



UNIVERSITI PUTRA MALAYSIA

**ECOLOGICAL STUDIES ON *PTEROMA PENDULA* JOANNIS AND
METISA PLANA WALKER (LEPIDOPTERA: PSYCHIDAE)
TOWARDS IMPROVED INTEGRATED MANAGEMENT
OF INFESTATIONS IN OIL PALM**

HO CHENG TUCK

FP 2002 26

**ECOLOGICAL STUDIES ON *PTEROMA PENDULA* JOANNIS AND
METISA PLANA WALKER (LEPIDOPTERA: PSYCHIDAE)
TOWARDS IMPROVED INTEGRATED MANAGEMENT
OF INFESTATIONS IN OIL PALM**

By

HO CHENG TUCK

**Thesis Submitted to the School of Graduate Studies,
Universiti Putra Malaysia, in Fulfilment of the Requirement for the
Degree of Doctor of Philosophy**

September 2002



To

Keng See and Kin Leong

for the sacrifices, support, and strength

“Though one may be overpowered,
two can defend themselves. A cord
of three strands is not quickly broken.”

Ecclesiastes 4: 12



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

**ECOLOGICAL STUDIES ON *PTEROMA PENDULA* JOANNIS AND
METISA PLANA WALKER (LEPIDOPTERA: PSYCHIDAE)
TOWARDS IMPROVED INTEGRATED MANAGEMENT OF
INFESTATIONS IN OIL PALM**

By

HO CHENG TUCK

September 2002

Chairman: Professor Khoo Khay Chong, Ph.D.

Faculty: Agriculture

Pteroma pendula Joannis and *Metisa plana* Walker are important pests of the oil palm *Elaeis guineensis* Jacquin, which is the primary agricultural crop of Malaysia. Although there is a history of the integrated management of the bagworms, information gaps exist with regard to their incidence, biology, dispersion and population dynamics. Work of this thesis was aimed at overcoming these deficiencies and using the new information to improve integrated management of the pests.

Analysis of historical records of bagworm infestations over 63,955 ha of oil palms in 69 estates in Peninsular Malaysia showed *P. pendula* and *M. plana* to be the primary pests. Infestations were single species or mixed and ranged from nil to 7,811 ha per year. Cumulative infestation was 18,297 ha, 4,904 ha and 14,607 ha for single species *P. pendula*, *M. plana* and mixed species *P. pendula* and *M. plana* respectively. This showed *P. pendula* to be the



predominant species. This was attributed to greater intrinsic rate of population increase, r_m , and finite rate of population increase, λ , for the species as well as its ability to survive very wet weather. Lower energy requirement for completion of life cycle and likewise propensity to balloon (which otherwise predisposed wash-off by rain) were established as reasons for this.

Synchrony of *P. pendula* and *M. plana* populations within and across estates was verified. Rainfall was indicated to be the primary factor synchronizing bagworm populations, particularly over wide areas, through their deleterious effects on survivorship of the pests. Short adult life span and overlapping if not synchronous emergence of males and females, pheromone-based male attraction to apterous females, regular dispersion of populations and natural enemies were postulated as other factors.

The use of multiple colonies that facilitated destructive and non-destructive sampling together with standardizing food media provided accurate details of the life history of *P. pendula* and *M. plana*. *Pteroma pendula* was confirmed to possess four larval stages with no difference in the number of instars and pupal development time between the sexes. Life history of *M. plana* followed report by earlier workers of 5-6 larval instars for males and 6-7 for females. There was, however, no difference in pupal development time and size. Sex ratio for both species was nevertheless 1:1 and more representative r_m and λ values were obtained. The last two statistics were nevertheless superior for *P. pendula* and insects bred in the field (r_m *P. pendula* 0.06459 laboratory, 0.07327 field and λ

1.06672 laboratory, 1.07603 field cf. r_m *M. plana* 0.04783 laboratory, 0.06061 field and λ 1.04899 laboratory, 1.06248 field).

Although *P. pendula* is the predominant pest species, results of this thesis showed pest status of *M. plana* to be not diminished owing to its greater damage potential and reproductive success through more efficient dispersion.

Through polynomial regression, standardized residual and relative net precision analyses, frond 17 was established as the representative sampling unit for experimental work and 10-19 for life-table construction. Lack of interspecific association suggested these sampling units to be applicable for single and mixed infestations. The bagworms were regularly dispersed in oil palm with a general mean-variance relationship of $\log(s^2) = 1.780 + 0.821 \log(\bar{x})$.

Road dust was shown to be directly detrimental to survival of bagworms and their parasitoids. However, in tall palms, there was insufficient dust deposition in the higher fronds to inhibit bagworm survival but was sufficient for their parasitoids. This allowed bagworm proliferation on such fronds, indicating road dust to more likely encourage outbreaks in tall than short palms.

Pupa number, adult female weight and favourable demographic statistics of *P. pendula* and *M. plana* were most consistently positively correlated with leaf nitrogen levels. Negative correlation of the above parameters with leaf magnesium and calcium levels was also indicated. As oil palm cultivation

targets maintenance of optimum foliar nitrogen levels, the crop is nutritionally supportive of bagworm populations. Further investigations on verifying the role of high Mg and Ca foliar levels in suppressing bagworm reproductive potential is merited.

Life-table studies showed that except for the abiotic factor of rainfall at the first larval instar to be the key factor for *M. plana*, natural enemies were important factors causing major fluctuations in population size of *P. pendula* and *M. plana*. As the natural enemies regulate populations in concert, the manipulation of the environment towards one that would conserve if not increase numbers of natural enemies would be a more practical first line of action. Increasing diversity of vegetation within the oil palm environment with the aim of encouraging and prolonging natural enemy activity through provision of shelter and nectar could meet this need. A combination of field bioefficacy and cage efficiency experiments showed usefulness of candidate plants to be *Euphorbia heterophylla* L. \equiv *Cassia cobanensis* (Britton) Lundell > *Antigonon leptopus* Hook. & Arn. \equiv *Crotalaria zanzibarica* Benth. \equiv *Turnera subulata* J.E. Smith > *Asystasia gangetica* (L.). On consideration of bioefficacy with ease of establishment and subsequent maintenance, the best mix would be *C. cobanensis* > *A. leptopus* \equiv *T. subulata*.

A highly efficient binomial sequential sampling plan based on the regression model $\bar{x} = 46.819 [-\log(1-P_i)]^{0.727}$ was developed. With this plan, 97% correct decisions were made with only 13 presence-absence samples for approximately 10 ha of palms, 100% correct decisions being achieved with a maximum of

136. A reliable enumeration-free census system is thus for the first time available for use in making control decisions for *P. pendula* and *M. plana* in oil palm.

The use of life-tables provided hitherto unavailable insight into the effects of insecticides commonly used against *P. pendula* and *M. plana*. Cypermethrin, a synthetic pyrethroid widely used against the pests by commercial growers, was shown to have lower direct toxicity to larvae and marked deleterious effect on natural enemies when compared with acephate and *Bacillus thuringiensis aizawai*. The last was demonstrated to be both toxic to larvae but safe against natural enemies, suggesting the biocide to be a good alternative to the use of cypermethrin and acephate. Trunk injection with methamidophos provided the best control, mode of action being high selective toxicity to pests and safety to natural enemies. The combined effect could break life cycles, explaining the frequently observed long periods of control achieved with a single injection.

The foregoing findings allowed better understanding of the anatomy of outbreaks of the two pests and thus their anticipation and pre-emption. The development of an improved census technique, avoidance of road dust, proper timing and use of target-specific insecticides in conjunction with the establishment of more effective nectariferous plants facilitate this. In addition, hitherto unavailable details of life history, demographic statistics, sampling units and experimental methodologies for the bagworms would be useful tools for future research.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**KAJIAN EKOLOGI KE ATAS *PTEROMA PENDULA* JOANNIS
DAN *METISA PLANA* WALKER (LEPIDOPTERA: PSYCHIDAE)
UNTUK PENINGKATAN PENGURUSAN PEROSAK
DI KAWASAN KELAPA SAWIT**

Oleh

HO CHENG TUCK

September 2002

Pengerusi: Profesor Khoo Khay Chong, Ph.D.

Fakulti: Pertanian

Pteroma pendula Joannis dan *Metisa plana* Walker adalah perosak-perosak penting kelapa sawit *Elaeis guineensis* Jacquin yang merupakan tanaman pertanian utama di Malaysia. Walaupun sejarah pengurusan bersepadu ulat bungkus sedia wujud, masih terdapat kekurangan maklumat tentang infestasi, biologi, penyebaran dan dinamik populasi ulat-ulat tersebut. Penyelidikan dalam tesis ini bertujuan untuk mengatasi kelemahan-kelemahan ini dan menggunakan maklumat baru yang dihasilkan untuk meningkatkan prestasi pengurusan perosak-perosak tersebut.

Analisis rekod-rekod sejarah infestasi ulat bungkus yang meliputi 63,955 ha kawasan kelapa sawit dalam 69 ladang menunjukkan bahawa *P. pendula* dan *M. plana* adalah perosak-perosak utama. Infestasi tersebut terdiri daripada spesies tunggal atau campuran dan meliputi luas kawasan antara sifar hingga 7,811 ha setahun. Infestasi kumulatif didapati sebanyak 18,297 ha, 4,904 ha dan 14,607 ha

masing-masing untuk spesies tunggal *P. pendula*, spesies tunggal *M. plana* dan spesies campuran *P. pendula* dan *M. plana*. Oleh itu, *P. pendula* ialah spesies yang dominan. Kejadian ini adalah berpunca daripada keupayaan peningkatan populasi inat, r_m , dan populasi finat, λ , yang lebih tinggi dan kebolehan spesies tersebut untuk mandiri dalam keadaan cuaca yang amat lembab. Keperluan tenaga yang rendah untuk melengkapkan kitaran hidup dan kecenderungan rendah untuk terapung dari benang sutera atau “ballooning” (dengan itu mengelakkan curahan oleh hujan) telah ditentukan sebagai faktor-faktor penyebab.

Singkroni populasi *P. pendula* dan *M. plana* telah ditentukan di dalam dan di kalangan ladang. Taburan hujan yang menjejaskan kemandirian perosak-perosak tersebut didapati sebagai faktor utama yang mempengaruhi singkroni populasi, terutamanya dalam kawasan yang luas.

Pteroma pendula didapati mempunyai empat peringkat larva tanpa perbezaan bilangan instar dan masa perkembangan kepompong di antara jantina. Sejarah hidup *M. plana* mengikuti laporan oleh penyelidik-penyelidik dahulu di mana bilangan instar ialah 5-6 untuk jantan dan 6-7 untuk betina. Namun, tiada perbezaan diperhatikan dari segi masa perkembangan dan saiz kepompong. Walau bagaimanapun, nisbah jantina kedua-dua spesies ialah 1:1 dan nilai-nilai r_m dan λ yang lebih mencerminkan keadaan semulajadi telah diperolehi. Namun, statistik r_m dan λ adalah lebih tinggi untuk *P. pendula* dan ulat-ulat yang dibiak di lapangan .

Walaupun *P. pendula* merupakan spesies perosak predominan, status *M. plana* sebagai perosak tidak susut disebabkan potensi kerosakannya yang lebih tinggi dan kejayaan pembiakannya melalui penyebaran yang lebih berkesan.

Pemilihan daun pelepah ke- 17 sebagai unit pensampelan untuk kerja penyelidikan dan ke- 10-19 untuk pembinaan jadual hayat telah ditentukan melalui regresi polinomial, piawai residual dan analisis ketepatan relatif bersih. Ulat bungkus didapati disebarkan serata di kawasan kelapa sawit mengikut perhubungan am purata-varian $\log (s^2) = 1.780 + 0.821 \log (\bar{x})$.

Habuk jalan secara langsung telah mengakibatkan kesan buruk terhadap kemandirian ulat bungkus dan parasitoidnya. Namun demikian, tidak banyak habuk jalan yang terlekat pada pelepah-pelepah bahagian atas pokok-pokok yang tinggi. Akibatnya, cuma kemandirian parasitoid sahaja terencat manakala ulat bungkus terus merebak di atas pelepah-pelepah tinggi. Dengan demikian, habuk jalan lebih berkemungkinan menggalakkan wabak ulat bungkus pada pokok-pokok yang tinggi berbanding yang rendah.

Bilangan kepompong, berat betina dewasa dan statistik demografi yang baik menunjukkan korelasi positif yang konsisten dengan aras kandungan nitrogen daun. Parameter-parameter tersebut menunjukkan korelasi negatif pula dengan aras kandungan magnesium dan kalsium daun.

Kajian jadual hayat menunjukkan bahawa musuh-musuh semulajadi merupakan faktor utama yang menyebabkan perubahan besar dalam saiz populasi *P. pendula* dan *M. plana*, melainkan faktor abiotik hujan yang menjadi faktor utama untuk *M. plana* pada peringkat instar larva pertama. Oleh sebab musuh-musuh semulajadi mengawal populasi secara bersepadu, manipulasi persekitaran kawasan kelapa sawit untuk memelihara atau meningkatkan bilangan musuh-musuh semulajadi adalah langkah tindakan pertama yang praktikal. Matlamat ini boleh dicapai dengan meningkatkan kepelbagaian tumbuhan di dalam persekitaran kawasan kelapa sawit. Ini bertujuan untuk memberi perlindungan dan nektar kepada musuh semulajadi yang seterusnya akan menggalak dan melanjutkan aktiviti hidup musuh semulajadi tersebut. Kombinasi eksperimen bioefikasi di lapangan dan kecekapan sangkar menunjukkan beberapa spesies tumbuhan yang berguna, iaitu, *Euphorbia heterophylla* L. \equiv *Cassia cobanensis* (Britton) Lundell > *Antigonon leptopus* Hook. & Arn. \equiv *Crotalaria zanzibarica* Benth. \equiv *Turnera subulata* J.E. Smith > *Asystasia gangetica* (L.).

Satu pelan pensampelan binomial berjujukan yang amat cekap berdasarkan model regresi $\bar{x} = 46.819 [-\log(1-P_i)]^{0.727}$ telah dicipta. Dengan mengguna pelan ini, 97% keputusan betul telah diperolehi dengan hanya 13 sampel hadir-tidak hadir dalam kira-kira 10 ha kawasan kelapa sawit, di mana 100% keputusan betul diperolehi dengan maksimum 136 sampel.

Penggunaan teknik jadual hayat telah dapat memberi penjelasan yang selama ini tidak diketahui berkenaan kesan racun-racun serangga yang kerap diguna untuk mengawal *P. pendula* dan *M. plana*. Sipermetrin, satu piretroid sintetik yang



banyak diguna oleh penanam komersial, telah didapati menghasilkan kesan toksik langsung yang lebih rendah terhadap larva dan kesan buruk yang nyata terhadap musuh-musuh semulajadi berbanding asefat dan *Bacillus thuringiensis aizawai*. *Bacillus thuringiensis aizawai* menunjukkan kesan toksik terhadap larva tetapi selamat untuk musuh-musuh semulajadi dan ini membayangkan biosid tersebut adalah alternatif yang baik untuk sipermetrin dan asefat. Suntikan metamidofos ke dalam batang kelapa sawit merupakan kaedah pengawalan yang paling baik di mana cara tindakannya tertumpu pada perosak tetapi mengelak dari musuh semulajadi. Gabungan kesan demikian boleh menghapuskan kitaran hidup ulat bungkus, menerangkan kejayaan pengawalan perosak dalam tempoh yang panjang dari satu suntikan.

Keputusan penyelidikan di atas menambah pemahaman mengenai anatomi dan juga jangkitan dan pengelakan perebakan *P. pendula* dan *M. plana*. Kawalan perebakan tersebut telah diselenggarakan melalui ciptaan satu kaedah bancian yang lebih efisien, pengelakan habuk jalan, penggunaan racun-racun serangga yang spesifik pada masa yang sesuai dan penubuhan tumbuh-tumbuhan bernektar yang lebih efektif. Tambahan lagi, pengetahuan baru yang diperolehi mengenai kitaran hidup, statistik demografi, unit-unit pensampelan dan metodologi eksperimen merupakan sumbangan bernilai untuk penyelidikan ulat bungkus di masa hadapan.

ACKNOWLEDGEMENTS

“The better work men do is always done
under stress and at great personal cost.”

William Carlos Williams

The undertaking of a part-time Ph.D. programme of the present width and depth was all of the above. I am nevertheless grateful for the many kindnesses and help that were extended to me during the course of this work, without which the completion of this thesis would have been impossible.

I am firstly grateful to my employers, Golden Hope Plantations Berhad, for permission to pursue this programme. The support of Dr. Mohamad Hashim Ahmad Tajudin, the Director of Research and Development, and Dr. Lee Chong Hee, Research Controller, Plant Science and Technology, were vital towards this. I also wish to thank members of my Supervisory Committee, Professor Dr. Khoo Khay Chong, Associate Professor Dr. Yusof Ibrahim and Associate Professor Dr. Dzolkhifli Omar for their guidance and support during the course of the work. I am particularly thankful to Professor Khoo for his commitment to see this student through his candidacy and for his constant encouragement.

The helpful discussions on the identification of bagworms with Dr. Norman Kamarudin and Dr. Gaden Robinson is acknowledged. Dr. Robinson's enthusiastic assistance in confirming identity of *Pteroma pendula* and *Metisa*



plana specimens collected in the course of research for this thesis deserves special mention. I also thank Professor Charles Krebs for his insights into the complexities of interpreting insect dispersion data.

The unavailability of many salient references in Malaysia was a problem faced in the course of the research. I am grateful to Dr. Marc Rhinds, Dr. Chia Tio Huat, Dr. Lim Jung Lee, Dr. Ang Ban Na, Mr. Chung Gait Fee and Mr. Shaji Thomas for helping me to overcome this through their creative methods of procurement. I am also thankful to Mr. Teh Chong Lay for the many useful discussions and moral support. Thanks are also due to Ms. Tan Sek Yee for her assistance at UPM.

Finally, I am deeply indebted to Puan Adina Rusdi, Encik Abdul Latif Ramlan, Encik Hasan Saleh, Encik Jalaludin Abdul Aziz, Encik Faizul Ariffin Mohd Saini, Encik Abdul Kaflee Ahmad, Encik Mohammad Rais Ramlan and Encik Sairul Misnun, members of the Plant Protection team at OPRS, without whose efficient assistance the voluminous and tedious recording and collation of data for this thesis would never have been possible. Thank you so much to all of you.



This thesis submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee are as follows:

KHOO KHAY CHONG, Ph.D.

Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Chairman)

YUSOF IBRAHIM, Ph.D.

Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

DZOLKHIFLI OMAR, Ph.D.

Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

AINI IDERIS, Ph.D.

Professor/Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:



TABLE OF CONTENTS

	Page
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	viii
ACKNOWLEDGEMENTS	xiii
APPROVAL	xv
DECLARATION	xvii
LIST OF TABLES	xxi
LIST OF FIGURES	xxix
LIST OF APPENDICES	xl
LIST OF ABBREVIATIONS AND NOTATIONS	xlv
 CHAPTER	
1 INTRODUCTION	1
1.1 Integrated Pest Management: A Dynamic Discipline	1
1.2 Oil Palm in Malaysia and Bagworm Pests	3
1.3 Advances in Bagworm Management and Research	5
1.4 Information Gaps	9
1.5 Research Objectives	11
 2 LITERATURE REVIEW	 14
2.1 The Psychidae	14
2.2 Biology	15
2.2.1 Eggs	15
2.2.2 Larvae	16
2.2.3 Pupae	18
2.2.4 Adults	19
2.2.5 Details of Life History	20
2.2.6 Methods for Study of Life History	27
2.3 Dispersion and Sampling	32
2.3.1 Dispersion Statistics and their Application	32
2.3.2 Dispersion of Bagworms	36
2.3.3 Sampling in Oil Palm	40
2.3.4 Bagworm Monitoring and Surveillance Systems	42
2.3.5 Economic Threshold	42
2.4 Population Dynamics	43
2.4.1 Factors Influencing Population Dynamics of Bagworms. Dispersal	45
2.4.2 Temperature and Insolation	46
2.4.3 Rain and Drought	48
2.4.4 Road Dust	50
2.4.5 Host-plant Quality	51
2.4.6 Natural Enemies	53



	Page
2.4.7 Insecticides	64
2.4.8 Vegetational Diversity	65
3 INCIDENCE OF <i>P. PENDULA</i> AND <i>M. PLANA</i>	72
3.1 Introduction	72
3.2 Materials and Methods	74
3.3 Results	78
3.4 Discussion	90
4 COMPARATIVE BIOLOGY OF <i>P. PENDULA</i> AND <i>M. PLANA</i>	103
4.1 Introduction	103
4.2 Materials and Methods	105
4.2.1 Life History Studies	105
4.2.2 Damage Potential	118
4.3 Results	120
4.3.1 Life History Studies – <i>P. pendula</i>	120
4.3.2 Life History Studies – <i>M. plana</i>	157
4.3.3 Damage Potential	192
4.4 Discussion	196
5 DISPERSION OF <i>P. PENDULA</i> AND <i>M. PLANA</i> IN OIL PALM	213
5.1 Introduction	213
5.2 Materials and Methods	215
5.2.1 Within-palm Distribution	215
5.2.2 Interspecific Association	220
5.2.3 Between-palm Distribution	222
5.3 Results	229
5.3.1 Within-palm Distribution	229
5.3.2 Interspecific Association	236
5.3.3 Between-palm Distribution	236
5.4 Discussion	240
6 BEHAVIOURAL AND ABIOTIC FACTORS INFLUENCING POPULATION DYNAMICS	250
6.1 Introduction	250
6.2 Mode of Spread of <i>P. pendula</i> and <i>M. plana</i>	252
6.2.1 Materials and Methods	252
6.2.2 Results	259
6.2.3 Discussion	280
6.3 Effect of Temperature on Population Dynamics	284
6.3.1 Materials and Methods	284
6.3.2 Results	287
6.3.3 Discussion	295
6.4 Effect of Insolation	298
6.4.1 Materials and Methods	298



	Page
6.4.2 Results	301
6.4.3 Discussion	310
6.5 Effect of Rain and Drought	312
6.5.1 Materials and Methods	312
6.5.2 Results	313
6.5.3 Discussion	325
6.6 Effect of Road Dust	331
6.6.1 Materials and Methods	331
6.6.2 Results	337
6.6.3 Discussion	358
6.7 Effect of Leaf Nutrient Levels	363
6.7.1 Materials and Methods	363
6.7.2 Results	367
6.7.3 Discussion	377
7 AGE-SPECIFIC LIFE-TABLES AND KEY FACTOR ANALYSIS	385
7.1 Introduction	385
7.2 Materials and Methods	386
7.3 Results	393
7.3.1 <i>Pteroma pendula</i>	393
7.3.2 <i>Metisa plana</i>	396
7.4 Discussion	401
8 ASPECTS OF THE MANAGEMENT OF <i>P. PENDULA</i> AND <i>M. PLANA</i> INFESTATIONS	413
8.1 Introduction	413
8.2 Sequential and Binomial Sampling	416
8.2.1 Materials and Methods	416
8.2.2 Results	422
8.2.3 Discussion	431
8.3 Use of Nectariferous Plants	434
8.3.1 Materials and Methods	434
8.3.2 Results	444
8.3.3 Discussion	452
8.4 Types and Timing of Insecticide Application	461
8.4.1 Materials and Methods	461
8.4.2 Results	464
8.4.3 Discussion	488
9 GENERAL DISCUSSION AND CONCLUSION	500
REFERENCES	524
APPENDICES	561
VITA	878

LIST OF TABLES

Table		Page
2.1	Life history information on psychids of economic importance	21
2.2	Methods used in the study of bagworm life histories and their comparative merits	28
2.3	Economic thresholds for bagworms in oil palm	44
2.4	Natural enemies of major bagworm pests of oil palm in Malaysia	55
2.5	Reports of plants attractive to beneficial insects of oil palm	68
3.1	Extent of above-threshold bagworm infestation with years for 69 estates	81
3.2	Species composition and age of palms of above-threshold bagworm infestations with years for 69 estates	82
3.3	Percent synchrony of life stage for total number of records (n) of bagworm infestations	91
3.4	Percent synchrony of life stage for total number of records (n) of <i>P. pendula</i> infestations within and/or across estates	95
3.5	Percent synchrony of life stage for total number of records (n) of <i>M. plana</i> infestations within and/or across estates	96
3.6	Percent synchrony of life stage for total number of records (n) of mixed <i>P. pendula</i> and <i>M. plana</i> infestations within and/or across estates	97
4.1	Breeding colonies for studies on biological characteristics of <i>P. pendula</i> and <i>M. plana</i>	106
4.2	Egg size, oviposition and incubation periods, numbers, fecundity and fertility of <i>P. pendula</i> in the laboratory and field	122
4.3	Head capsule width (mm) of various instars of <i>P. pendula</i> in the laboratory and field	129



Table	Page
4.4 Head capsule width (mm) of laboratory bred female and male <i>P. pendula</i>	130
4.5 Duration (days) of various larval instars of <i>P. pendula</i> in the laboratory and field	131
4.6 Duration (days) of laboratory bred larval female and male <i>P. pendula</i>	132
4.7 Larval bag length and weight by destructive sampling of various instars of <i>P. pendula</i> in the laboratory and field	134
4.8 Larval bag length (mm) by non-destructive sampling of various instars of male and female <i>P. pendula</i> in the laboratory	135
4.9 Larval length and weight by destructive sampling of various instars of <i>P. pendula</i> in the laboratory and field	136
4.10 Duration (days) of female pupal and adult stages and processes of <i>P. pendula</i> in the laboratory and field	141
4.11 Duration (days) of male pupal and adult stages of <i>P. pendula</i> in the laboratory and field	142
4.12 Pupal and adult bag length and weight of <i>P. pendula</i> in the laboratory and field	143
4.13 Pupal and adult length and weight of <i>P. pendula</i> in the laboratory and field	144
4.14 Wing span (mm) of adult <i>P. pendula</i> bred in the laboratory and field	146
4.15 Sex ratio of <i>P. pendula</i> colonies bred in the laboratory and field	150
4.16 Mean egg-to-adult and egg-to-egg generation time (days) of <i>P. pendula</i> in the laboratory and field	151
4.17 Demographic statistics of <i>P. pendula</i> bred in the laboratory and field	156
4.18 Egg size, oviposition and incubation periods, numbers, fecundity and fertility of <i>M. plana</i> in the laboratory and field	159



Table	Page
4.19 Head capsule width (mm) of various instars of <i>M. plana</i> in the laboratory and field	166
4.20 Head capsule width (mm) of various laboratory bred female and male <i>M. plana</i> originating from different maximum larval instar stages	167
4.21 Duration (days) of various larval instars of <i>M. plana</i> in the laboratory and field	169
4.22 Duration (days) of various instars of laboratory bred female and male <i>M. plana</i> originating from different maximum larval instar stages	170
4.23 Larval bag length and weight by destructive sampling of various instars of <i>M. plana</i> in the laboratory and field	171
4.24 Larval bag length (mm) by non-destructive sampling of various instars of male and female <i>M. plana</i> in the laboratory	172
4.25 Larval length and weight by destructive sampling of various instars of <i>M. plana</i> in the laboratory and field	174
4.26 Duration (days) of female pupal and adult stages and processes of <i>M. plana</i> in the laboratory and field	177
4.27 Duration (days) of male pupal and adult stages of <i>M. plana</i> in the laboratory and field	178
4.28 Pupal and adult bag length and weight of <i>M. plana</i> in the laboratory and field	179
4.29 Pupal and adult length and weight of <i>M. plana</i> in the laboratory and field	180
4.30 Wing span (mm) of adult <i>M. plana</i> bred in the laboratory and field	182
4.31 Sex ratio of <i>M. plana</i> colonies bred in the laboratory and field	186
4.32 Mean egg-to-adult and egg-to-egg generation time (days) of <i>M. plana</i> in the laboratory and field	187



Table	Page
4.33 Demographic statistics of <i>M. plana</i> bred in the laboratory and field	193
4.34 Mean leaf area (mm ²) damaged by single <i>P. pendula</i> larva at various instars	194
4.35 Mean leaf biomass (mg dry weight) removed by single <i>P. pendula</i> larva at various instars	194
4.36 Mean leaf area (mm ²) damaged by single <i>M. plana</i> larva at various instars	195
4.37 Mean leaf biomass (mg dry weight) removed by single <i>M. plana</i> larva at various instars	195
5.1 Parameters of measurement for within-palm spatial distribution of single and mixed populations of <i>P. pendula</i> and <i>M. plana</i>	216
5.2 Parameters of measurement for between-palm spatial distribution of single and mixed populations of <i>P. pendula</i> and <i>M. plana</i>	223
5.3 Descriptive statistics of frond numbers at $\geq 95\%$ of peak bagworm density	231
5.4 Distribution of lowest mean deviation of standardized residual from zero for within-palm distribution of <i>P. pendula</i> and <i>M. plana</i>	234
5.5 Distribution of relative variation (RV) within 25% and 10% precision and relative net precision (RNP) values with sample unit size for 150 palm categories	235
5.6 Mean number of bagworm stage per palm with visual damage category and palm height	237
5.7 Interspecific association test statistics and indices between <i>P. pendula</i> and <i>M. plana</i> in short and tall oil palms	238
5.8 Linear regression for Taylor's Power Law and Iwao's patchiness regression for 40 oil palm sampling blocks of various bagworm species, life stages, infestation types and height	241