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Research Article

Species Composition of *Anopheles* Mosquitoes in Danum Valley, Lahad Datu, Sabah

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ABSTRACT

Malaria continues to be a public health concern globally, while in Malaysia, cases remain high among interior communities in Borneo, including in Sabah. We studied the *Anopheles* species in Danum Valley, Lahad Datu, by random sampling of mosquitoes in the virgin forest of the Danum Valley Conservation Area (VF), low-ground regenerated forest (100m above sea level) (LRF) and high-ground regenerated forest (400m above sea level) (HRF). Over 12 trap nights, a total of 839 individuals of *Anopheles* mosquitoes belonging to nine species were collected with mosquito magnet: *Anopheles asiaticus* (94), *An. balabacensis* (12), *An. barbumbrosus* (7), *An. fragilis* (640), *An. interruptus* (38), *An. jamesii* (9), *An. latens* (5), *An. maculatus* (17) and *An. montanus* (17). Among them, are vectors for zoonotic malaria in Malaysia namely *Anopheles balabacensis* (1.43%), *An. maculatus* (2.03%) and *An. latens* (0.60%), albeit relatively low in numbers. HRF had the highest number of *Anopheles* mosquitoes collected (670), followed by LRF (130) and VF (39). Both Simpson's (D) and Shannon-Wiener (H) diversity indices were highest at LRF (D = 2.07; H = 1.2 with highest Species Evenness, E = 0.58), followed by HRF (D = 1.62; H = 0.8; E = 0.39) and VF (D = 1.31; H = 0.47; E = 0.43. Greater numbers of the malaria vectors were found in LRF and HRF, compared to VF suggesting that there may be greater exposure to vectors and vector-associated diseases when entering these regenerated forests. Significant differences ($p < 0.05$) for different forest types were detected for the total number of mosquitoes, total *Anopheles* and *An. fragilis* between different forest types.

Keywords: *Anopheles*; tropical rainforest; malaria vectors; DVFC.

INTRODUCTION

The World Health Organization (WHO) (2015) estimated that about 4.3 million deaths were due to malaria vector mosquitoes between the years 2001 and 2013, making these insects the most dangerous animals in the world. In 2017 alone, approximately 435,000 malaria deaths were recorded worldwide (WHO, 2018).

In Malaysia, 16,500 malaria cases were recorded from 2013 to 2017. Sabah (7150 cases; 43.3%) and Sarawak (5684 cases; 34.4%) were the major contributors of malaria cases (Hussin, 2020). The malaria parasites transmitted between humans in Malaysia are *Plasmodium falciparum*, *Plasmodium malariae*, *Plasmodium vivax*, and *Plasmodium ovale.* While the cases of *P. falciparum* and *P. vivax* have decreased, zoonotic malaria originating from monkeys caused by *Plasmodium knowlesi* continues to increase (Cooper et al., 2019). *Plasmodium knowlesi* is the most common malaria causing parasite species in East Malaysia near forest regions, meanwhile more cases of *P. vivax* were recorded in West Malaysia.

Forests in Sabah have long been heavily logged (or exploited) due to economic globalisation and local socio-political dynamics (Gunggut et al., 2014). This has resulted in rise of *P. knowlesi* incidence in humans, and strong linkage between deforestation and *P. knowlesi* cases has been demonstrated (Fornace et al., 2016). The main vectors of *P. knowlesi* belong to the Leucosphyrus group of mosquitoes (Tan et al., 2008; Vythilingam et al., 2008; Hii et al., 1985) with high biting rates for vector *Anopheles* mosquitoes being recorded at farm edges bordering forest and forest areas.

The main agent of forest disturbance in Sabah has been the timber industry and whose logging activities has left relatively small undisturbed lowland dipterocarp forest areas (Marsh & Greer, 1992). Habitats that have been fragmented create transition areas with increased spatial overlap among humans, mosquitoes, and wildlife populations or altered vector ecology can also increase the frequency of disease transmission (Hutchings et al., 2011; Overgaard et al., 2003). The detrimental effects of these environmental alterations at forest edges have been documented for malaria and other vector-borne zoonotic diseases (Lambin et al., 2010; Vanwambeke et al., 2007). Effects of deforestation and land cover changes for agricultural purposes contributed to temperature rise, vector species dynamics and abundance changes with time strongly linked to land use changes (Kweka et al*.,* 2016).

The diversity and species composition of *Anopheles* mosquitoes dwelling in Danum Valley Conservation Area (DVCA) is poorly studied. With monkey malaria cases caused by *P. knowlesi* transmitted by *An. balabacensis* rising in Sabah and becoming a threat to the planned malaria elimination programme in Malaysia (William et al., 2013), more information on the mosquitoes fauna will be needed. Therefore, this study was conducted to determine the composition and diversity of *Anopheles* mosquitoes in the DVCA based on different forest types and hopefully such information will help formulate control strategies.

METHODOLOGY

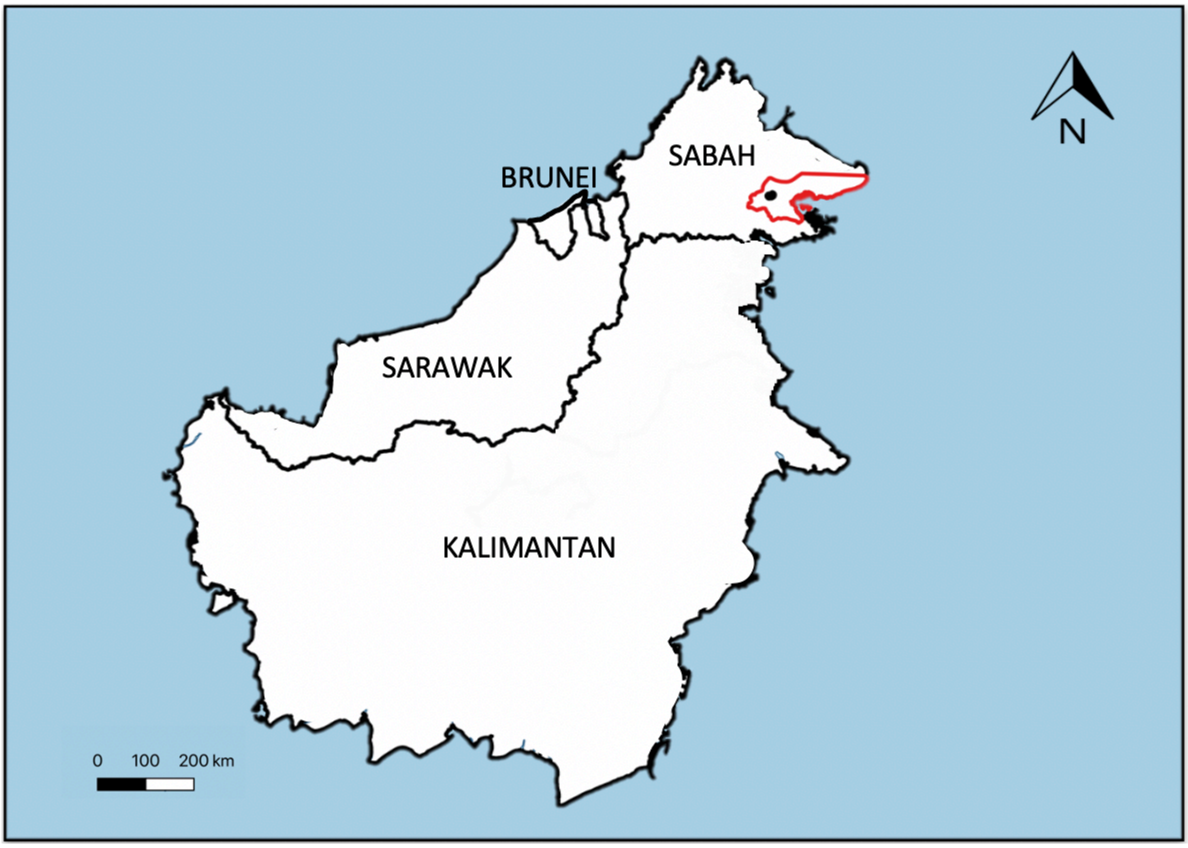

Figure 1: Map of Borneo Island. Danum Valley Conservation Area is demarcated in red and located within Lahad Datu, Sabah.

The Danum Valley Conservation Area (DVCA) (N 04°57.829' E 117°48.055') situated in Lahad Datu was selected for this study. The DVCA is located 81.1km from Lahad Datu Airport and it takes approximately 2 hours 30 minutes by four-wheel drive to reach Danum Valley Field Centre (Fig. 1).

The DVCA is a well-known Class 1 Forest Reserve managed by Yayasan Sabah and Royal Society's Southeast Asia Rainforest Research Programme (SEARRP). The virgin forest area includes the uninhabited 43,800 ha of lowland forest (Marsh & Greer, 1992). The DVCA presents opportunities for ecological research to obtain scientific understanding of ecological processes and evolutionary mechanisms operation within tropical rainforests (Marsh & Greer, 1992) .

Danum Valley comprises dense, undisturbed lowland forests with mostly dipterocarp species, mangroves, montane forest, swamps and transitional forest and re-logged forest at least once (Marsh & Greer, 1992; Reynolds et al., 2011). During rainy periods, animal tracks in the lowland forest easily get flooded; becoming temporary breeding grounds for mosquitoes, long enough for larvae to become adults. Dense tree canopies in the forest minimise sunlight exposure to the ground, which makes the environment moist and humid; perfect for mosquitoes to breed.

The influence of the weather on mast fruiting is reportedly strongest in the eastern part of Borneo (Ashton et al., 1988). During the transition months following the equinoxes (May–June and October–November), the study area experiences highest rainfall, and at the height of the northerly monsoon in December and January (as cited by Clarke & Walsh, 2006). The months of August and September are drier as the south-westerly monsoon reaches its height, and rainfall is also occasionally lower in March and April, which are the months most vulnerable to low rainfall in El Nino Southern Oscillation (ENSO) atmospheric conditions (Walsh & Newbery, 1999).

Anopheles mosquitoes were collected with Mosquito Magnet® Independence MM3200 traps (MMTs) using the mosquito attractants, Lurex3 and Octenol. The cartridge of the Lurex3 contained lactic acid, a chemical compound found in human skin odour (Steib et al., 2001), whereas Octenol mimics human breath (Chaiphongpachara et al., 2018). The MMTs were powered by four AA batteries and the combustion process was facilitated by a 30kg propane gas cylinder. During the combustion of propane, MMTs produce carbon dioxide. Supplemented with a cartridge of Lurex3 and Octenol for each trap, MMTs give off heat, humidity, lactic acid provided by the cartridge of Lurex3, human breath from Octenol and carbon dioxide gas simulating the human presence (Sant'Ana et al., 2014).

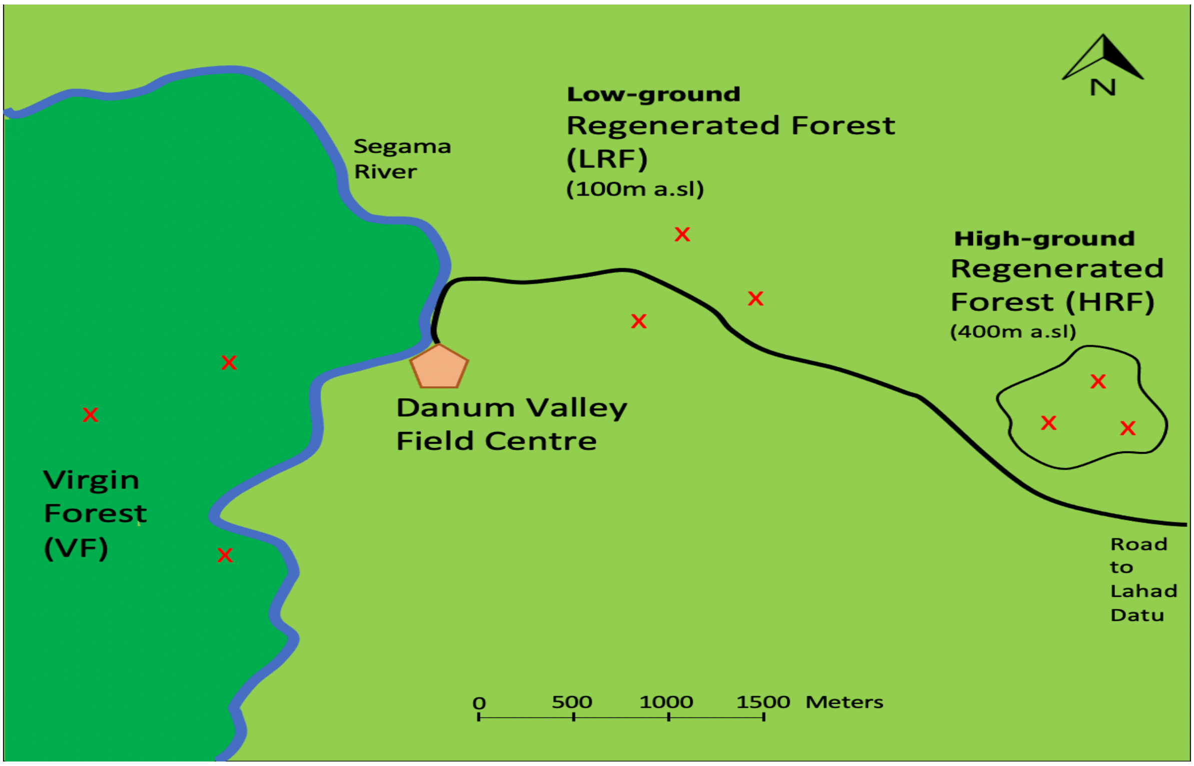

Figure 2: The symbols, X, indicate the trap sites within different forest types of Danum Valley: Virgin Forest (DVCA) = VF, Low-ground Regenerated Forest =LRF, High-ground Regenerated Forest = HRF (400m a.s.l.).

The MMTs were set at random sites within the virgin forest (VF), low-ground regenerated forest (LRF) and 400m above sea level high-ground regenerated forest (HRF) (Fig. 2); approximately 1 km apart from each trap. MMTs were set up at 8.00 am on Day 1 and remained switched on until 8.00 am of Day 2. The MMT nets containing mosquitoes were collected every 24 hours and new fresh nets were placed daily for a total of 12 trap nights at each site. In the sampling months of May and January, three MMT were used, but in October only one

MMT was used due to mechanical issues. Mosquito sampling was carried out in the first week of May 2019, October 2019 and January 2020. A total of six trap nights for the month of May 2019 sampling, and three trap nights for October 2019 and January 2020 were carried out at each site.

MMT nets with *Anopheles* mosquitoes were taken to the Danum Valley Field Centre (DVFC) Scientific Laboratory for further processing. The mosquitoes were killed in a –30°C freezer, mounted individually and placed into 1.5 µl microcentrifuge tubes and stored in the –30°C freezer temporarily prior to being transferred out from Danum Valley. They were later carefully packaged and transported to the Faculty of Medicine and Health Sciences Entomology Laboratory in Universiti Malaysia Sabah for identification process.

Anopheles mosquitoes were identified to the species level using the identification keys of Rattanarithikul et al., (2006) and Sallum et al. (2005). Species richness, along with species diversity, were assessed through the application of Simpson's Reciprocal Diversity Index (D), Shannon-Wiener Diversity Index (H), and Evenness (E). Statistical analysis was done using R programming language for statistical analysis (version 3.5.2). A generalized linear mixed-effect model (GLMM, with R glmmTMB package) was used to analyse mosquito abundance (*An. fragilis*, the most abundant species and total *Anopheles*) as a function of the dependent variables (VF, LRF and HRF), using day and site as random factors, and Poisson distribution as the underlying distribution. The numbers for the other species were too low and too zero inflated for meaningful analysis. In all analyses, different forest types were considered as a fixed effect. Month of sampling was fit alternatively as a fixed (to predict monthly values) or random effect (to test for differences between forest types while controlling for seasonal variation). Poisson distribution was used in the analysis of mosquito abundance.

Models testing associations between response variables (mosquito abundance) explanatory variables (forest types and month of sampling) were assessed through comparison on the basis of having higher log-likelihood and lower Akaike information criterion (AIC) values. Tukey post hoc contrasts were used to differentiate the nature of statistical differences between forest types.

RESULTS

A total of 839 female *Anopheles* mosquitoes belonging to nine different *Anopheles* species were collected from all sites (Fig. 3). The dominant species was *Anopheles fragilis* (76.28%), followed by *An. asiaticus* (11.20%), *An. interruptus* (4.53%), *An. maculatus* and *An. montanus* 2.03% respectively, *An. balabacensis* (1.43%), *An. jamesii* (1.07%), *An. barbumbrosus* (0.83%) and *An. latens* (0.60%). The total *Anopheles* recorded in HRF constituted 78.9% of all mosquitoes caught, while in VF it was only 4.65%. Mosquito traps were set up in the various sampling sites using similar amounts of the same baits. Thus, the catch should reflect mosquito abundance. It is unlikely that under sampling has occurred on one site and not another.

Three species of vectors, namely *Anopheles balabacensis, An. latens* and *An. maculatus* were recorded at LRF and HRF (Fig. 1). These vectors were collected in small numbers at LRF: *Anopheles balabacensis* (4), *An. latens* (4), and *An. maculatus* (13). The numbers of the same three species from HRF were 6, 1 and 4, respectively, while at VF, only two individuals of *An. balabacensis* were collected.

Higher numbers of *Anopheles* mosquito at HRF were caught in all three sampling dates in May, October 2019 and January 2020. The number of *Anopheles* mosquitoes trapped at VF was the lowest with 39 individuals. Furthermore, *An. balabacensis* was caught in all three sites whereas *An. latens* and *An. maculatus* were only caught in LRF and HRF (Fig. 3).

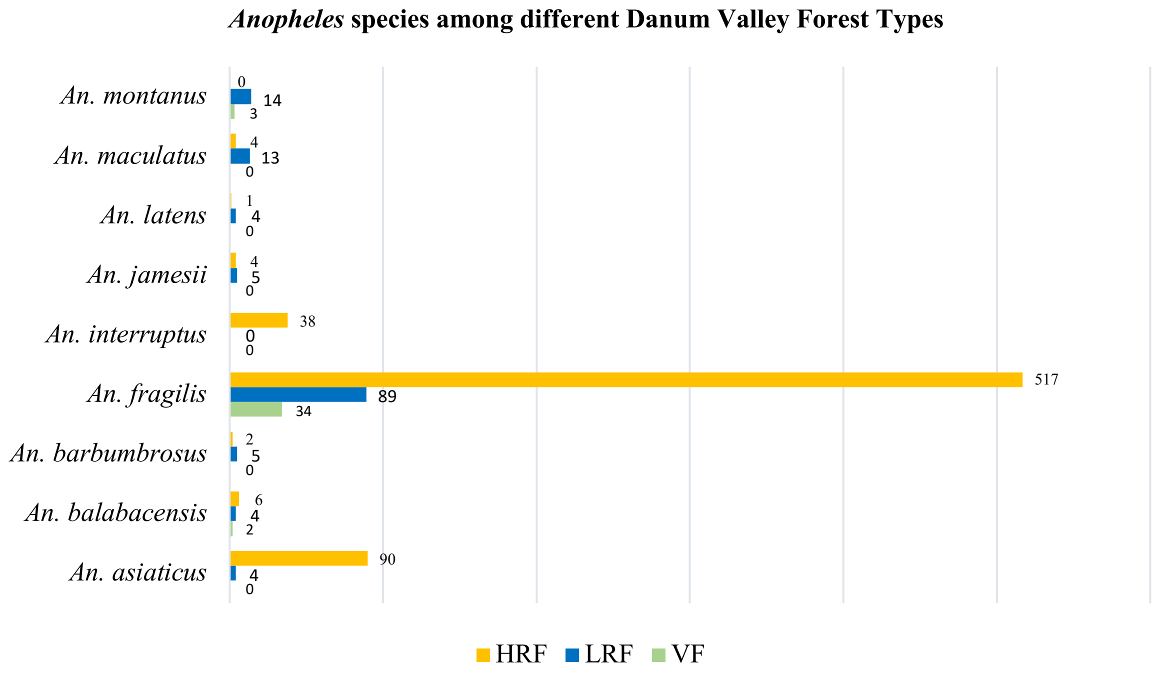

Figure 3: The number of individuals for each *Anopheles* sp. collected from different forest types. VF = virgin forest; LRF = low-ground regenerated forest; HRF = high-ground regenerated forest.

Anopheles species richness, *S* at HRF and LRF are eight and three species found in VF (Table 1). Both Simpson's and Shannon Wiener Diversity Indices were highest at LRF (D = 2.29, H = 1.28). HRF (D = 1.58, H = 0.76) and lowest at virgin forest (D = 1.31, H = 0.47) (Table 1). The three *Anopheles* species found at VF are *An. balabacensis, An. fragilis* and *An. montanus* (Fig. 3).

Table 1: *Anopheles* species richness and diversity indices by forest types. VF = virgin forest; LRF = low-ground regenerated forest; HRF = high-ground regenerated forest.

Species richness and diversity Index	VF	LRF	HRF
Species richness, *S*	3	8	8
Simpson Reciprocal Index, *D*	1.31	2.29	1.58
Shannon-Weiner Index, *H*	0.47	1.28	0.76
Evenness, *E*	0.43	0.62	0.36

Significant differences in the total number of *Anopheles* mosquitoes and the most abundant species, *An. fragilis* were detected for different forest types (Table 2). HRF had the highest mean catch per trap per night (46.5±10.24), but LRF had the lowest mean catch per trap per night (16.2±3.64) although it had significantly higher predicted mean catch per trap per night than VF (22.6± 5.03) for total *Anopheles* mosquitoes. Similarly, significant differences were observed in mosquito catch across the months ($P < 0.1$). January 2020 had a significantly higher number of total mosquitoes caught per trap per night (50.6±11.20) than May 2019 (30.4±6.65) and October 2019 (11.0±2.56).

The dominant *Anopheles* species is *An. fragilis* (78.9% of all *Anopheles*) (Figure 3) and the lowest predicted mean catch per trap per night for *An. fragilis* at VF was (1.35±0.42). A formal comparison of this dominant species in all three types of forest revealed this species has a significant preference in HRF with highest predicted mean per trap per night (20.55±5.34) followed by LRF (3.54±0.98) and VF (1.35±0.42).

Table 2: Fitting GLMM models for total *Anopheles* and *An. fragilis* trapped at Danum Valley. The predicted means and 95% standard error were calculated from the model.

	Forest type	**Predicted mean catch/trap/night**	**p-value for difference of 2 means**	**AIC**
Total *Anopheles*	High-ground regenerated forest	26.96±6.75 [a]	a-b <0.0001	424.81
	Low-ground regenerated forest	5.62±1.47 [b]	a-c <0.0001	
	Virgin forest	1.59±0.47[c]	b-c <0.0001	
Anopheles fragilis	High-ground regenerated forest	20.55±5.34 [a]	a-b <0.0001	397.92
	Low-ground regenerated forest	3.54±0.98 [b]	a-c <0.0001	
	Virgin forest	1.35±0.42 [c]	b-c =0.001	

DISCUSSION

Anopheles mosquitoes in Danum Valley

This study presents initial findings regarding the species composition and diversity of *Anopheles* species across different forest types within Danum Valley. To our knowledge, this is the first study conducted in Danum Valley concerning the diversity of *Anopheles* mosquitoes. Our analysis showed that the highest diversity of *Anopheles* mosquitoes was found in HRF whereas VF has the lowest diversity of *Anopheles* mosquitoes. Only three species of *Anopheles* mosquitoes were recorded from VF. These suggest that human disruptive activities in regenerated forests gives rise to more mosquito species than that of an undisturbed forest. The Intermediate Disturbance Hypothesis (IDH) provides an explanation for the role of disturbance coexistence of climax and colonist species (Loaiza et al., 2017). Assuming that, in undisturbed VF, disturbance-intolerant species (climax species) tend to monopolise resources (e.g., space and food sources), driving less competitive species to local extinction and reducing overall species diversity.

In our study *An. fragilis* is the predominant species found in all forest types and the highest number caught was in HRF despite being a more disturbed area. According to Reid (1965), *An. fragilis* (Aitkeni group) is known to be distributed on lowland in Malaya, Indonesia, Borneo and the Philippines. The Aitkeni group has not been found to be involved in disease transmission yet, but more information is needed on their biology and ecology. Forest land alteration at HRF environment seems to be more favourable to *An. fragilis* than LRF and VF. There is limited knowledge on why *An. fragilis* is found in abundance in HRF. However, the current knowledge by Byrne et al. (2021) shows that land use change is creating more suitable habitats for *Anopheles* vector larvae and this may be contributing to the abundance of *An. fragilis* in the regenerated forest of Danum Valley. The forest floor of the virgin forest tends to be shaded and covered with thick leaf litter and acidic water environments whereas logged lands tend to have sunlit neutral water environments (Brant, 2011). Logged lands are also prone to form temporary breeding puddles. Habitat requirements vary across different mosquito species and this gives a succession of vector species through different forest types (Patz et al., 2000; Norris, 2004). Landscape changes strongly provide significant affect to mictoclimate of a habitat, such as temperature, runoff, evapotranspiration (Patz & Olson, 2006). Hence, these factors are key in determining the abundance, survivorship and diversity of *Anopheles* mosquitoes (Patz & Olson, 2006).

In May and January, higher numbers of mosquitoes were collected because these months coincide with Sabah’s two main rainy seasons (December to February and May to July). The increase in mosquito number could be due to more temporary breeding grounds for mosquitoes such as road puddles, rain pools, animal prints in the forest, potholes and tyre prints in human settlements, resulting from the rain (Hamza & Rayah, 2016; Hawkes et al., 2019). The number of trap nights for the first sampling trip at the DVCA was longer compared to the other two sampling trips in October and January. Three MMT were used in the first and third sampling trips which may be one of the reasons why the number of *Anopheles* mosquitoes was the highest in the month of May.

In October, the number of *Anopheles* mosquitoes collected was the lowest; a possible reason may be due to less rain as compared with May and January. The fruiting season in Danum Valley roughly corresponds to the period from the end of the rainy to the dry season, and the period at the beginning of the rainy season (Tomoko et al., 2010). The abundance and richness of mosquitoes highly depends on biotic factors (oviposition, presence of hosts for food and plants as shelter) and to abiotic factors (relative humidity, seasonality and temperature) (Abella-Medrano et al., 2020). *Plasmodium knowlesi* has been shown to be very infectious, with rhesus monkeys (*Macaca mulatta*) developing blood stage infections if one or more *P. knowlesi*-infected female *Anopheles* mosquitoes successfully feed on them (Murphy et al., 2014). Our temporal variation data to show the correlation between rainforest types and the effect on mosquito abundance is still lacking. There are other limitations such as difficulties in identifying microscopically incomplete or damaged mosquitoes resulting from over handling and transportation of fragile mosquitoes from DVCA to the UMS faculty laboratory, and loss of characters in specimens stored over an extended period of time. There was also limited equipment for the molecular screening of parasites in the mosquitoes.

Relationship between *Anopheles* mosquitoes and forest types

GLMM model (Table 2) fitting showed that in general, the highest number of mosquitoes caught were from the high-ground regenerated forest. The INFAPRO Tower was built around HRF for the purpose of tourism and meteorological study station for scientists. The construction of a gravel road up to the tower and the clearing of trees to build the tower had changed the environment of the ecosystem. Other alterations of the forested environment include logging of the rain forest with notably abandoned logging tracks, gullies, heavily disturbed or compacted areas causing detrimental effects on the terrain components and leading to soil erosion (Clarke & Walsh, 2006). Landscape features largely control the ability of female vectors to spread from their breeding sites to hosts, increases host-vector contacts (Raffy & Tran, 2005). Land cover alterations, such as deforestation and agricultural expansion had been associated with altered dynamics and geographical distribution of malaria and other vector borne diseases (Lambin et al., 2010) caused by *P. knowlesi* in Sabah.

Forest habitats and the linkage of emerging diseases

Some of the *Anopheles* species caught are confirmed vectors of zoonotic malaria. In Sabah, *An. balabacensis* (Wong et al., 2015*;* Ang et al., 2020) and *An. latens* (Vythilingam et al., 2006) are *P. knowlesi* malaria vectors belonging to the Leucosphyrus group. *Anopheles maculatus* is a vector of human malaria in Peninsular Malaysia (Vythilingam et al., 1995). The majority of these *Anopheles* vectors are found in LRF and HRF in the DVCA where there was a degree of man-initiated disturbances to the forest. People will have a greater risk of exposure to zoonotic diseases when living at the forest fringe and working or entering the forest, reason being their proximity with the malaria parasite reservoir monkeys and the *Anopheles* vectors (Singh & Daneshvar, 2013; Anstey & Grigg, 2019). Our findings are consistent with recent findings where *An. balabacensis* were found to increase in abundance in disturbed forests (Brant et al., 2016; Chua et al., 2019; Wong et al., 2015).

Plasmodium knowlesi is responsible for approximately 70% of the reported malaria cases affecting humans in Malaysian Borneo (William et al., 2013). This could be due to the vector *An. balabacensis* which transmits the malaria parasite, being frequently found in disturbed forest habitats of regenerated forests as a result of human activities involving land-use changes. Such alterations create a pathway for both macaque hosts and highly adaptable vectors to migrate closer to human settlements, increasing interactions between man and mosquitoes. At night, when female mosquitoes generally feed, most of the hosts like humans and animals are immobile (Lambin et al., 2010). Logging and deforestation create a strong bridge, in which it increases interactions between humans, mosquito vectors and the macaque hosts of *P. knowlesi.* Evidence suggests that agricultural expansion and forest fragmentation affect *P. knowlesi* exposure, which supports linkages between land use change and *P. knowlesi* transmission (Fornace et al., 2019).

Factors that influence the diversity, abundance and range of host and *Anopheles* vector species are socio ecological processes such as man-made land use change, globalization of agricultural settings, population growth, and climate change (Davidson et al., 2019). The effect of land cover changes according to Fornace et al. (2019) are associated with the increased risks of *Plasmodium knowlesi* exposure and disease transmission. Alterations of landscapes have massive potential to threaten any future malaria eradication efforts (Fornace et al., 2021). Our findings indicate that land use alteration creates more favourable habitats for Anopheles vector larvae, thus contributing to more diverse Anopheles mosquitoes in the regenerated forest of Danum Valley. Byrne et al. (2021) working elsewhere in Sabah had similar finding."

CONCLUSIONS

This study focused on mosquito diversity within different forest types of Danum Valley and their medical importance. We believe this study has provided significant baseline data on vector mosquitoes within the pristine forest of Sabah that can be used for future research directions. The findings will be useful to plan a strategic vector control programme for villagers staying near forest fringes. More research is needed to gather data on the effects of wind, rainfall and feeding time of mosquitoes for effective fogging treatments for *Anopheles* in Sabah. Molecular work for pathogen screening will reveal more about the *Plasmodium* parasite species and uncover newly emergent malaria parasites carried by the *Anopheles* mosquitoes found in the pristine rainforest of Borneo

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