.5365) indicating a higher stabilising effect in a case where the mite was absent. It can therefore be concluded that although high egg mortality and high incidence of the mite has been observed in association with the moth in the past, (Graham, 1970a, b and c) the two populations were not seen to be correlated in this study and that therefore, the mite is not a key determinant of the variation in the moth population in a direct way and possibly there is no density dependence. This indicates that the mite cannot singly be relied upon to give an effective, regular and complete control of the moth.

CHAPTER 6

EVALUATION OF POTENTIAL AND CONVENTIONAL INSECTICIDES IN THE CONTROL OF E. CAUTELLA AND ASSOCIATED PESTS IN THE PRESENCE OF B. TARSALIS AS A PREDATOR

6.1 Introduction

It has been shown in past studies that the levels at which populations of E. cautella stabilize while under predation by the mite, B. tarsalis, are higher than those which can be tolerated in storage (Graham, 1966; McFarlane, 1970). Under such circumstances chemical pesticides would be needed to suppress those levels further. Also, during the periods that the population of E. cautella would be considered to be under the control of B. tarsalis as observed by Graham (1970b), other associated pests, particularly T. castaneum, have already established themselves to an extent of requiring attention through other means apart from predation by this mite. It is, therefore, necessary to consider chemicals as a complementary method of achieving the required control of these pests in the maize storage warehouses.

Standard official recommendations for insecticides use on maize by the Ministry of Agriculture released in 1972 comprised mainly organophosphate compounds. These are categorized into two groups; those suitable for admixture into grain and those considered appropriate for space and surface application including bag treatment. Those approved for admixture with grain are; 2% malathion , 1.0% pirimiphos-methyl, 2.0% bromophos and 3.25% tetrachlorvinphos all formulated in dust form. On the other hand, those approved for space and surface spray treatment are; malathion at 1-2 gm/sq.m, pyrethrins synergized with piperonyl butoxide at 0.1% pyrethrins:1.0% piperonyl butoxide at 0.1g:1.0g/sq.m., bromophos at 0.5g/sq.m, fenitrothion at 0.5 to 1.0 gm/sq.m and

dichlorvos at 1.0 gm/sq.m. Through the use of these chemicals especially those recommended for space and surface treatments, complete control of the target pests has not always been achieved and with some such as malathion, only minimal suppression of both E. cautella and T. castaneum has been obtained. The new organophosphate insecticide dusts included in these trials were 2.0% methacrifos applied at 10 ppm and 2.0% chloropyrifos-methyl at 8 ppm. The pyrethroids; 0.2% deltamethrin applied at 1.0 ppm and 0.5% permethrin at 2.5 ppm were also included in this trial. Dimilin (diflubenzuron), an insect growth regulator which had previously been shown to have a potentially useful mortality effect on coleopterous pests of storage (Mcgregor and Kramer, 1976) was also included.

Among the conventionally used insecticide dusts, the commonest are pirimiphos-methyl, malathion and bromophos in this order, while pirimiphos-methyl and dichlorvos have gained widespread use as sprays. Tetrachlorvinphos as a 3.25% dust though recommended, it's usage has not been established due to marketing problems. The popularity of pirimiphos-methyl over malathion both as an admixture and as a spray, has stemmed from its observed better performance (McDonald and Gillenwater, 1976). In the present screening process, the ideal pesticide would initially be expected to excel in efficacy in the control of E. cautella and T. castaneum while having a minimal effect on B. tarsalis to retain the control through this predator. Candidate pesticides were, therefore, initially tested against the two pests and subsequently, on E. cautella under predation by B. tarsalis. The insecticides identified as being effective were thereafter tested in a simulated warehouse situation to enable one getting an insight into the effects of these pesticides when some factors which could obscure these effects were excluded. Later, the most effective of these pesticides would be studied in the field under natural conditions in conventional maize storage warehouses.

An important factor causing variability in the effectiveness of these chemicals is the development of resistance in storage insect pests. For instance, despite the known resistance in various storage pests, particularly S. zeamais, E. cautella and T. castaneum against malathion (Champ and Dyte, 1976), this insecticide continues to be used for the protection of stored maize in Kenya. The reason for this is, presumably, due to its historical background, its safety, low cost and broad-spectrum activity on the majority of key storage pests. For this reason, it was included in these trials to serve as a standard. Dichlorvos and pirimiphos-methyl have complementary roles in their effect on storage insect pests whereby the former is better on lepidopterous infestations while the latter is better on coleopterans. Demonstration of performance of these chemicals under field situations is necessary since the results of laboratory testing cannot always realistically be extrapolated to field application. Conditions in the field not only fluctuate widely but also have certain unique features such as the fabric surfaces where these may be either wooden or concrete.

6.2 Materials and methods

In the screening of these pesticides for their efficacy adult moths of E. cautella, aged up to 48 hours old were used in control experiments. These had been cultured in the laboratory in a controlled temperature and relative humidity room at 27±2°C and 70±5% relative humidity. The adult stage of the moth was preferred to other developmental stages since it is most mobile, occurring not only on the grain itself but also on stack surfaces, bags, walls, roofs and other store surfaces.

Adults, for this reason, are the most accessible stage to both sprays and insecticide dusts admixed into grain. Adults of T. castaneum obtained from laboratory cultures were also used in

these trials. The cultures were initiated with specimens obtained from maize in Eldoret. The culturing medium used for T. castaneum was the conventional wheat meal, yeast and glycerol in ratio of 12:1:3. Adults aged up to 7 days were used in these trials. The candidate insecticides used are shown in Table 19. These were acquired directly from manufacturers except for dichlorvos which was diluted with water from 48% emulsifiable concentrate. The dosages used were those recommended by the manufacturers based on various trials on efficacy and safety in accordance with requirements of both FAO and WHO on these properties. For E. cautella cultures, a measured quantity of insecticide as indicated in Table 19 was added to 100g whole maize grain at 13.4 percent moisture content as determined with a Burrows moisture meter. This was admixed thoroughly, then divided into 25g lots which were placed into small kilner jars to make 4 replicates.

In the case of E. cautella, ten fourth instar larvae were introduced into the above preparation. Mortality was assessed after 24, 48, 72 and 168 hours where during each assessment dead larvae were removed. Thereafter, the grain with the remaining live larvae was retained until one week after the first adult had emerged at which time the adult count was made. In the parallel bioassay where E. cautella under predation by B. tarsalis were exposed to those insecticides the adult moths used were collected from maize storage warehouses in Nairobi since the previous survey had shown that these contained mites. By killing samples of these moths with ethyl acetate and shaking them to free the mites, the level of predation had hitherto been estimated, there being too few moths to count after 1 month. In each case, a control treatment was included.

In later trials where selected insecticides were further tested under laboratory cage ecosystems to simulate field conditions, the cages used were identical to those described

Table 19. Candidate insecticides for the bioassays on E. cautella and T. castaneum.

Insecticide	Dosage ppm	Concentration	Amount per 100 g maize (mg)
Dimilin	2.0	1.0% dust	20.0
Dichlorvos	6.8	48.0% e.c	1.368
Pirimiphos-methyl	5.0	1.0% dust	20.0
Damfin	10.0	2.0% dust	50.0
Fenitrothion	7.5	1.5% dust	50.0
Malathion	10.0	2.0% dust	50.0
Etrimfos	5.0	1.0% dust	50.0
Deltamethrin	1.0	1.0% dust	50.0
Permethrin	2.5	0.5% dust	50.0
Chlorpyrifos methyl	8.0	2.0% dust	100.0
*Pyrethrins	2.0	0.4% dust	50.0

* With a synergist piperonyl butoxide at 1:10 ratio

in Chapter 5. In these cages, paper trays were used to contain the food medium which consisted of whole maize extracted from bag stacks in warehouses in Nairobi. The maize already carried a low level of infestation by T. castaneum. Fifty E. cautella adults under natural predation by B. tarsalis were placed in each cage. The cages were then maintained for 14 weeks to allow the populations of the two pests and the mite to become established before applying the insecticide sprays. These candidate insecticides are shown in Table 20. The chemicals were formulated specifically for these trials by the suppliers. They were diluted with ordinary tap water to make the required spray and applied at the rates indicated. A control treatment in which no chemical was applied was included. Sprays into the cages were performed using a simple "flit" sprayer which was introduced through the access sleeve. Thereafter, the cages were sustained for a further 10 weeks. During the entire 25 weeks of the experimentation, 9 boxes in a row were extracted from each cage each week and insect counts made from the food medium spread out on a tray. Thereafter, new boxes with new food were introduced in replacement. Thus like the cages in Chapter 5, all the food in the cage would gradually be replaced so that after 9 weeks all the food in the 81 boxes in the cage was renewed.

In determining the efficacy of these insecticides on E. cautella, dead 5th instar larvae, pupae and adults were counted weekly for 25 weeks. In the case of T. castaneum, only adults were counted while for the mite B. tarsalis, both nymphs and adults were counted. Both free-living mites within the food and phoretic ones extracted by shaking the mites off the adult moths were enumerated. During the 25 weeks duration of the trial, 6 generations of both E. cautella and T. castaneum were obtained, 3 each before and after the insecticidal application. In the case of B. tarsalis which has a much shorter developmental period than either of the other two species, more generations were expected to have been realised.

Table 20. Insecticides in laboratory cage ecosystems and their application rates

Chemical name	Local name	Conc. percent a.i.	Formulation	Application rate (a.i.)
Permethrin	Coopex	20.0	e.c.	0.5g/m^2
Malathion	Killpest	50.0	e.c.	1.0g/m^2
Pyrethrins	-	25.0	oil conc.	0.5g/m^2
Dichlorvos	Vapona	48.0	e.c.	1.0g/m^2
Pirimiphos-methyl	Actellic	50.0	e.c.	0.5g/m^2

In order to test the selected chemicals in field situations, 4 conventional bag storage warehouses with masonry walls and asbestos roof containing one stack of maize in each were used. The stacks of maize were made in such a way that a space of 60 cm was left between the stacks and the walls and 2 metres from the top of the stack to the roof. The space between the walls and the stacks is necessary for ventilation, for stock inspection and also provides a working area for pest control operations. The space above the stack, on the other hand, serves a similar purpose but also separates the grain from contact and proximity to the roof which influences the immediate space with varying temperatures through heat conduction and loss.

The stores in which these trials were carried out were located in Lunga Lunga depot in the Industrial Area of Nairobi. These were designated numbers 2, 3, 4 and 5. Store 2 contained 30,220 bags of maize which had earlier been fumigated with phosphine and simultaneously sprayed with dichlorvos on 15th May, 1989. Store 3 contained 29,701 bags of maize which had received similar treatment to Store 2. Store 4 carried 26,170 bags of maize fumigated in December, 1988 but had been sprayed with dichlorvos on 15th May, 1989 while Store 5 which contained 30,500 bags had received similar treatment to Store 4 . Each bag of maize normally weighs 91 kg composed of 90kg of the grain itself and 1 kg for the empty bag. Bags are made from a combination of jute and sisal fabrics. Fumigations and sprays are carried out in the warehouses as and when the population levels of the insects are deemed to be economically important, each warehouse forming a storage unit. On the other hand, stores are often disinfested in clusters in order to curb cross-infestation.

Warehouses 2, 3 and 4 were sprayed with the candidate insecticides on 20th June, 1989 and 29th June, 1989 following 3 weeks of monitoring to assess initial infestation. The

chemicals used were pirimiphos-methyl 50% e.c. applied at 500 mg/sq.m., malathion 50% e.c. applied at 1000 mg/sq.m. and dichlorvos 48% e.c. at the same rate. All surfaces inside the stores were sprayed including walls, floors, doors, roofs and stack surfaces. Dichlorvos and pirimiphos-methyl which were identified as the more effective ones from the screening biossays were included while malathion served as a standard. Store 2 was treated with pirimiphos-methyl, Store 3 with malathion, Store 4 with dichlorvos while Store 5 remained untreated for comparison.

Insect samples were collected from one square metre marked areas on wall surfaces and on grain stacks and bag surfaces. All insects on these areas were collected at weekly intervals by use of a small paint brush to extricate those sandwiched in the crevices. Each sampling point consisted of two opposing marked areas on the wall and on the stack surfaces. There were 4 such sampling points in each store. Sampling was carried out weekly for 9 weeks from 25th May, 1989 to 10th August, 1989. The population of T. castaneum rose to a level that necessitated fumigation on 3rd August, 1989 after 8 weeks of sampling, especially in Store 5 which had received no insecticidal spray. At this juncture, all the stores were fumigated with phosphine and sprayed with pirimiphos-methyl and the trial terminated after only one further sampling during the 9th week.

6.3 Results and discussion

6.3.1 Performance of common and new insecticides in the control of E. cautella and T. castaneum including E. cautella under B. tarsalis predation

Percentage cumulative mortality of E. cautella larvae after 24, 48, 72 and 168 hours exposure to insecticides with corresponding adult mortality one week after emergence and

total adult emergence at the end of the trial, is shown in Table 21. Analysis of variance of percent cumulative mortality during the four stages of assessment as shown in Table 22 indicates that the differences between the treatments were significant at 5% level after 24, 72 and 168 hour counts. In the 48th hour mortality count, however, these differences did not appear significant. Despite this lack of consistency, differences in the performance of these chemicals were considered to have been clear enough. The cumulative mortality after 168 hours was thereafter analyzed using Duncan's Multiple Range Test to enable ranking of these insecticides in order of efficacy as shown in Table 23. It was found that dichlorvos, deltamethrin and fenitrothion gave the best performance, followed by etrimfos and damfin in this order. Mortality one week after first emergence as shown in Table 20 indicates the relative persistence of these insecticides but this could not be reliably used as an indicator of ranking the efficacy of these insecticides since the emergence was too small numerically. Hence, the most reliable factor for the ranking of these insecticides was the 168 hour cumulative mortality of the larvae. In terms of this mortality, the least effective insecticide was permethrin which was seen to perform not distinctly better than the control. This indicates almost total lack of control of E. cautella larvae by this chemical. It is noted too, that organophosphates pirimiphos-methyl and malathion gave inferior control of the moth larvae as did the pyrethrins.

The results for adult T. castaneum cumulative mortality over 24, 48, 72, and 168 hours (Table 24) show that malathion achieved a mere 1.25 percent mortality after 168 hours exposure. Deltamethrin and chlorpyrifos-methyl, though showing

total adult emergence at the end of the trial, is shown in Table 21. Analysis of variance of percent cumulative mortality during the four stages of assessment as shown in Table 22 indicates that the differences between the treatments were significant at 5% level after 24, 72 and 168 hour counts. In the 48th hour mortality count, however, these differences did not appear significant. Despite this lack of consistency, differences in the performance of these chemicals were considered to have been clear enough. The cumulative mortality after 168 hours was thereafter analyzed using Duncan's Multiple Range Test to enable ranking of these insecticides in order of efficacy as shown in Table 23. It was found that dichlorvos, deltamethrin and fenitrothion gave the best performance, followed by etrimfos and damfin in this order. Mortality one week after first emergence as shown in Table 20 indicates the relative persistence of these insecticides but this could not be reliably used as an indicator of ranking the efficacy of these insecticides since the emergence was too small numerically. Hence, the most reliable factor for the ranking of these insecticides was the 168 hour cumulative mortality of the larvae. In terms of this mortality, the least effective insecticide was permethrin which was seen to perform not distinctly better than the control. This indicates almost total lack of control of E. cautella larvae by this chemical. It is noted too, that organophosphates pirimiphos-methyl and malathion gave inferior control of the moth larvae as did the pyrethrins.

The results for adult T. castaneum cumulative mortality over 24, 48, 72, and 168 hours (Table 24) show that malathion achieved a mere 1.25 percent mortality after 168 hours exposure. Deltamethrin and chlorpyrifos-methyl, though showing a remarkably superior performance compared to malathion, did not give 100% kill throughout the entire exposure period. This shows that the insecticides which would be expected to give good control of this pest are; dichlorvos,

Table 21. Results of screening of 11 insecticides against *E. cautella*. Mean percent mortality of 4 replicates.

Insecticide	Dosage in ppm	Cumulative larval mortality				Adult mortality 1 week after emergence	Total emergence
		24 hrs	48 hrs	72 hrs	168 hrs		
Dimilin	2.0	5.0	30.0	32.5	32.5	0	5
Dichlorvos	1.0	10.0	37.9	60.0	80.0	100.0	8
Pirimiphos-methyl	5.0	2.5	22.5	27.5	30.0	11.8	24
Damfin	10.0	7.5	42.5	55.0	57.5	0	10
Fenitrothion	7.5	2.5	32.5	52.5	62.5	0	6
Malathion	10.0	20.0	37.5	42.5	42.5	6.7	18
Etrimfos	5.0	5.0	35.0	50.0	60.0	50.0	16
Deltamethrin	1.0	7.5	22.5	32.5	70.0	0	0
Permethrin	2.5	7.5	20.0	22.5	25.0	55.6	17
Chlorpyrifos-methyl	8.0	2.5	25.0	35.0	40.0	56.3	16
Pyrethrins	2.0	2.5	12.5	30.0	30.0	31.6	23
Control	-	0.0	19.5	23.2	26.8	8.3	15

Table 22. Analysis of variance for percent cumulative mortality in E. cautella arising from exposure to various insecticides for 24, 48, 72, and 168 hours.

(a) Mortality after 24 hours

Source of variation	Degrees of freedom	Sum of squares	Variance	F
Total	47	2947.9		
Replication	3	72.9	24.3	0.5
Insecticides	11	1222.9	111.2	2.2*
Error	33	1652.1	50.1	

(b) Mortality after 48 hours

Source of variation	Degrees of freedom	Sum of squares	Variance	F
Total	47	9518.0		
Replication	3	298.5	99.5	0.59
Insecticides	11	3640.0	330.9	1.96*
Error	33	5579.5	169.1	

(c) Mortality after 72 hours

Source of variation	Degrees of freedom	Sum of squares	Variance	F
Total	47	13259.0		
Replication	3	690.1	220.0	1.1
Insecticides	11	5757.1	523.4	2.5*
Error	33	6811.8	206.4	

(d) Mortality after 168 hours

Source of variation	Degrees of freedom	Sum of squares	Variance	F
Total	47	22064.7		
Replication	3	474.0	158.0	0.9
Insecticides	11	15534.8	1412.3	7.7*
Error	33	6055.2	183.5	

* Significant at 5% level.

Table 23. Duncan's Multiple-Range test applied to the insecticidal bioassay data in Table 22 for the 168 hours cumulative mortality of E. cautella larvae.

Treatment	Mean % kill of larvae	Angles	No. of means	Significant studentised range	Difference
Permethrin	25.0	30.0	12	16.3	a
Control	26.8	31.3	11	16.2	a
Pirimiphos-methyl	30.0	33.2	10	16.1	a
Pyrethrins	30.0	33.2	9	16.0	a
Dimilin	32.5	34.8	8	15.9	a
Chlorpyrifos-methyl	40.0	39.2	7	15.7	a
Malathion	42.5	40.7	6	15.3	a
Damfin	57.5	49.3	5	15.3	a
Etrimfos	60.0	50.8	4	15.0	b
Fenitrothion	62.5	52.2	3	14.5	b
Deltamethrin	70.0	56.8	2	13.8	b
Dichlorvos	80.0	63.4			b

Means designated by the same letters are not significantly different at the 5 percent level. Others are.

Table 24. Results of screening 11 insecticides against *T. castaneum* adults.

Insecticide	Dosage in ppm	Cumulative percent mortality			
		24 hrs	48 hrs	72 hrs	168 hrs
Dimilin	2.0	0.00	0.00	0.00	0.00
Dichlorvos	1.0	98.75	100.00	100.00	100.00
Pirimiphos-methyl	5.0	94.38	99.38	100.00	100.00
Damfin	10.0	100.00	100.00	100.00	100.00
Fenitrothion	7.5	51.25	81.25	100.00	100.00
Malathion	10.0	0.00	0.00	0.00	1.25
Etrimfos	5.0	99.38	100.00	100.00	100.00
Deltamethrin	1.0	1.25	6.25	13.13	65.00
Permethrin	2.5	0.00	0.00	0.00	0.00
Chlorpyrifos-methyl	8.0	0.00	15.63	51.25	98.75
Pyrethrins	2.0	0.00	0.00	0.00	0.00
Control	-	0.00	0.00	0.00	0.00

pirimiphos-methyl, damfin, fenitrothion and etrimfos with the most rapid kill being shown by damfin, etrimfos and dichlorvos in this order. Chlorpyrifos methyl although achieving 98.75 percent kill after 168 hours was inferior to these others on account of its slow-acting tendency. After 48 hours these others had already achieved 100 percent mortality.

In the bioassay on E. cautella under predation by B. tarsalis, the adult emergence of E. cautella after 2 months and 3 months is shown in Table 25. Numbers counted were rather small especially after 3 months. However, upon observing the figures for 2 months the lowest emergence is demonstrated by etrimfos followed by permethrin with pirimiphos-methyl and chloropyrifos-methyl equal in third place. Higher emergence than in the control was shown in dimilin. Emergence after 3 months, being too low, cannot be relied upon for drawing inferences. It is notable as well that no insecticide was able to completely suppress the development of E. cautella population despite their varied persistence.

In this investigation, it was expected that these insecticides would demonstrate differential effects in the mortality of both the moth and the mite whereby higher mortality in the mite would stimulate a higher multiplication rate in the moth. It is recognised, however, that under normal storage, the insecticide affects both the moth and the mite. Here, mortality in the moth is a combination of two factors; the kill by the insecticide and predation by the mite. Mite mortality is also caused by the diminution of egg availability after death of the adult moth from insecticidal activity and also by the effect of the insecticide on the mite itself. It is, therefore, difficult to examine each of these effects in isolation since combinations of factors are involved. At best, the effect of the insecticide in these interactions can only be discerned through the mortality achieved in the moth as the target pest.

Table 24. Results of screening 11 insecticides against *T. castaneum* adults.

Insecticide	Dosage in ppm	Cumulative percent mortality			
		24 hrs	48 hrs	72 hrs	168 hrs
Dimilin	2.0	0.00	0.00	0.00	0.00
Dichlorvos	1.0	98.75	100.00	100.00	100.00
Pirimiphos-methyl	5.0	94.38	99.38	100.00	100.00
Damfin	10.0	100.00	100.00	100.00	100.00
Fenitrothion	7.5	51.25	81.25	100.00	100.00
Malathion	10.0	0.00	0.00	0.00	1.25
Etrimfos	5.0	99.38	100.00	100.00	100.00
Deltamethrin	1.0	1.25	6.25	13.13	65.00
Permethrin	2.5	0.00	0.00	0.00	0.00
Chlorpyrifos-methyl	8.0	0.00	15.63	51.25	98.75
Pyrethrins	2.0	0.00	0.00	0.00	0.00
Control	-	0.00	0.00	0.00	0.00

Table 25. Total (1+d) number (4 replicates) of emerged adult *E. cautella* after introducing adults infested by *B. tarsalis* into insecticide treated grain

Insecticide	Dosage in ppm	Emergence after 2 months	Emergence after 3 months
Dimilin	2.0	21	7
Dichlorvos	1.0	12	0
Pirimiphos-methyl	5.0	6	1
Damfin	10.0	9	12
Fenitrothion	7.5	8	1
Malathion	10.0	11	8
Etrimfos	5.0	2	1
Deltamethrin	1.0	7	1
Permethrin	2.5	3	3
Chlorpyrifos-methyl	8.0	6	2
Pyrethrins	2.0	13	4
Control	-	19	6

Table 25. Total (1+d) number (4 replicates) of emerged adult E. cautella after introducing adults infested by B. tarsalis into insecticide treated grain

Insecticide	Dosage in ppm	Emergence after 2 months	Emergence after 3 months
Dimilin	2.0	21	7
Dichlorvos	1.0	12	0
Pirimiphos-methyl	5.0	6	1
Damfin	10.0	9	12
Fenitrothion	7.5	8	1
Malathion	10.0	11	8
Etrimfos	5.0	2	1
Deltamethrin	1.0	7	1
Permethrin	2.5	3	3
Chlorpyrifos-methyl	8.0	6	2
Pyrethrins	2.0	13	4
Control	-	19	6

Assessment of the performance of these insecticides on the mites alone in a bioassay is not easy since the mite is phoretic on the moth. Hence, under normal circumstances the amount of insecticide presented to the mite is not only minimal but also the moth would invariably in such exposure be killed in the process. For these reasons, it was considered feasible to obtain the effect of the insecticide on the moth as an indirect indicator of its effect on the mite by contrasting the mortality of the moth with and without the mite. Mortality of the mite arising from the insecticidal effect would then lead to a higher multiplication rate in the moth due to the resultant decreased mite population and consequently reduced predation on the moth's eggs.

Thus the criteria used for the identification of candidate insecticides for further trials in the laboratory under field simulated cage ecosystems was, first and foremost, effectiveness in the control of E. cautella, secondly, in the control of T. castaneum and thirdly, possession of superiority in performance in a system where the moth was under predation by the mite. Dichlorvos satisfied the first requirement while pirimiphos-methyl satisfied the second. In terms of efficacy on E. cautella under predation by B. tarsalis, these two insecticides did not demonstrate superiority but less weight was placed on this test since adult emergence was insufficient for the effects to be clear. It is noted that from a safety consideration deltamethrin is still unapproved as a protectant of stored grain while fenitrothion is only approved as a clean-up compound. Damfin and chlorpyrifos-methyl did not give outstanding performance but even though both have not been sanctioned for this usage. These conditions precluded further testing of these chemicals in the field.

6.3.2 Population growth of E. cautella, T. castaneum and B. tarsalis under the influence of selected pesticides in a laboratory setting

Weekly total counts of individuals of the three species are shown in Table 26 where apparently there was a variation in

Table 26. Population growth of E. cautella, T. castaneum and B. tarsalis after application of various insecticides in laboratory cage ecosystems.

Systems	Species Combination	Stage	Time in weeks																							
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1. Permethrin	E. cautella	Larva 5	-	9	-	18	-	-	36	108	27	27	27	396	261	63	27	18	117	243	54	36	72	1737	675	909	99
		Pupa	-	18	-	18	-	36	36	45	9	27	-	18	18	243	36	81	90	315	378	81	36	135	198	117	27
		Adult	81	45	81	90	36	63	27	45	18	63	72	27	45	28	9	27	27	144	135	198	90	63	18	117	54
	T. castaneum	Adult	9	9	-	81	18	45	9	63	54	18	45	-	-	-	27	9	9	-	-	36	72	81	108	90	27
	B. tarsalis	Adult + Nymph	-	-	-	-	63	-	-	36	9	9	108	9	-	-	27	-	-	-	-	-	36	54	54	-	-
2. Malathion	E. cautella	Larva 5	18	9	27	-	9	36	117	45	36	18	45	9	18	90	9	63	531	189	297	36	99	315	45	36	261
		Pupa	36	63	9	-	27	-	36	18	72	45	-	18	81	63	243	9	117	639	633	432	315	315	36	18	45
		Adult	63	18	36	18	36	36	9	36	135	279	99	36	9	18	90	36	126	72	234	99	171	315	162	153	180
	T. castaneum	Adult	36	9	-	-	9	27	90	18	72	90	9	27	36	18	-	27	9	-	-	-	27	117	81	54	72
	B. tarsalis	Adult + Nymph	-	-	45	45	-	36	9	18	-	63	27	-	-	45	-	27	9	-	63	36	99	243	117	63	135
3. Pyrethrins	E. cautella	Larva 5	18	9	-	18	9	18	-	45	27	9	9	-	-	63	27	9	-	-	54	18	-	36	-	-	9
		Pupa	9	27	9	-	-	18	27	-	54	18	-	-	-	9	45	45	1	-	27	54	9	9	-	-	-
		Adult	9	36	36	9	54	27	27	45	27	18	27	27	27	-	9	27	27	36	117	81	18	9	-	9	-
	T. castaneum	Adult	27	63	9	27	36	18	54	27	108	36	63	36	9	18	9	72	72	90	153	27	135	171	324	225	252
	B. tarsalis	Adult + Nymph	-	-	45	36	27	-	9	18	-	-	-	-	-	45	-	9	9	-	18	-	-	-	-	-	-
4. None	E. cautella	Larva 5	9	18	9	-	-	-	-	-	-	18	54	27	27	180	54	27	36	9	162	144	45	-	27	54	99
		Pupa	-	9	-	18	9	-	-	18	9	18	72	45	18	9	54	45	45	18	9	99	180	54	9	72	27
		Adult	27	18	45	36	45	27	27	9	27	-	36	72	-	-	18	54	90	180	261	63	90	225	126	117	27
	T. castaneum	Adult	27	27	-	54	27	9	18	45	216	63	36	45	27	18	9	27	63	18	-	63	81	207	63	108	171
	B. tarsalis	Adult + Nymph	-	18	-	-	9	-	-	-	-	-	-	36	81	6	18	72	144	99	63	-	-	27	9	-	-
5. Dichlorvos 48%	E. cautella	Larva 5	18	9	9	27	27	9	18	18	18	27	-	-	18	18	-	-	-	-	9	-	-	-	-	-	-
		Pupa	-	-	18	18	-	45	27	54	18	18	-	-	54	126	144	18	-	9	9	-	-	27	-	9	-
		Adult	27	9	9	18	90	72	27	18	27	54	-	54	63	-	72	27	72	135	153	63	-	27	9	36	-
	T. castaneum	Adult	-	27	-	9	36	18	18	27	18	18	-	27	-	18	54	9	-	-	36	-	9	9	18	45	18
	B. tarsalis	Adult + Nymph	-	-	-	-	-	9	-	-	-	-	-	36	54	-	72	18	-	-	-	-	-	-	-	-	54
6. Pirimiphos-methyl	E. cautella	Larva 5	18	-	-	-	18	-	27	72	45	-	9	36	36	36	-	9	-	-	-	-	-	-	-	-	27
		Pupa	-	9	-	-	-	-	-	-	-	18	54	27	9	99	27	27	18	27	18	-	9	18	-	9	-
		Adult	27	18	18	18	27	45	18	9	45	45	54	81	36	72	27	54	72	108	144	9	27	-	-	-	27
	T. castaneum	Adult	18	27	9	9	-	-	18	36	18	9	18	9	18	27	27	9	-	9	27	18	-	9	9	27	72
	B. tarsalis	Adult + Nymph	-	-	-	9	9	-	9	-	-	-	-	45	-	54	54	9	-	-	-	-	-	-	18	-	-

the rate of establishment of the three species prior to insecticide application in all the 6 cages. There was, for instance, poor establishment of populations in cages treated with pirimiphos-methyl, dichlorvos and pyrethrins. Despite this, the performance of these insecticides could be discerned by comparison of the numbers prior to and following insecticidal application. In Table 27, comparison is made between the numbers of the three species in the middle of the period before and after insecticidal application. It is apparent that dichlorvos and pirimiphos-methyl sprays were more effective against E. cautella than either malathion or permethrin since the ratio of the number of adults prior to and after insecticidal application was 0.4 for both dichlorvos and pirimiphos-methyl as compared to 5.8 and 2.0 for malathion and permethrin respectively. However, for T. castaneum, no difference was observed in pirimophos-methyl, dichlorvos and malathion in the ratios of adult numbers before and after application of these insecticides. Permethrin, on the other hand, appeared to give even poorer performance than the control, where no insecticide was applied. Malathion had the least effect on E. cautella. In these trials, the numbers of B. tarsalis counted were too small for any meaningful comparison to be attempted on the insecticidal performance.

The requirement that a pesticide be broad-spectrum in its action against the majority of the main storage pests to qualify as potentially useful is as important as in other spheres of pest control, perhaps more so, since as little residues as possible can be tolerated on a stored product. In this trial therefore, the insecticides which can be considered potentially beneficial are those that are effective not only on E. cautella, but also on T. castaneum. These are dichlorvos and pirimiphos-methyl among those tested. Of these two, dichlorvos has minimal residual characteristics especially on coleopterous pests and hence would be less preferred to pirimiphos-methyl. Nonetheless, dichlorvos possesses a profound vapour effect enabling greater penetration into

Table 27. Comparison of total numbers of *E. cautella* (EC), *T. castaneum* (TC) and *B. tarsalis* (BT) during the middle of the period before and after insecticidal application.

Insecticide	Species	(2) Before application (8th & 9th week)	(1) After application (20th & 21st week)	Ratio of (1) to (2)
Permethrin	EC	252	513	2.0
	TC	117	108	0.9
	BT	45	36	0.8
Malathion	EC	198	1152	5.8
	TC	90	27	0.3
	BT	18	135	7.5
Dichlorvos	EC	153	63	0.4
	TC	35	9	0.3
	BT	0	0	-
Pirimiphos-methyl	EC	153	63	0.4
	TC	35	9	0.3
	BT	0	0	-
None	EC	63	621	9.9
	TC	171	144	0.4
	BT	0	0	-

the deeper layers of a grain bulk.

Among these chemicals, resistance has previously been demonstrated in T. castaneum against malathion in Kenya and elsewhere (Champ and Dyte, 1976). It may therefore not qualify as a pesticide of choice in terms of its demonstrated performance than pirimiphos-methyl against T. castaneum. In Kenya, McFarlane (1963) and Graham (1966) had already demonstrated the inadequacy of malathion for control of E. cautella. Moreover, among the five candidate pesticides in this trial, dichlorvos and pirimiphos-methyl stand out as having given superior control performances than the rest especially against E. cautella. It is also observed in Table 26 that under these conditions where the moth E. cautella was under predation by the mite B. tarsalis, pyrethrins, dichlorvos and pirimiphos-methyl superseded permethrin and malathion in the control of this moth.

6.3.3 Performance of selected insecticides in the control of E. cautella in a field situation

Figures of numbers of insects collected from the walls, stack surfaces and from samples of grain extracted using a spear probe are shown in Table 28 for all the important species observed. Each figure in the case of samples collected from the walls and stack surfaces stands for a combination of 4 sampling points in each store. From this Table, it is apparent that numbers of most species remained initially low during the first 5 weeks after fumigation. Numbers of T. castaneum, S. zeamais and Liposcelis entomophilus were consistently higher than the rest while moth numbers particularly, E. cautella and C. cephalonica remained relatively low during the 9 weeks duration of the trial and particularly after the decline upon spray treatment on 20th and 29th June 1989. Moreover, although the numbers of T. castaneum appeared to be generally higher during most of the time after spraying in Store 5 which had received no insecticidal treatment, there were no profound

Table 28. Populations of various species of storage insect pests before and after spraying with various pesticides in 4 warehouses in Nairobi Lunga Lunga depot.

Week	Store	S. zeamais			T. castaneus				E. cautella			C. cephalonica			R. dominica			Cryptolestes spp			B. tarsalis			Psocids		
		W	St	Sa	W	St	Sa	T	W	St	Sa	W	St	Sa	W	St	Sa	W	St	Sa	W	St	Sa	W	St	Sa
1	2	-	-	3	1	-	-	1	1	1	-	10	4	-	-	-	-	-	-	-	-	-	-	-	23	10
29/05/89	3	-	-	53	2	1	4	7	1	-	-	2	1	-	1	-	-	-	-	8	-	-	-	3	-	3
	4	-	-	1	-	-	6	6	2	1	-	3	1	-	1	-	-	-	-	4	-	-	-	6	32	8
	5	-	-	-	4	1	-	5	-	1	-	7	4	-	1	-	-	-	-	-	-	-	-	-	17	5
2	2	-	-	-	-	-	-	-	1	1	-	10	6	-	-	-	-	-	-	-	73	30	-	-	10	-
15/06/89	3	-	-	-	1	-	-	1	1	-	-	2	2	-	-	-	-	1	-	-	5	7	-	-	9	-
	4	-	-	-	3	3	-	6	-	-	-	1	-	-	-	-	-	-	-	-	7	-	-	7	18	-
	5	2	-	-	6	3	-	9	-	-	-	2	-	-	-	-	-	-	-	-	-	5	-	-	-	-
3	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	-	-	40
Sprayed with	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
trial chemicals	4	-	-	18	-	-	2	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17
on 20/6/89 & 29/6/89	5	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	2	-	-	13	2	-	3	5	1	-	-	1	2	-	-	-	1	1	-	-	2	8	-	7	-	16
7/7/89	3	-	-	-	8	-	-	8	-	-	-	-	-	-	15	-	-	-	-	-	-	-	2	29	-	13
	4	-	-	-	3	9	-	12	-	-	-	1	-	-	-	-	-	-	-	-	-	-	1	-	7	2
	5	-	4	3	-	7	-	7	-	-	-	-	-	-	-	-	-	-	1	-	-	-	6	-	3	8
5	2	2	-	-	4	-	-	4	-	-	-	6	-	-	1	-	-	1	-	-	27	-	-	6	17	-
13/7/89	3	-	-	-	1	5	-	6	2	-	-	-	-	-	1	11	-	-	18	-	6	-	-	8	13	-
	4	-	-	-	2	3	-	5	-	-	-	2	-	-	1	-	-	1	3	-	4	-	-	5	7	-
	5	-	2	-	6	10	-	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	13	-
6	2	-	-	-	4	2	-	6	-	-	-	4	3	-	-	-	-	2	-	-	32	12	-	9	7	-
20/7/89	3	-	1	-	9	2	-	11	1	-	-	1	-	-	-	3	-	1	10	-	-	-	-	14	16	-
	4	1	-	-	4	3	-	7	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	14	10	-
	5	-	-	-	14	6	-	20	1	-	-	1	2	-	-	-	-	1	-	-	76	13	-	7	4	-
7	2	2	-	-	2	1	-	3	-	-	-	4	2	-	1	-	-	1	1	-	45	36	-	15	11	-
27/7/89	3	-	13	-	4	21	-	25	1	-	-	-	-	-	-	-	-	-	7	-	1	-	-	39	44	-
	4	-	-	-	4	3	-	7	-	-	-	-	1	-	-	-	-	-	-	-	-	3	-	2	11	-
	5	1	1	-	13	24	-	37	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	6	-
Fumigated	2	-	-	-	2	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-
8	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3/8/89	4	-	2	-	-	5	-	5	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	4	12	-
	5	6	8	-	7	18	-	25	-	-	-	1	-	-	1	-	-	-	-	-	15	-	-	8	10	-
9	2	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	3	-	-	-	-	3	-	-
10/8/89	3	-	-	-	1	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	-	-
	4	2	-	-	-	1	-	1	-	-	-	2	-	-	-	-	-	-	-	-	17	-	-	-	-	-
	5	5	-	-	5	3	-	8	-	-	-	2	-	-	-	-	-	-	-	-	7	-	-	2	-	-

W = insects collected from wall surfaces
St = insects collected from stack surfaces
Sa = insects collected from grain samples
T = total for I. castaneus

differences in insect numbers among the insecticide treated stores. However, a minor but probably indicative trend is obtained through the total numbers of T. castaneum adults counted from the wall samples and stack surfaces following insecticide spraying. The lowest numbers are obtained in Store 2 treated with pirimiphos-methyl, followed by Store 4 treated with dichlorvos and lastly, Store 3 treated with malathion, thus reflecting this order of performance where the best control of this pest was obtained from pirimiphos-methyl. In particular, the initial infestation by both E. cautella and C. cephalonica disappeared almost entirely after these insecticidal sprays. For the rest of the insect species, no differences in numbers were apparent in all stores including that without insecticidal treatment.

These results tended to indicate that either all these chemicals were generally effective in suppressing the populations of these pests or that the initial population levels were too low for a profound impact to be made by insecticidal application to bring out the differences. This would imply that there was a base infestation level under the storage conditions in this experimental site which will persist despite insecticidal application. The only exception to this trend was L. entomophilus which remained high both before and after insecticidal application. Also, since the trial was carried out on commercial maize, infestation could not be allowed to escalate dangerously since the trial would then be intolerably expensive. Hence, the maize had to be fumigated and sprayed in the conventional way during the 8th week to avoid any further increase in pest numbers.

In a field trial of this kind, such a development where numbers of insects fail to increase, thereby resulting in the chemicals being tested not showing differences clearly, is not unusual. At the same time, replication often may not be meaningful since the greater the number of warehouses included

as replicates the greater the variation in environmental characteristics of each. Frequently also, the storage units in a particular storage site may be inadequate for optimum replication. The need to avoid economic damage on the stored maize and the need to permit development of sufficiently high numbers of insects for the differences in these insecticides to be apparent are opposing requirements limiting the productivity of such a field trial. This emphasizes the value of comparisons of the efficacy of these insecticides made at the other level of the experimentation in bioassay and field simulated systems. However, the ranking of these pesticides has not been invalidated in this large scale demonstration.

CHAPTER 7
GENERAL DISCUSSION AND CONCLUSIONS

7.1 General Discussion

Maize constitutes the chief staple food grain for the majority of the population in Kenya both in the rural and in the urban areas. On average, production is sufficient to meet the requirements in the country and to have some surplus for export. Therefore, the grain forms an additional source of needed foreign exchange earnings as well. For these reasons, it is imperative that factors which limit its continued availability be checked at all times. These factors include post-harvest and storage losses.

Estimates on storage losses on maize in Kenya have been scarce but these are recognised as being intolerably high. De Lima in 1978 estimated farm storage losses to be in the order of 6.0 percent per annum comprising 4.5 percent due to insect pests and 1.5 percent due to rodents. In conventional warehouse storage, De Lima (1979) estimated these losses to be 2.0 percent per annum. Earlier, Hall (1970) and Wheatley (1973) had both given overall annual losses of 23.0 percent as a fair estimate of stored grain losses in tropical and subtropical countries. This study concentrated on the central stored grain which is approximately 700,000 tons annually comprising 25 percent of the maize production. The grain constitutes strategic famine reserves and buffer stocks. This magnitude of losses is, therefore, considerable, necessitating studies such as this one to explore sound techniques for its reduction. In this study, the problem of insect infestation in maize was found to originate right in the field in nearly all places where maize is cultivated in this country. This observation agreed with earlier studies by Giles and Ashman (1971) and De Lima (1973). As a result when maize is eventually received into central storage, it always carries a certain level of

infestation no matter how briefly it had been stored in the farm. Surveys in central stores clearly demonstrated this as all grain was invariably infested even if it had been only recently received. Since there are no practically feasible methods of controlling infestation in the field, the maize crop is usually promptly harvested soon after maturity and placed in storage in order to minimise exposure and escalation of this infestation.

Maize grain at intake was found to contain infestation by S. zeamais, S. cerealella and C. dimidiatus. As demonstrated by De Lima (1973), S. zeamais is more prominent in the warmer regions of the country such as in Machakos, Sagana and Nakuru while S. cerealella is dominant in the cooler regions such as Nyahururu, Nanyuki and Eldama Ravine. C. dimidiatus is a pest of minor importance. S. cerealella ceases to be important once the crop is brought into central storage and is fumigated. The standard practice of dusting the grain at intake with bromophos, pirimiphos-methyl or malathion partially checked this initial infestation during the period between intake and stacking in the warehouses. Stack fumigation under gas-proof sheets using either phosphine or methyl bromide was subsequently used to control most of this infestation. Adequate control is not achieved through insecticidal dusting, firstly, because of the variability in the effectiveness of these pesticides where, for instance some degrade rapidly on exposure to undried grain and secondly, because rarely is homogeneity in application achieved on grain when dust admixing is carried out on the farm. The incentive to achieve such homogeneity in insectidal dusting is often lacking as the farmers motive in insecticidal treatment is mainly to gain acceptance of the maize for purchase and as such farmers do not experience the effects of insufficient treatment.

It was observed from these surveys too that maize storage in conventional warehouses commenced with relatively clean grain following fumigation. This situation was only temporary as the

maize soon became re-infested through re-entry into the grain of insect populations subsisting in various sections of the store fabric and through cross-infestation from the neighbouring warehouses or even the warehouse precincts outside. This infestation comprised E. cautella and T. castaneum as the most frequent and the most abundant pests but other moths such as Corcyra cephalonica and P. interpunctella were important in certain areas. The severity of these re-infestations was dependent not only upon temperature and relative humidity levels but also upon availability of ready sources of infestation. Its recurrence reduced the value of fumigations which are expensive and may not therefore be carried out very frequently.

It was found that other insect pests such as Oryzeaphilus surinamensis, Cryptolestes spp and Rhizopertha dominica occurred in small numbers during most of the storage period but particularly after the grain had been stored in excess of 6 months. These pests were also evident when the quality of grain had substantially declined due to E. cautella and T. castaneum infestations. Certain pests were also observed to be important in particular circumstances. For instance, C. cephalonica was observed to be in abundance in Nairobi, Thika and Konza depots and less important in other depots while R. dominica was found to occur on grain stored in excess of two years and which had suffered severe damage from other primary and secondary pests (Plate 4). In the present study, it was found that this trend in pest succession became frequently interrupted through normal storage operations whereby due to entry of new grain, even pests like S. zeamais which is normally controlled through the first fumigation became introduced. Large infestations by this pest, however, did not recur for the rest of the storage period. This infestation occurred despite sprays with malathion, lindane and pyrethrins (Graham 1970) and as found in this study, with dichlorvos and pirimiphos-methyl but to a lesser degree. Among these pests,

Plate 4. Characteristic damage on maize grain by major storage pests including *E. cautella*.

E. cautella, in particular appeared to escape control in most of the warehouses visited recurring soon after insecticidal sprays in alarming populations as observed in the present and previous studies (Graham, 1970 a, b and c; Ashman, 1964). Hence, it is necessary that the functional pesticide be capable of controlling not only the observed more important pests following fumigations but also the rest of the less abundant pests. Warehouse pest monitoring surveys where the pesticides were in use showed that the required control was not being obtained since these pests recurred within less than 4 weeks following sprays and that even one week after spraying, a residual infestation remained.

These failures in containing this infestation stimulated search for other techniques to supplement and complement the insecticidal sprays to evolve an integrated control approach. Such an approach as defined by Way (1977) involved the compatible use of a combination of appropriate methods of pest control including as Norgaard (1976) states, "biological control, cultural practices and chemicals". In such a system, pesticide sprays would be carried out only when necessary to avoid predictable economic damage where biological control or cultural practices failed to maintain insect populations below economic injury levels. In these surveys it was observed that sprays were required every 2-3 weeks, a frequency which is too high and which could be reduced with advantages.

The studies reported here and previous observations in Kenya by Graham (1970 a, b and c) identify B. tarsalis as a predator on E. cautella as a possible biological means of regulating the moth's population although no density dependence effect of the mite on the moth can be clearly demonstrated. Graham's trials which were based on insecticidal treatment on a stack of 300 bags of maize showed that following fumigations, moth numbers increased to a high level. These declined to a very low level within 8 months. In the present trials, the mite was

present on the moth throughout the storage period. Furthermore, Graham considered that the mite was sustained by T. castaneum whose eggs provided an alternative host to the mite when moth numbers declined. In the present study it was, in addition, found that the mite was frequent in all the depots visited and practically in all areas where the moth occurred. It was found too, that the mite was very voracious destroying more eggs than it actually consumed and that it was well distributed in all surfaces of the store fabric. Other pyralid moths namely; C. cephalonica and P. interpunctella which occurred in lesser numbers in most of these sites were also susceptible to the mite. Thus, good survival possibilities of the mite abounded during the periods when E. cautella populations were scarce. Furthermore, it was found that the adult male E. cautella was also subject to phoresy by the mite thus further increasing the searching ability of the mite.

In a continuous interaction between the moth and the mite the effect of the mite is first manifested in the moth's egg stage whereby the mite's feeding reduces the number of individual moths reaching adulthood. In the cage ecosystem studies here, mortality in the moth egg stage, k_1, was observed to be the key factor determining the fluctuations in the moth population in four out of the five systems studied. This mortality had a number of components apart from the mite's predation and the role of the mite was hypothesised to be one of the components in this mortality. In similar studies by White & Huffaker (1969a, b) on B. tarsalis and Anagasta kuhniella, another pyralid moth, the mite was found to contribute to the suppression of the moth population and the relationship appeared to be density dependent although no systematic population analysis was carried out.

Pest surveys carried out in maize storage warehouses in the present studies and in earlier work by Graham (1970a, b and c)

indicate a potentially prominent role by the mite in regulating E. cautella populations. In the present study it is also recognised that despite this, the mite cannot solely be relied upon to control the pest to a level that would be economically acceptable. This is so since although density dependence was observed in egg mortality and that this mortality was the key factor regulating the moth population, the role played by the mite was not definite. However, the observed non-specificity of the mite on E. cautella whereby the mite is also a predator on C. cephalonica, P. interpunctella and T. castaneum eggs is an asset on the one hand, but a liability on the other. It is, for instance, an advantage when the population of the moth has declined and the mite population can then only be sustained through these alternative hosts, and a disadvantage in that these alternative hosts constitute pests in their own right and are also likely to increase to levels beyond the economic threshold. In this respect, Simmonds (1967) notes that "When several different pests occur simultaneously, or almost so, on one crop, biological control is at a disadvantage, since it is necessary to introduce successfully, a variety of natural enemies to deal with these, and each species represents a separate problem". Moreover, the regulatory effect of B. tarsalis on these other pest populations although not studied in detail previously has not been recognised as being important for control. The role of the mite on E. cautella is therefore relevant only when storage insects including the alternative hosts occur at levels below economic injury.

Thus, under these circumstance and as shown in Fig. 22, control through B. tarsalis should have its best application only in situations where E. cautella is the main pest in the infestation complex and T. castaneum is present in low numbers to provide an alternative host once E. cautella numbers have been suppressed to an uneconomic level. Thereafter, since the mite is not known to be capable of keeping T. castaneum in

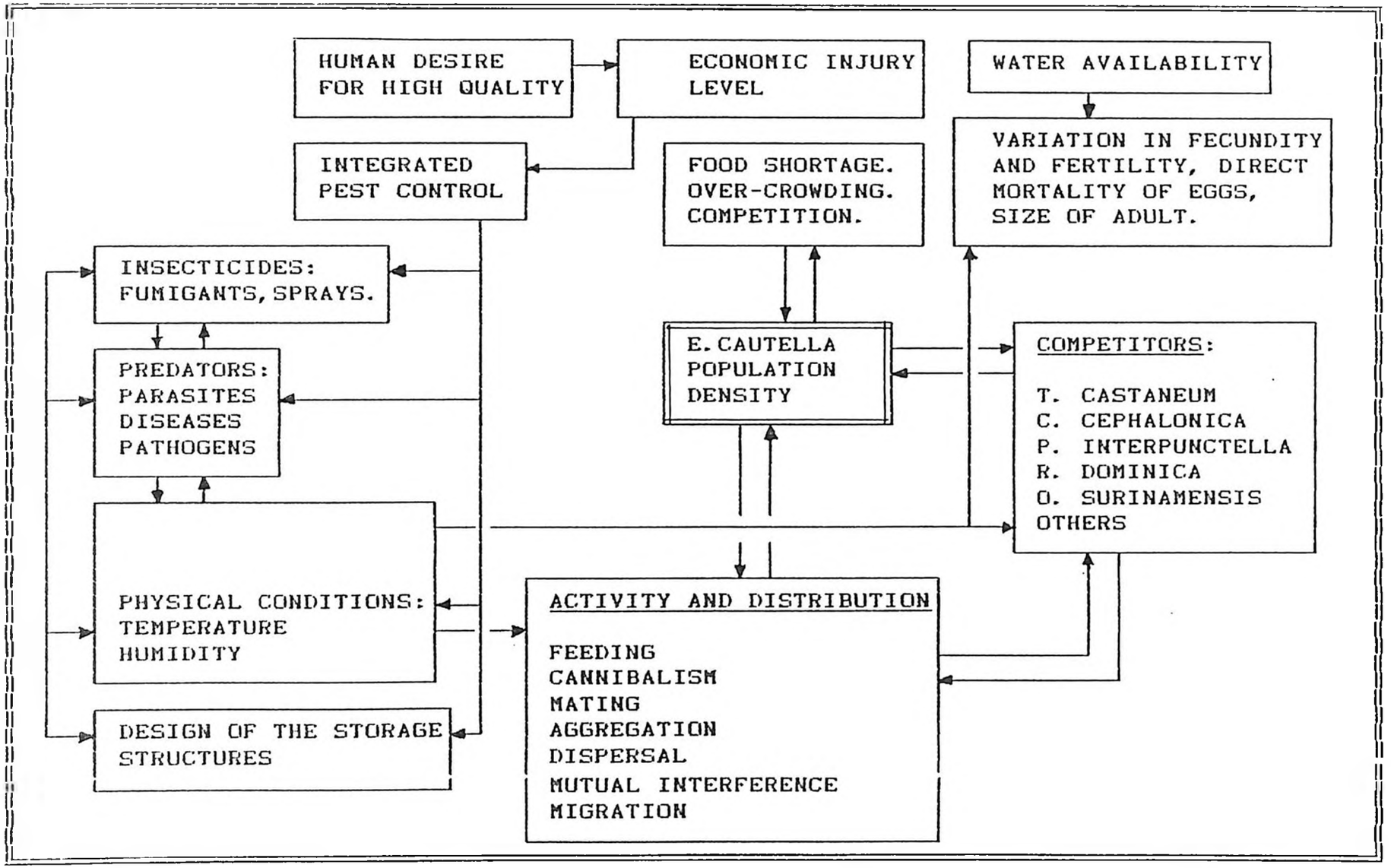

FIG. 22 Ecological interrelationships affecting an E. cautella population.

check, it will be necessary to identify an alternate method of checking its numbers should these increase beyond economic injury level. The same applies to the other associated infestations such as C. cephalonica and P. interpunctella.
In investigating the possible role of B. tarsalis in the control of E. cautella it was recognised that biological control often presents peculiar difficulties when attempts are made to apply it in stored products pest management either on its own or as a component of an integrated pest control approach. The main drawback is that the economic injury level in stored products management is often set too low (Hebblethwaite, 1985; De Lima 1978), such that, even the lowest numbers necessary to sustain a predator or parasite population may be considered to cause damage levels which cannot be tolerated. This is more so in central storage where sensitivity to weight and quality loss is even higher as compared to farm storage. This not only narrows down the scope of application of biological control in this area but also emphasises the need for alternative or complementary strategies to evolve an integrated control approach. The use of a suitable pesticide is considered to be an appropriate option for this role to enhance the control achieved through B. tarsalis on E. cautella and to further depress the minimum infestation of E. cautella that is observed to sustain this relationship.

Thus, identification of an efficacious pesticide was attempted to evolve an alternative method for curtailing progressive rise of E. cautella populations during the upper levels of its oscillations while under the mite predation. Such an insecticide would also further depress the minimum levels of E. cautella to sustain the mite without eliminating the moth completely so that this control is sustained (Aveling, 1981a). The intervals between successive applications of this insecticide would then be longer than otherwise in the absence of control by the mite since insecticidal sprays would only be

required when moth levels escalated to economic injury levels. For such an insecticide, possession of residual characteristics would require minimal emphasis.

In the pesticide screening trials, insecticides which controlled both E. cautella and T. castaneum were selected. These were further screened in cage ecosystems to simulate field conditions in the laboratory, where the performance with and without mite predation was evaluated. Dichlorvos, pirimiphos-methyl, permethrin and pyrethrins were further examined for their performance in laboratory systems simulating field conditions whereby superiority was demonstrated in dichlorvos and pirimiphos-methyl. Control of these and other pests in actual warehouses was found to be acceptable when the two chemicals were used on stacked maize. Both chemicals effectively maintained E. cautella and T. castaneum populations in check for 5 weeks before fumigation became necessary. This is therefore the minimum interval to be maintained between two successive spray operations. The two chemicals in these tests were therefore demonstrated to give individual control of E. cautella and T. castaneum and also to control the two pests in an actual field situation where other pests were also present. In this field situation, the mite was present as a predator on the moth with T. castaneum acting as an alternative host.

Thus, since these pesticides demonstrated superiority in a system where predation was also present, they can be considered as being most compatible with the mite's role as a predator since resurgence of the moth pest was prevented as demonstrated in the field trials. Thus, this is determined to be the most profound application of a biological control technique in the storage pest management of central storage warehouses like in the ones studied, without allowing the onset of economic damage. From these trials and earlier observations during pest survey, it is also noted that even

under these pest control regimes, maintenance of a pest-free situation for a prolonged period under warehouse storage is economically and practically impossible. A certain basic minimum level of infestation tends to persist as seen in Table 28 where apart from E. cautella, T. castaneum and B. tarsalis, six other pest species were observed throughout the study period although at sub-economic levels.

Apart from the recognised benefits of the pesticides and the predator there are various other factors necessary to enhance control of the moth as shown in Fig. 22 depending on the nature and level of intervention adopted to control the pest. The pest population levels are observed to be influenced by physical conditions, insecticides, food and water availability and biological control agents including competition. At the periphery of these interrelationships but of considerable importance is the design of storage structures which determines the level of control which can be achieved. Warehouses, when used for maize storage, for instance, do not exclude external infestations, being open structures. Therefore, re-infestation is always bound to occur. Their design and construction also does not eliminate crevices and nooks for insects to hide and escape from both fumigants and sprays. Further, it is seen that all these factors are themselves interrelated making it necessary to adopt a holistic approach in devising control strategies. It is recognised that the level of intervention depends upon the community's sensitivity to quality in grain and subsequently the economic injury level considered to be functional.

This study had dwelt on pest control possibilities of warehouse pests, specifically E. cautella under predation by B. tarsalis basing such control on the ecological relationships pertaining to these situations. Warehouses are inexpensive and versatile structures for storage of maize and other commodities but they have certain basic limitations in

their ability to preserve grain quality. The principal limitation is their openness which allows re-infestation of stored commodities following spraying or fumigation (Webley, 1985). Even when residual pesticide sprays are used these do not afford absolute protection since a compromise has to be made between toxicity and efficacy. The need to provide ventilation also prevents insects exclusion otherwise achievable through either covering of stacks with tarpaulins or fumigation sheets at the termination of fumigations. For the same reason actual vents on the store fabric have to be provided. Therefore, the recommendations made in this study take these limitations into consideration to propose a compromise between what is expedient from biological and ecological considerations in evolving an integrated pest control approach.

7.2 Principal observations and conclusions

1. It was shown that the major pests of stored grain throughout Kenya comprise S. zeamais, S. cerealella, E. cautella, T. castaneum, R. dominica, Oryzaephilus surinamensis, C. cephalonica and lately P. truncatus. All these pests are important on farm stored grain especially if the storage period exceeds 6 months. On the crop that is purchased and received into central storage, initial infestation is normally due to S. zeamais and S. cerealella which cause primary infestation especially if the crop is not stored for more than 2 months. In central storage, the primary infestation is arrested through initial fumigation but secondary pests continue to attack and re-attack the stored grain. In both farm storage and central storage the abundance and intensity of infestation are basically dependent upon local climatic conditions.

2. It was found that in central storage, even if an intensive pest control programme is in use, most of the key pests

particularly E. cautella and T. castaneum could not be eradicated from maize storage warehouses due to recurrence of infestations. A certain low level of infestation by these pests persisted despite repeated sprays and fumigations. This was observed in all storage warehouses throughout the country. In some cases this low level of infestation included some primary pests such as Sitophilus spp. and R. dominica.

3. Among the secondary pests which re-infest warehouses is C. cephalonica which is found in warehouses around Nairobi namely; Machakos, Konza, Thika, Sagana and Embu. The pest was introduced into Kenya through imported famine relief yellow maize in 1979. The pest has shown high tolerance of pesticides used to control other storage moths.

4. Predation by the mite B. tarsalis on E. cautella was found to occur in all warehouses where this pest is found. The mite has a high consumption rate of the moth's eggs in relation to its size and is also a wasteful feeder destroying more eggs of the host moth than it actually feeds on. It occurs on all surfaces of the store fabric and on the stack surfaces thus being present at all sites where the moth is likely to inhabit. It was found that in a continuous interaction between the moth and the mite, the key factor determining the changes in the moth population, to the greatest extent was the mortality in the egg stage. This key factor was complex, having many other contributory factors, but included feeding and destruction of eggs by this mite. The mortality was also found to be density dependent probably attributed to the role of the mite, among other factors. This predation however, was found to be insufficient not only on the moth E. cautella itself but also because its role on the pests which occurred in the same place was not defined and appeared unsatisfactory.

5. Enhancement of control by mite predation through use of insecticides was therefore considered. Insecticidal screening

trials on 11 insecticides was carried out whereby it was found out that dichlorvos, pirimiphos-methyl, permethrin and pyrethrins were the most effective chemicals on both E. cautella and T. castaneum even when the moth was under the mite predation. Further trials under simulated and actual field conditions showed that dichlorvos and pirimiphos-methyl were the most suitable chemicals for adoption into an integrated pest control programme for management of infestations in these warehouses. In these screening trials, malathion which has been in use in Kenya since the 1960s for the control of storage pests both in farm storage and in central storage situations was found to be ineffective against these pests. The insecticide particularly gave poor performance against E. cautella and T. castaneum which are important pests in central storage.

6. It was found that suitable biological techniques compatible with a sound integrated pest control programme needed to be effective not just on E. cautella but also on other major pests in the system. This was seen to be neither possible nor practical and hence the application of biological control in a strict sense of the term where B. tarsalis was principally used to suppress E. cautella populations was of limited use. It was therefore necessary to enhance this control with the use of suitable pesticides in this control in this case identified as dichlorvos, pirimiphos-methyl, permethrins and pyrethrins. This strategy combined with sound sanitation practices and suitably designed storage structure to impart favourable physical conditions would lead to an acceptable level of pest control.

7. It was also observed that under warehouse storage conditions it was, in practice, not possible to ensure a pest-free situation at all times due to recurrence of infestations from the surroundings. The long-term solution to

this was perceived to be a change from warehouse storage to other forms of storage where grain is physically excluded from cross-infestation such as in silos or hermetically sealed bins. Under the prevailing conditions, the short-term solution should be to sustain the continued reliance on pesticides to maintain insect levels below economic injury levels. This reliance on insecticides can only be minimized by improvement on other factors that are favourable to sound preservation of maize and other stored grains in conventional warehouses.

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