RELATIONSHIP BETWEEN *Metisa plana* AND ITS PARASITOIDS (BRACONIDAE AND ICHNEUMONIDAE) AT DIFFERENT TIME-LAGS IN OIL PALM PLANTATION

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ABSTRACT

Bagworm or *Metisa plana*, is the most important defoliator insect in the oil palm cultivation, while parasitoids such as Braconidae and Ichneumonidae are the common main natural enemies for bagworm. Although the relationship between natural enemies with its insect pest has been broadly investigated, little is dedicated for assessing the delayed effects of the bagworm population on parasitoids. In this study, the abundance relationship between bagworm and its common parasitoids (Braconidae and Ichneumonidae) was assessed at different time-lags under field condition. Bagworm censuses for instar stages first (L1) to seven (L7) were conducted biweekly in an oil palm plantation belongs to TH Plantation Berhad in Muadzam Shah, Pahang from July 2016 to July 2017, along with bagworm's parasitoid from Braconidae and Ichneumonidae family. The results revealed that Braconidae presence was associated positively with bagworm at week 6 to 12, whereby the associations were stronger for late instar stages. On the other hand, Ichneumonidae presence was positively related to middle instar stages at early time-lag i.e. week 2 to 6. In other words, Ichneumonidae population is expected to increase after 2 to 6 weeks given increasing population of bagworm, while Braconidae population is likely to rise after 6 to 12 weeks of the increasing population of bagworm.

Keywords: Bagworm, natural enemies, time-lags

ABSTRAK

Ulat bungkus atau *Metisa plana,* merupakan salah satu pemakan daun dalam pengeluaran tanaman kelapa sawit, manakala parasitoid seperti Braconidae dan Ichneumonidae adalah musuh semula jadi yang menyerang ulat bungkus. Walaupun perkaitan di antara pemusuh semula jadi dengan serangga perosak telah dikaji secara meluas, kajian terhadap kesan sela masa oleh parasitoid terhadap ulat bungkus masih terhad. Kajian ini dijalankan untuk menentukan hubungan kelimpahan di antara ulat bungkus dan parasitoidnya (Braconidae dan Ichneumonidae) pada sela masa yang berbeza di lapangan. Bancian terhadap ulat bungkus untuk instar pertama (L1) sehingga ke tujuh (L7) dan musuh semulajadi ulat bungkus, Braconidae dan Ichneumonidae, dijalankan setiap dua minggu di ladang kelapa sawit milik TH Plantation Berhad di Muadzam Shah, Pahang bermula Julai 2016 hingga Julai 2017. Hasil kajian menunjukkan bahawa kehadiran Braconidae berkait secara positif dengan ulat bungkus pada sela masa 6 sehingga 12 minggu, di mana kaitan tersebut semakin kuat untuk instar yang lebih matang. Walaubagaimanapun, Ichneumonidae juga berasosiasi secara positif dengan ulat bungkus tetapi dengan instar tahap pertengahan pada sela masa yang awal iaitu minggu 2 sehingga 6. Dalam kata lain, populasi Ichneumonidae dijangka akan meningkat 2 hingga 6 minggu selepas populasi ulat bungkus meningkat, manakala populasi Braconidae akan mengambil masa 6 hingga 12 minggu selepas populasi ulat bungkus meningkat.

Kata kunci: Ulat bungkus, musuh semulajadi, sela masa

INTRODUCTION

The oil palm is the most outstanding oil-producing crop that gives yield of 4-5 tons of crude palm oil (CPO) per ha per year (Basiron 2008; Ludin et al. 2014) and about 10 times of the yield of soybean in a single harvest cycle (Plantation 2014). It is so effective that it needs only 0.26 ha land to produce 1 ton of oil whereas soybean, sunflower, and rapeseed need 2.22, 2.00, and 1.52 ha, respectively. This evidence shows the importance of oil palm as oil-producing crop not only in Malaysia but in the world. In Malaysia, oil palm is considered the most important commodity as it contributes to Malaysia's Gross Domestic Product (GDP) foreign exchange earnings and creation of employment opportunities. Nevertheless, the presence of pest such as bagworm can potentially threaten the yield production of palm oil.

Bagworm is the most important insect defoliator of Malaysian oil palm due to its ability to cause outbreaks through successful dispersion owing to their nature of ballooning (Basri & Kevan 1995). *Metisa plana* (Walker) and *Pteroma pendula* (Joannis) are reported to be formidable species of bagworms in Malaysia, with the former as the most aggressive bagworm in Peninsular (Basri et al. 1988; Pierre & Idris 2013). The economic loss caused by defoliating activity of this species is immeasurable. Of all stages of bagworm, only larval stages are the damaging stage. They consume oil palm leaves by scrapping and cutting in order to survive, growth, and remake of their bag as they increase in size.

Parasitoids and predators are generally acceptable in tropics in maintaining a balanced pest population (Libra et al. 2019; Sampaio et al. 2009). Basri et al. (1995) proposed that the incidence of bagworm outbreaks in oil palm plantation clearly indicates disruptions in the natural pest control population. There are vast species of parasitoids and predators normally found in oil palm plantation. These includes *Dolichogenidea metesae*, *Goryphus bunoh*, *Aulosaphes psychidivorus*, *Brachymeria* sp., *Pediobius* sp., *Eupelmus catoxanthae*, *Eurytoma* sp., *Temelucha* sp., *Callimerus arcufer*, and *Cosmelestes picticeps*, *Eupelmus cotoxanthae*, *Busymania oxymora, Apanteles aluella, Apanteles sp. 1, Spinaria spinator, and Brachymeria carinata* (Basri & Kevan 1995; Cheong et al. 2010; Halim et al. 2018a, b; Halim et al. 2019; Mahadi et al. 2012; Sankaran et al. 1972; Zulkifli et al. 2010). Interactions of natural enemies with bagworm had been studied widely. Basri & Kevan (1995) found a significant correlation between some of parasitoid and predator which consists of *Dolichogenidea metesae*, *Pediobius anomalus, Pediobius imbrues*, *Eupelmus catoxanthae*, and *Callimerus arcufer* with bagworm population by using monthly data.

The parasitoids are the main natural enemies for bagworm as they have the largest correlation compared to the predator. The combination of several enemies such as parasitoid, predator, and some fungus has been found to affect the mortality of bagworm (Cheong et al. 2010; Exelis 2013). This is furthermore being supported by the lower number of bagworms as the number of parasitoid and predator increases (Kamarudin & Wahid 2010; Mahadi et al. 2012). Likewise, parasitoids are the most important natural enemies in controlling the population of bagworm (Basri et al. 1995; Potineni & Saravanan 2013). As found by Basri et al. (1995) and Mahadi et al. (2012), the parasitoid from the family of Braconidae and Ichneumonidae are likely to be found in the study of bagworm although some species of Ichneumonidae are rare. In addition, parasitoid from family Braconidae is the second highest to find after Eulophidae. Nevertheless, *D. metesae* is the most significant parasitoid of bagworm (Cheong et al. 2010; Halim et al. 2018b).

There is a relatively few attentions have been paid on with time series or time-lag analysis in pest population studies. The real-time analysis concerns with direct or immediate effects of independent variables towards dependent variables; nevertheless, it is a common knowledge that external factors such as weather parameters do not impact living organism immediately. By using time-lag analysis, the lag or delay effect can be investigated. While the relationship between natural enemies with its insect pest has been broadly investigated, many of these studies had conducted in a real-time aspect. A research by Aukema et al. (2005) revealed that the population of pine engraver (*Ips pini)* were suppressed by its predators in a two-month time lag. This supports the notion that the reduction of pests by its natural enemies is not immediate. Given the limited study conducted on the delayed effects of parasitoid on bagworm population, this study was conducted to determine the relationship between *Metisa plana* and its common parasitoids (Braconidae and Ichneumonidae), at different time-lags under field condition.

MATERIAL AND METHODS

Study Site

This study was conducted in an oil palm plantation belongs to TH Plantation Berhad in Ladang Sungai Mengah, Muadzam Shah, Pahang, Malaysia from July 2016 to July 2017. The oil palm ages in this estate ranged from 10 to 20 years old. Two fields were chosen (Figure 1) in this study, namely Block 16 (B16) (2˚59’53.63’’N, 102˚54’24.31’’E) and Block 21 (B21) (3˚0’46.64’’N, 102˚52’58.84’’E). The latter recorded the most severe infestations of bagworms, whereas the former had the lowest records of infestation. The palm ages in both blocks during the census were identified in the prime mature group; being 14 years old for Block 16, while the oil palms for Block 21 were 11 years old. Although both blocks are in the same age group, have similar topography characteristics and practice similar agronomic managements concerning fertilization and weeding, differences were observed in the palms’ height and amount of ground covers. The management of bagworms in the previous years followed the plantation's agronomic practices, which consisted of injecting methamidophos to the trunk on a bimonthly basis if the infestation exceeded the defined economic loss, i.e., ten larvae per frond.

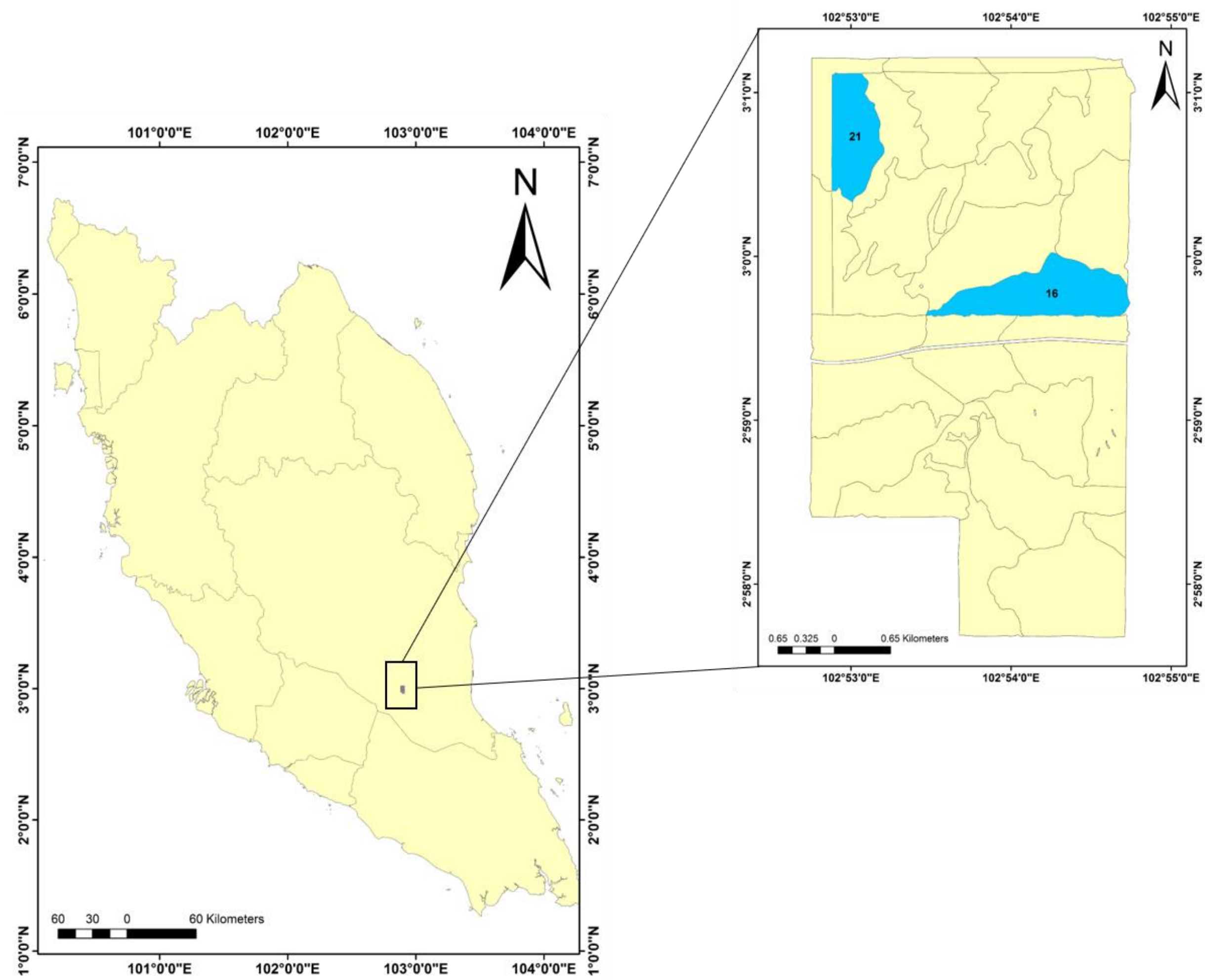

Figure 1. Map of Sungai Mengah estate, Kota Bahagia (Bl6: Highest infestation; B21: Lowest infestation).

Data Collection

Bagworm census

The bagworm grouping and counting was conducted at each selected block in a delineated 1 ha area from July 2016 to July 2017. For each block, 13 palms were systematically censused every two weeks and randomly selected, whereby the censuses were repeated 26 times. Hence, a total of 676 palms was censused throughout this study period. In order to measure the population of bagworm, frond 17 was chosen because of its reliability to portray the bagworm population (Rhainds et al. 1996) and the highest larval population could be achieved frequently between frond 15 to 25 (Ang et al. 1997). Frond number 17 was pruned for each sample palm. Each bagworm collected from the pruned frond were sorted, counted, and recorded according to their larval stages; 1.3–2.5 mm, 2.2–3.2 mm, 3.5–4.4 mm, 4.4 -6.5 mm, 7.3–8.8 mm, 7.6–10.1 mm, and 9.3–11 mm for the LI to L7 (first to seventh instar), respectively (Figure 2) (Basri & Kevan, 1995). The grouping and counting were conducted individually for each bagworm, nevertheless, at the end of each census, the bagworms were summed to produce a biweekly total.

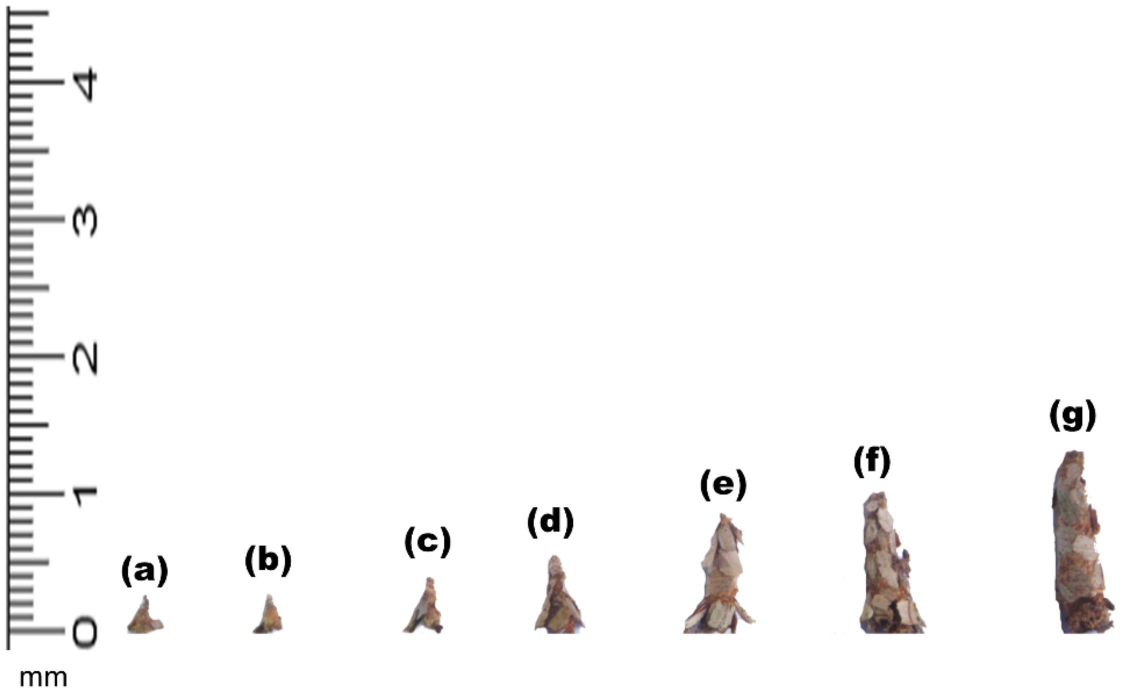

Figure 2. Larval stages of bagworm; (a) L1, (b) L2, (c) L3, (d) L4, (e) L5, (f) L6, and (g) L7.

Parasitoid

While common parasitoids in oil palm are numerous such as Eulophidae, Braconidae and Ichneumonidae (Cheong et al. 2010; Halim et al. 2018b), the target focus of this study were the last two (Cheong et al. 2010; Potineni & Saravanan 2013). Malaise traps were used to trap natural enemies; four malaise traps for each field, from July 2016 to July 2017 (Figure 3). The location of the malaise trap in the sampling area was located in the center of four edges of the sampling area so that it represents the average of the sampling area. These traps perform by manipulating insect behaviour. The white colour of the net roof attracts the insects. When the insects enter the trap, they will fly upward towards the roof. They will then enter the catchment bottle that is filled with 70% ethanol through the entrance hole. After being trapped in the bottle, they cannot escape due to their nature that only fly forward and upward. The ethanol is functioned to preserve the insects from desiccation. Once per week the insects were collected and taken back for sorting and family identification by referring to guidelines provided by Marsh (1994). The identification and counting were conducted individually for each parasitoid, nevertheless, at the end of each census, the parasitoids were summed to produce a biweekly total.

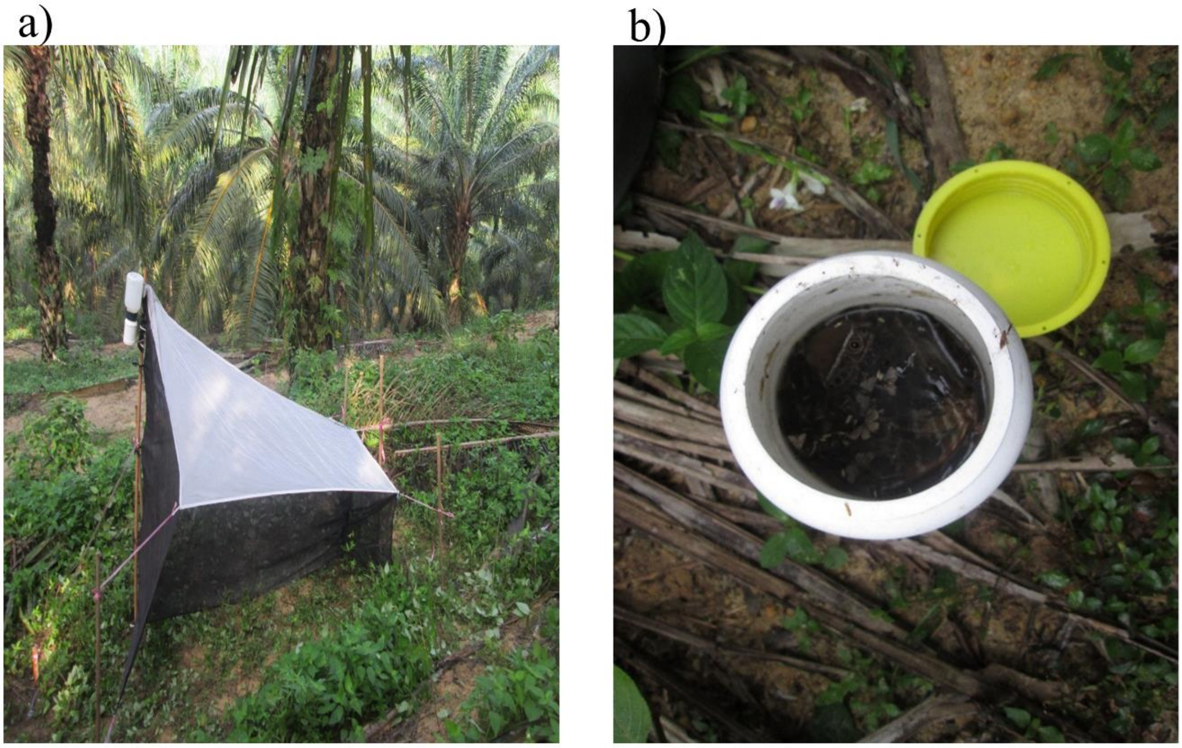

Figure 3. (a) Malaise trap and (b) Catchment bottle.

Data Analysis

The relationship between the summed bagworm's numbers with the summed number of parasitoids was executed through Spearman correlation by using SAS statistical package version 9.2 ($p = 0.5$) at certain time-lags. Similarly, the time lag analysis refers to the correlation of the mean of each parasitoid with the predecessor's total number of parasitoids in every two-week time lag, from the first two weeks (T1), fourth weeks (T2), sixth weeks (T3) to the twelfth weeks (T6).

RESULTS

Table 1 shows the correlation coefficient between bagworms and parasitoids for Block 16 at different time-lags from week 2 (T1) to week 12 (T6). Bagworm stages were all positively correlated to both Braconidae and Ichneumonidae at T3 to T6 and no correlations were found prior to T3. Ichneumonidae was found to have only one interaction with bagworm while the remaining interaction were Braconidae's. The range of correlations between parasitoids with all bagworm larval stages were mostly weak to strong: 0.44 to 0.78 for Braconidae and 0.47 for Ichneumonidae. Additionally, the increasing correlations pattern is noticeable as the time lags increase: T3 = 0.52, T4 = 0.44 to 0.47, T5 = 0.45 to 0.46, and T6 = 0.48 to 0.78. A similar observation can also be made for the bagworm larval stages; lower correlation coefficients for the early larval stages and higher for later stages (i.e., 0.44 to 0.52, 0.45, 0.46, 0.47 to 0.48, 0.71, 0.78, and 0.67) for the LI to L7, respectively.

Table 1. Correlation coefficient between bagworms and parasitoids in Block 16 at different time-lags.

Bagworm stage	Parasitoids	Time lag					
		Week 2 (T1)	**Week 4 (T2)**	**Week 6 (T3)**	**Week 8 (T4)**	**Week 10 (T5)**	**Week 12 (T6)**
L1	Braconidae			0.52^{*}	0.44^{*}		
	Ichneumonidae						
L2	Braconidae					0.45^{*}	
	Ichneumonidae						
L3	Braconidae					0.46^{*}	
	Ichneumonidae						
L4	Braconidae						0.48^{*}
	Ichneumonidae				0.47^{*}		
L5	Braconidae						0.71^{**}
	Ichneumonidae						
L6	Braconidae						0.78^{**}
	Ichneumonidae						
L7	Braconidae						0.67^{**}
	Ichneumonidae						

* and ** denote significant value at $p = 0.05$ and 0.01, respectively.

The distribution of bagworm larval stages against correlated parasitoids and time lags for Block 16 is illustrated in Figure 4. Major bagworm infestations occurred during November 2016 to February 2017. It is noticeable that the number of Braconidae would decline just before the major infestation period and increase right after the period ended. Interaction between all bagworm larval stages and parasitoids occurred at different time lags: for Braconidae, L1 at T3, L2 and L3 at T5, L4, L5, L6 and L7 at T6; for Ichneumonidae, L4 at T4. The interaction in Figure 4.a suggests that the number of L1 started to increase in December 2016, 6 weeks after the number of Braconidae increased between 0 to 2 in October 2016. Both L2 and L3 possessed the same pattern of increment in December 2016, 10 weeks after Braconidae increased between 0 to 2 in September 2016 (Figure 4.b-c). The number of L4, L5, L6 and L7 bagworms in January 2017 increased 12 weeks after Braconidae increased between 0 to 8 in August 2016 and 0 to 2 in October 2016 (Figure 4.e-h). Lastly, the interaction between L4 and Ichneumonidae in Figure 4.d resulted in the increase of L4 between January and February 2017, 8 weeks after the number of Ichneumonidae increased between 1 to 15 between November and December 2016.

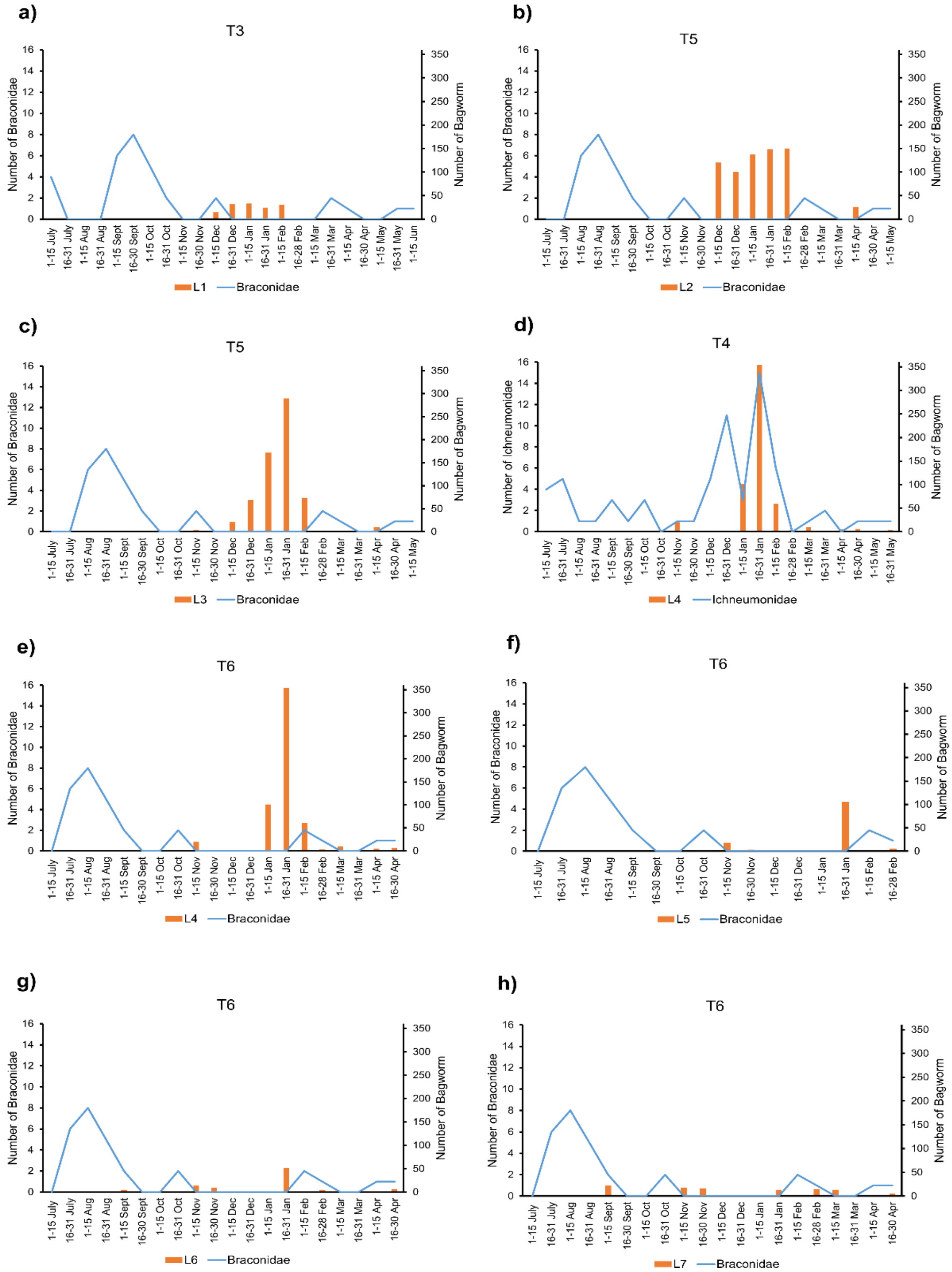

Figure 4. Correlation between bagworm with parasitoids at significant time-lags in Block 16.

Similarly, Table 2 shows the correlation coefficient between bagworms and parasitoids for Block 21 at different time lags from T1 to T6. The L1 bagworm stages was absent during this study period. All bagworm stages were positively correlated to both Braconidae and Ichneumonidae at T1, T2 and T6 and no correlations were found for T4 to T5. Braconidae was found to have only one interaction with bagworm while the remaining interactions were for Ichneumonidae. The range of correlations between parasitoids with all bagworm stages were mostly weak to moderate and slightly lower than in Block 16: 0.47 for Braconidae and 0.43 to 0.58 for Ichneumonidae. A general pattern of decreasing correlation coefficients was found towards the later time lags: T1 = 0.51 to 0.58, T2 = 0.45, T3 = 0.43, and T6 = 0.47. Similarly, the correlation coefficients for bagworm larval stages were higher in the early stages and lower in the later stages (i.e., 0.47 to 0.58 for L3, 0.45 to 0.51 for L4 and 0.43 for L7).

The distribution of bagworm larval stages against correlated parasitoids and time lags for Block 21 is illustrated in Figure 5. In comparison, the bagworm larvae in Block 21 were significantly lower than Block 16. In addition, most of the interactions between bagworm and parasitoids occurred at later time lags in Block 16 but at early time lags in Block 21. Braconidae in Block 21 exhibited a similar pattern as in Block 16 where the number of Braconidae would decline prior to an increase of bagworm numbers (Figure 5.a). The only significant interactions between bagworm and Braconidae was with the L3 larval stage from December 2016 to mid-April 2017 at time lag T6. The increased of Braconidae in September 2016 between 0 to 6 resulted in the increased of L3 bagworm numbers in December 2016. The interaction between L3 and Ichneumonidae occurred multiple times throughout the sampling year where the number of L3 started to increase 2 weeks after the number of Ichneumonidae increased between 0 to 3 in November and December 2016, and March 2017 (Figure 5.b). Similarly, the interaction for L4 and Ichneumonidae occurred multiple times at both time lag T1 and T2. The number of L4 started to increase 2 to 4 weeks after the number of Ichneumonidae increased between 0 to 14 in February for T1 and January for T2 (Figure 5.c-d). Lastly, the number of L7 started to increase 6 weeks after Ichneumonidae increased between 0 to 13 in November and December 2016, January, March, and April 2017 (Figure 5.e).

Taken together, these results imply that there is an association between bagworm and its parasitoids. An important insight that arises from these results is that the abundance of bagworm population reflects upon the parasitoids. Future increment or decrement of bagworm population could be observed following the parasitoids number.

Table 2. Correlation coefficient between bagworms and parasitoids in Block 21 at different time-lags

Bagworm stage	**Parasitoids**	**Time lag**					
		Week 2 (T1)	**Week 4 (T2)**	**Week 6 (T3)**	**Week 8 (T4)**	**Week 10 (T5)**	**Week 12 (T6)**
L2	Braconidae						
	Ichneumonidae						
L3	Braconidae						0.47*
	Ichneumonidae	0.58**					
L4	Braconidae						
	Ichneumonidae	0.51*	0.45*				
L5	Braconidae						
	Ichneumonidae						
L6	Braconidae						
	Ichneumonidae						
L7	Braconidae						
	Ichneumonidae			0.43*			

* and ** denote significant value at $p = 0.05$ and 0.01, respectively.

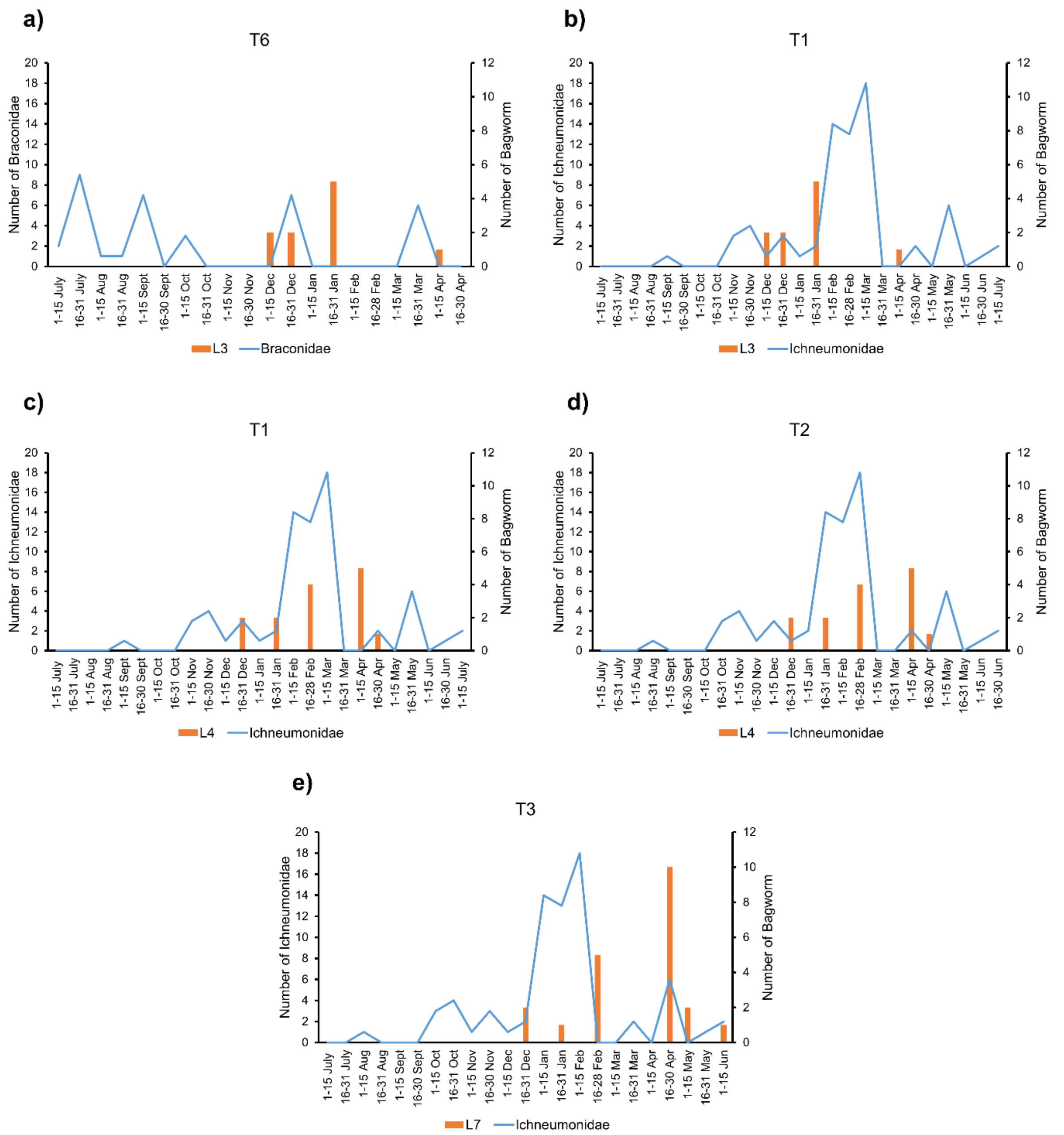

Figure 5. Correlation between bagworm with parasitoids at significant time-lags in Block 21.

DISCUSSION

Different parasitoids exhibited different patterns of temporal distribution (Figure 6). Despite different blocks, Braconidae number generally declined from 15 July 2016 to 15 December 2016 although the fluctuation occurred in the way and then lessened until the end of the study. Meanwhile, Ichneumonidae showed an increased in number at a certain period. From visual observation, this finding suggests that these two parasitoids had different time frames at which they dominate. Contrary to the expectation, Ichneumonidae outperformed Braconidae in terms of number, regardless of blocks. Previous studies revealed that Braconidae is the most significant parasitoid attacking the bagworm larvae alongside Ichneumonidae (Basri et al. 1995; Cheong et al. 2010). A possible explanation for this case is that the mortality factor of

Braconidae which might be caused by hyperparasitoid from Eulophidae family (Kamarudin et al. 1996; Halim et al. 2018b).

Table 1 shows that all bagworm stages revealed significant, positive interaction with parasitoids at T3 to T6 in Block 16. This suggests that parasitism effect is subject to delay impact, rather than immediate; a finding parallel to Aukema et al. (2005) who revealed that the population of pine engraver (*Ips pini)* were suppressed by its predators in a two-month time lag. Besides, L4 larval stage revealed significant interaction with both parasitoids, Braconidae and Ichneumonidae, at T6 and T4, respectively. This suggests that L4 has more impacts towards bagworm parasitism regardless of parasitoid species. Furthermore, it is obvious that the most significant interaction of bagworm with parasitoids occurred at T6. Thus, one can hypothesize that increasing number of Braconidae at 12 weeks prior will cause inclination of bagworm number at present.

Similar to Block 16, Block 21 (Table 2) also revealed positive correlations between bagworms and parasitoids. In contrast to Block 16, the correlation occurred at early time lag i.e. T1 to T3. As compared to Block 16, almost all significant correlations were between bagworms and Ichneumonidae, rather than Braconidae. This suggests that Ichneumonidae impacted bagworm slightly delayed as compared to Braconidae. Nevertheless, unlike Block 16, L4 larval stage showed the most significant correlation with Ichneumonidae only. It can be hypothesized that the L4 stage should be put as an indicator for the effectiveness of biological control by parasitoids as parasitoids commonly attack the host at late instar i.e. third to final instar (Basri et al. 1995; Favaro et al. 2018).

From the view of different oil palm blocks, it is hypothesized that the ground covers between the two blocks might influence the interaction between bagworms and parasitoids in some manners. Based on visual observation, Block 16 is covered by many ground covers as compared to Block 21, which ultimately provide shelter and beneficial to parasitoids. Kamarudin & Wahid (2010) proved that in condition where beneficial plant such *Cassia cobanensis* is absence, the ground covers is favorable to natural enemies. In conjunction with this, Jamian et al. (2017) showed that other type of natural enemy that is predator, is also attracted to beneficial plants such as *Cassia cobanensis.* They discovered that the population of *Sycanus dichotomus* and *Cosmolestes picticeps* rise as the abundance of beneficial plant increases. However, one of the main challenges are the maintenance of beneficial plants, for example, *Cassia cobanensis* requires consecutive replanting since it is an annual plant. Thus, labor costing should be considered in the pest management. On the other hand, Block 16 has the highest bagworm infestation as compared to Block 21. Therefore, the interaction between bagworm and parasitoids may differ as parasitoids population depends on bagworm number.

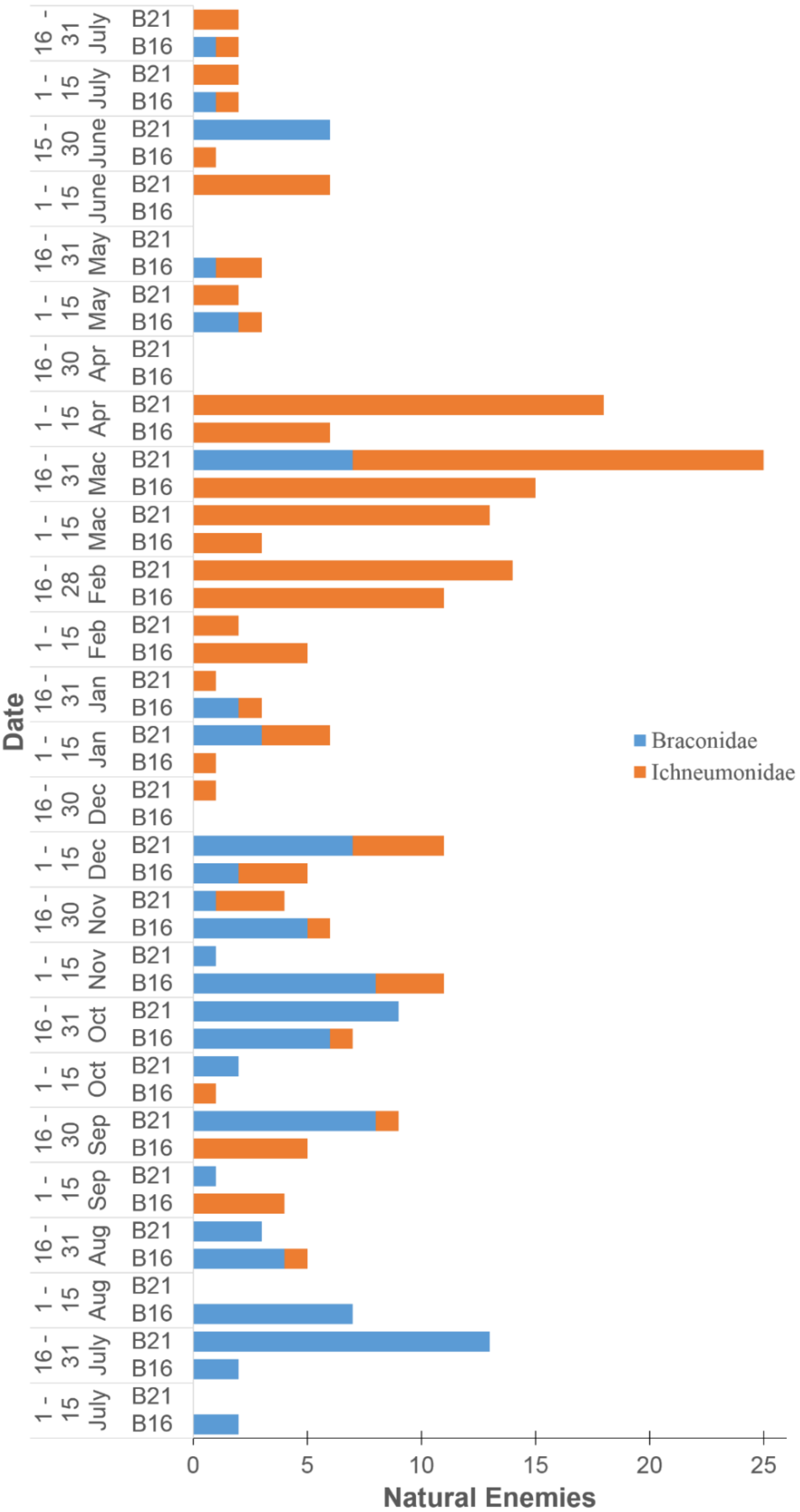

Figure 6. Distribution of parasitoids in Block 16 and Block 21

Throughout different blocks, both Braconidae and Ichneumonidae played an important role in manipulating the population of bagworm given a delayed time. The distinction is that the impact of Braconidae on bagworm could be seen in later time-lags as compared to Ichneumonidae, implying that Ichneumonidae is capable to alter the population in a shorter time. Furthermore, our study found that bagworm populations were dependent on the parasitoids populations, as found by the previous study by Mahadi et al. (2012) in which they discovered that parasitoids populations especially *Goryphus bunoh* (Ichneumonidae) were highly correlated with bagworm. The dependency of natural enemy towards its host had been elaborated by Jamian et al. (2017) who illustrated that the populations of predator i.e. *Sycanus dichotomus* and *Cosmolestes picticeps* were higher in bagworm outbreak field as compared to non-outbreak field. Thus, any fluctuating number of bagworms may affect the natural enemy. Nevertheless, the time-lags effect of natural enemy towards bagworm was not mentioned in this study.

Although the oil palm plantation management in this study applied methamidophos to control the bagworm infestation, this insecticide is known to not cause any harm towards natural enemy directly. Wu et al. (2004) demonstrated that both host species *Plutella xylostella* and its parasitoid *Cotesia plutella* was found to develop insensitivity and resistance towards methamidophos. The finding is supported by Wu et al. (2009) who reported that adult *Diaeretilla rapae*, parasitoid of *Lipaphis erysimi*, were found to be less susceptible to methamidophos and developed insecticide resistance. Additionally, the abundance of natural enemy is depending on the population of the host (bagworm) (Basri et al. 1995; Mahadi et al. 2012). If the population of bagworm were lessened by the insecticide, it is expected that the parasitoids would also decline in number. Finally, based on the correlation analysis, the optimum range of Braconidae number to affect the growth of bagworm was from 0 to 7, while as for Ichneumonidae, the favorable number ranged from 0 to 18.

CONCLUSIONS

Parasitoids studied demonstrated positive associations with bagworm presence at different time-lags. Ichneumonidae population was expected to increase after 2 to 6 weeks given increasing population of middle instar bagworm (L3 to L4) while Braconidae population was likely to rise after 6 to 12 weeks of increasing population of bagworm, regardless of instar stages.

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REFERENCES

Ang, B., Chua, T., Chew, P. & Min, M. 1997. Distribution of *Darna trima* (Moore) and *D. bradleyi* Holloway larvae (Lepidoptera: Limacodidae) in oil palm canopy, in a single species and a double species. *Planter* 73(852): 107–118.

Aukema, B.H., Clayton, M.K. & Raffa, K.F. 2005. Modeling flight activity and population dynamics of the pine engraver, Ips pini, in the Great Lakes region: Effects of weather and predators over short time scales. *Population Ecology* 47(1): 61–69.

Basiron, Y. 2008. Global oils and fats. *Malaysian Palm Oil Council* 5(4): 1–7.

Basri, M.W., Hassan, A.H. & Zulkefli, M. 1988. Bagworms (Lepidoptera: Psychidae) of oil palm in Malaysia. PORIM Occasional Paper No. 23.

Basri, M.W. & Kevan, P.G. 1995. Life history and feeding behaviour of the oil palm bagworm, Metisa plana Walker (Lepidoptera: Psychidae). *Elaeis* 7(1): 18–34.

Basri, M.W., Norman, K. & Hamdan, A.B. 1995. Natural enemies of the bagworm, *Metisa plana* Walker (Lepidoptera: Psychidae) and their impact on host population regulation. *Crop Protection* 14(8): 637–645.

Cheong, Y.L., Sajap, A.S., Hafidzi, M.N., Omar, D. & Abood, F. 2010. Outbreak and natural enemy of bagworm. *Journal of Entomology* 7(3): 141–151.

Exelis, M.P. 2013. An ecological study of *Pteroma Pendula* (Lepidoptera: Psychidae) in oil palm plantations with emphasis on the predatory activities of *Oecophylla smaragdina* (Hymenoptera: Formicidae) on the bagworm. Master thesis, University Of Malaya.

Favaro, R., Roved, J., Girolami, V., Martinez-Sañudo, I. & Mazzon, L. 2018. Host instar influence on offspring sex ratio and female preference of *Neodryinus typhlocybae* (Ashmead) (Hymenoptera, Dryinidae) parasitoid of *Metcalfa pruinosa* (Say) (Homoptera, Flatidae). *Biological Control* 125: 113–120.

Halim, M., Aman-Zuki, A., Syed Ahmad, S. Z., Mohammad Din, A. M., Abdul Rahim, A., Mohd Masri, M. M., Badrul, B. M. & Yaakop, S. 2018a. Exploring the abundance and DNA barcode information of eight parasitoid wasps species (Hymenoptera), the natural enemies of the important pest of oil palm, bagworm, *Metisa plana* (Lepidoptera: Psychidae) toward the biocontrol approach and it's application. *Journal of Asia-Pacific Entomology* 21(4):1359–1365.

Halim, M., Muhaimin, A.D., & Masri, M.M. 2018b. Evaluation of infestation in parasitoids on *Metisa plana* Walker (Lepidoptera: Psychidae) in three oil palm plantations in Peninsular Malaysia. *Serangga* 22(2): 135-149.

Halim, M., Ahmad, S.Z.S., Din, A.M.M. & Yaakop, S. 2019. The diversity and abundance of potential hymenopteran parasitoids assemblage associated with *Metisa plana* (Lepidoptera: Psychidae) in three infested oil palm plantations in Peninsular Malaysia. *AIP Conference Proceedings* 2111: 060024.

Jamian, S., Norhisham, A., Ghazali, A., Zakaria, A. & Azhar, B. 2017. Impacts of 2 species of predatory Reduviidae on bagworms in oil palm plantations. *Insect Science* 24(2): 285–294.

Kamarudin, N. & Wahid, M.B. 2010. Interactions of the bagworm, *Pteroma pendula* (Lepidoptera: Psychidae), and its natural enemies in an oil palm plantation in Perak. *Journal of Oil Palm Research* 22: 758–764.

Libra, M., Tulai, S., Novotny, V. & Hrcek, J. 2019. Elevational contrast in predation and parasitism risk to caterpillars in a tropical rainforest. *Entomologia Experimentalis et Applicata* 167(11): 922–931.

Ludin, N.A., Bakri, M.A.M., Kamaruddin, N., Sopian, K., Deraman, M. S., Hamid, N. H., Asim, N. & Othman, M.Y. 2014. Malaysian oil palm plantation sector: Exploiting renewable energy toward sustainability production. *Journal of Cleaner Production* 65: 9–15.

Mahadi, N.A., Muhamad, R. & Adam, N.A. 2012. Relationship between bagworm *Pteroma Pendula* Joannis (Lepidoptera: Psychidae) populations, parasitoids, and weather parameters in oil palm plantation. *Journal of Agricultural Science* 4(12): 13–17.

Marsh, P.M. 1994. Hymenoptera of the World: An identification guide to families. *American Entomologist* 40(2): 115–116.

Pierre, E.M. & Idris, A.H. 2013. Studies on the predatory activities of *Oecophylla smaragdina* (Hymenoptera: Formicidae) on *Pteroma pendula* (Lepidoptera: Psychidae) in oil palm plantations in Teluk Intan, Perak (Malaysia). *Asian Myrmecology* 5(1): 163–176.

Plantation, S.D. 2014. *Palm Oil Facts and Figures: Palm Oil Facts and Figures*. Malaysia: Sime Darby Plantation

Potineni, K. & Saravanan, L. 2013. Natural enemies of oil palm defoliators and their impact on pest population. *Pest Management in Horticultural Ecosystems* 19(2): 179–184.

Rhainds, M., Gries, G. & Chinchilla, C. 1996. Development of a sampling method for first instar Oiketicus kirbyi (Lepidoptera: Psychidae) in oil palm plantations. *Journal of Economic Entomology* 89(2): 396–401.

Sampaio, M.V., Bueno, V.H.P., Silveira, L.C.P. & Auad, A.M. 2009. Biological control of insect pests in the tropics. *Tropical Biology and Conservation Management.* Eolss Publishers, Oxford, United Kingdom: 28-70.

Sankaran, T., Syed, R.A. & others. 1972. The natural enemies of bagworms on oil palms in Sabah, East Malaysia. *Pacific Insects* 14(1): 57–71.

Wu, G., Jiang, S. & Miyata, T. 2004. Seasonal changes of methamidophos susceptibility and biochemical properties in *Plutella xylostella* (Lepidoptera: Yponomeutidae) and its parasitoid *Cotesia plutellae* (Hymenoptera: Braconidae). *Journal of Economic Entomology* 97(5): 1689-1698.

Wu, G., Lin, Y.W., Miyata, T., Jiang, S.R. & Xie, L.H. 2009. Positive correlation of methamidophos resistance between *Lipaphis erysimi* and *Diaeretilla rapae* and effects of methamidophos ingested by host insect on the parasitoid. *Insect Science* 16: 165-173.