Impact of deforestation on the abundance, diversity, and richness of *Culex* mosquitoes in a southwest Cameroon tropical rainforest

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ABSTRACT: Deforestation is a major threat to biodiversity but little data exist on how deforestation in real-time affects the overall mosquito species community despite its known role in the transmission of diseases. We compared the abundance and diversity of *Culex* mosquitoes before and after deforestation along a gradient of three different anthropogenic disturbance levels in a tropical rainforest in southwestern Cameroon. The collections were conducted in unlogged forest (January, 2016), selectively logged forest (January, 2017), and within a young palm plantation (October, 2017) using net traps, sweep nets, resting traps, and dipping for immature stages in water bodies. Mosquitoes were morphologically identified to subspecies, groups, and species. A total of 2,556 mosquitoes was collected of which 1,663 (65.06%) belong to the genus *Culex*, (n=427 (25.68%) in the unlogged forest; n=900 (54.12%) in the selectively logged forest; and n=336 (20.2%) in the young palm plantation) with a significant difference among the habitats. Diversity and richness of mosquitoes varied significantly among habitats with the highest values found in the selectively logged forest (H=2.4; DS=0.87; S=33) and the lowest value in the unlogged forest (H=1.37; DS=0.68; S=13). The results of this study showed that deforestation affects the abundance and diversity of *Culex* mosquitoes and favors the invasion of anthropophilic mosquitoes. Higher mosquito abundance and diversity in the selectively logged forest than in the pristine forest is notable and some explanations for these differences are discussed. ***Journal of Vector Ecology* 2019. 44 (2): 271-281.**

Keyword Index: Deforestation, emerging diseases, mosquitoes, *Culex*, diversity, Cameroon.

INTRODUCTION

Global climate change and increasing human population growth, together with human-induced modifications of terrestrial ecosystems, have been implicated as major factors contributing to the emergence of new and previously known infectious diseases (Leisnham and Juliano 2012, Kweka et al. 2016, Tucker et al. 2017). Among the most obvious habitat losses is the large-scale tropical deforestation (Lewis et al. 2015) that is likely responsible for global climate changes (Bala et al. 2007, Shukla et al. 1990). The global rate of tropical deforestation is increasing rapidly and 500,000 sq. km of African land is estimated to be degraded (Blaser 2011). Cameroon accounts for the second highest rate of deforestation among the Congo Basin countries. The expansion of palm oil plantations in tropical regions is a major driver of deforestation and affects the biodiversity of organisms, including arthropods like mosquitoes (Ghazali et al. 2016, Vijay et al. 2016).

Mosquitoes are among the most important group of arthropods in public health and, like other organisms, show a direct relation to environmental and habitat heterogeneity or host preferences (Becker et al. 2010). In Cameroon, extensive studies have been carried out on multiple *Anopheles* species (Antonio- Nkondjio et al. 2005, Bamou et al. 2018) that are responsible for the transmission of human malaria, but not much data exist on the systematics and ecology of other mosquito species, including those in the genus *Culex*. In addition to the nuisance they cause, some important *Culex* species that blood feed on humans, such as *Cx. neavei*, *Cx. univittatus*, *Cx. quinquefasciatus,* and *Cx. antennatus,* that are important vectors of filarial worms and West Nile virus in Africa. Also, *Culex* mosquitoes have been incriminated as vectors in the transmission of avian malaria parasites (Njabo et al. 2011, Zele et al. 2014, Schmid et al. 2017), as well as multiple zoonotic agents such as Rift valley, Kamese viruses, St. Louis encephalitis, and Japanese encephalitis (Braack et al. 2018). Because of their potential medical and veterinary importance, it is essential to improve our taxonomic understanding and bio-ecology, especially of the forest-dwelling mosquitoes of the genus *Culex*. An understanding of mosquito bio-ecology, mosquito diversity, and pathogens transmitted by mosquitoes is essential for control strategies and for building predictive models of disease emergence in humans and wildlife in response to environmental changes (Lutomiah et al. 2013, Ribeiro et al. 2012).

Alterations to the landscape and environment due to human activity can influence disease epidemiology indirectly through changes in vector populations, ecology, biology and host-seeking behaviors of vectors searching for alternative habitats and new blood-feeding sources (Enayati and Hemingway 2010, Keesing et al. 2010, Kweka et al. 2016). Deforestation, as an example of human activity, has been linked to changes in feeding behavior of vectors and to the increased prevalence of mosquito and sand fly species (Burkett-Cadena and Vittor 2018, Kamdem et al. 2012, Manga et al. 1995). Deforestation alters the life table characteristics of mosquitoes (Kweka et al. 2016) and parasite development due to changes in ambient and water temperatures, and in the availability of breeding and resting sites (Afrane et al. 2012, Tuno et al. 2005).

Multiple examples implicate the direct linkage between deforestation and emergence of certain human infectious diseases (Epstein et al. 2006, Jones et al. 2008, Plowright et al. 2011). In the southeastern part of Cote d'Ivoire, where large parts of rainforest have been converted into oil palm plantations, several outbreaks of yellow fever and dengue have been documented (Komono 2012), and around 60 examples of linkage between deforestation and land-use changes, and increases in mosquito populations and malaria risk were noted by Yasuoka and Levins (2007). It should be pointed out, though, that the effects that deforestation has had on human malaria is complex, where the changes from low to high, high to low, and no change in prevalence is very region specific (Austin et al. 2017, Bamou et al. 2018, Tucker et al. 2017). Another example of the devastating effects of habitat disturbances was in Hawaii, where virulent *Plasmodium relictum* infected native Hawaiian birds and led to their deaths and extinction. The parasite was introduced on the island by the invasion and spread of infected *Culex quinquefasciatus* due to forest fragmentation and agriculture (LaPointe et al. 2005).

Although it is known that deforestation is a major threat to biodiversity in tropical regions and increasing loss of biodiversity would lead to the occurrence of emerging and re-emerging infectious diseases (Kutz et al. 2005), few studies have investigated how deforestation and forest fragmentation can affect communities of mosquitoes. To investigate the effects of deforestation on the *Culex* mosquito community, we chose to focus collections in Talangaye rainforest, in the southwest region of Cameroon that had areas of pristine and disturbed forests and palm oil plantations. We hypothesized that, due to the destruction of most of their larval and adult habitats by deforestation, the abundance and diversity of *Culex* mosquitoes would decrease drastically, especially in the palm oil plantation where deforestation is occurring.

MATERIALS AND METHODS

Study area

This study was carried out in the Talangaye Rainforest in the Nguti sub-division, within the Kupe-Muanenguba division, of the southwest region of Cameroon (Figure 1). It is a rainforest corridor located between four protected areas in Cameroon (Korup National Park, Bayang Mbo Wildlife Sanctuary, Rumpi Hills Forest Reserve, and the Bakossi Mountains Reserve). This area is within the equatorial climatic zone with an average annual rainfall of 3,000 mm and experiences two main seasons: a dry season (mid-October to mid-March) and a rainy season (mid-March to mid-October). Temperatures range from 25° to 35° C for most of the year and the relative humidity is usually above 75%. The Talangaye Rainforest is being deforested and palms (*Elaeis guineensis*) have been planted by Sithe Global-Sustainable Oils Cameroon (SG-SOC), an affiliate of Herakles Farms. This exercise creates the establishment of habitats with different landscape types and exposes the indigenous human population to possible known and unknown pathogens through mosquito vector contact and eventually increases their vulnerability to vector-borne diseases.

Data collection and habitats characterization

To produce a gradient from forested areas to palm plantation, mosquitoes were collected during the dry season in two sites, "camp 2" and "camp 6" (Figure 1). In each habitat type, a camp was set up for the team members during the sampling periods (two weeks per habitat type) and represented the sampling reference points. Camp 2 (5.175407 N, 9.345436E) was inside a surface area of about 1,360 km^2 and was chosen to assess the "before and after" effect of deforestation in real time (per site comparison). Camp 6 (5.174872N, 9.418014E) was set inside a surface area of about 225 km^2 and was chosen for the presence of the young palm plantation. The distance between the two sites was about 15 km. The mean temperature and relative humidity for each site measured by data loggers were 23.3° C and 95.3% in camp 2 (January, 2016), 23.9° C and 93.3% in camp 2 (January, 2017), and 25.7° C and 99.9% in camp 6 (October, 2017). In camp 2 (January, 2016 and 2017), almost no rain was observed while in camp 6 (October, 2017), some rain was recorded.

Habitat types were distinguished along a gradient of three different anthropogenic disturbance levels based on logging and palm oil trees settlement as follows: a) unlogged forest (camp 2 – January, 2016): pristine forest showing no evidence of logging with mature and tall trees of about seven to ten m in height forming a continuous canopy of about 70%; b) selectively logged forest (camp 2 – January, 2017): forest slightly fragmented due to selective logging of especially hard wood trees; the canopy was slightly fragmented though and allowed sunlight penetration; c) young palm plantation (camp 6 – October, 2017): young palm trees (less than one year old) with windrows of deadwood and grass, bordered by forest patches as buffers along rivers. Forest patches were found at a closer distance (≤150m) from the plantation.

Mosquito sampling, identification, and preservation

Five methods of sampling were used to increase the probability of getting a high diversity of mosquitoes in the different habitats, as sampling methods can influence the community of collected mosquitoes (Carlson et al. 2015). The five methods included the collection of immature stages (eggs, larvae, and pupae), sweep nets, CDC light traps, resting traps, and bird-baited net traps. Immature stages were reared to adults before immobilization and identification. Larvae were

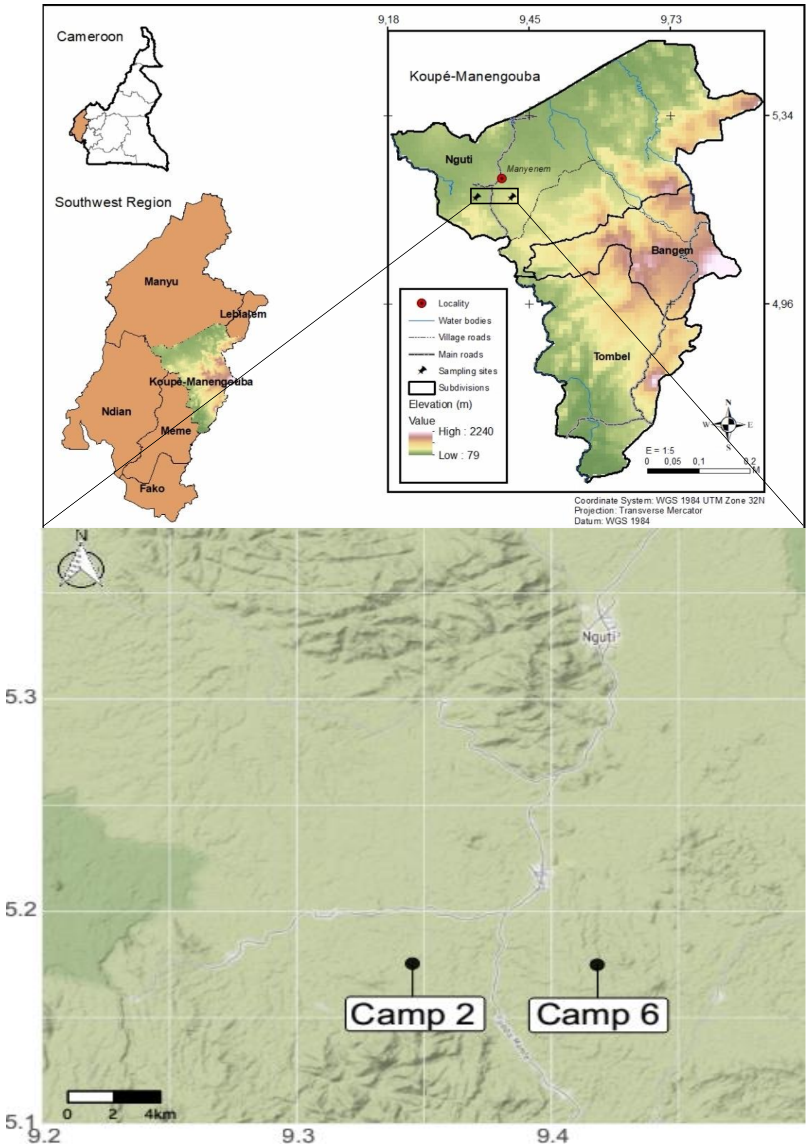

Figure 1. Map showing the study area and sampling sites in the southwest region of Cameroon.

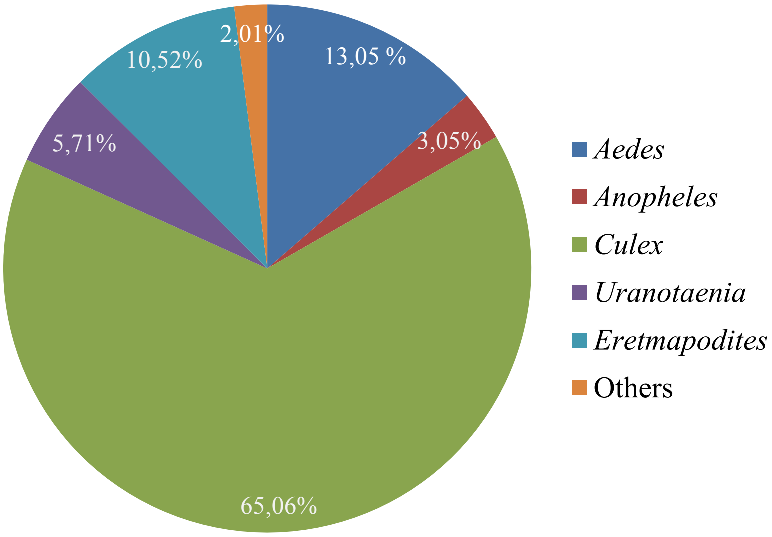

Figure 2. Mosquito abundance within each genus in the southwest region of Cameroon (Others: *Culiseta*, *Ficalbia*, *Hodgesia*, *Malaya*, *Mimmomyia*, *Toxorhynchites,* and unidentified mosquitoes).

given a supply of food consisting of finely ground Tetramin™ fish food. Resting and bird-baited net traps were constructed on the floor with tree branches of about 2 m in height and about 1x1 m in breadth and depth. Bird-baited traps were used with chickens and pigeons held in cages within mosquito nets free of insecticide. The cages holding the birds were placed on a table or trestle made from tree branches. The legs of the table or trestle were covered with petroleum jelly to prevent ants climbing into the cages that held the birds. Both traps were set up for 24 h periods and checked every morning and evening by four to six people, while the CDC miniature light traps were only set up at dusk (for about 12 h) and were removed from the study because they were not productive. Sweep netting, on the other hand, was done daily, especially in the afternoon for at least two to four h by four to six people. Unlike resting and net traps which were fixed traps, sweep netting required more movement in the forest to look for mosquitoes resting on the vegetation. Evening sweep nettings were done in the plantation because of the heat during the day. All the traps were set right inside each habitat type and not far from the camp sites. Following sampling and adult emergence, mosquitoes were removed from the collection cups using an aspirator and then immobilized with triethylamine before identification and preservation.

Immobilized mosquitoes were sorted by sex and identified to species using morphological keys (Edwards 1941, Service 1990). Both male and female mosquitoes were then either pinned (to serve as voucher specimens) or placed in 1.5 ml Eppendorf tubes holding a small amount of silica to keep the mosquitoes dry (until further processing once at the laboratory).

In many Afrotropical *Culex* mosquitoes, closely related species cannot be identified by female characters because the females are morphologically identical. For this reason, significant attempts were made to collect males, and their genitalia were dissected, slide mounted, and then examined at 100X to 600X magnification for identification of cryptic groups.

Data analysis

Statistical analyses were performed using the software R (ver. 3.4.1). Mosquito abundance or the number of individuals of each species captured was determined per habitat type. Shannon-Wiener (H) and Simpson's (DS) indices were used to determine the diversity of mosquitoes among habitat types. Species richness (number of species or taxa in the community) was determined per habitat type. To estimate the number of rare and undetected species and add them to the observed richness, two estimators of the 'true' number of species in each site, Chao1 and ACE (Abundance-base Coverage Estimator), were calculated. Similarity between habitat types was assessed. ANOVA test was used to test for significant differences in mosquito abundance, diversity, and richness among habitat types. In case a significant difference was found, a *post hoc* analysis (Tukey's test) was performed.

RESULTS

Mosquito abundance within each genus among habitat types

Mosquitoes were initially sorted by genera and the number of mosquitoes collected within each genus according to each of the three habitats is represented in Table 1. A total of 2,556 adult mosquitoes belonging to 11 genera was collected. Of these, 586 (22.93%) were captured in the unlogged forest, 1,442 (56.42%) in the selectively logged

Table 1. Abundance of mosquitoes within genera among habitat types in the southwest region of Cameroon.

Mosquito genera	Habitat types			Total (%)
	Unlogged forest	Selectively logged forest	Young palm plantation	
Aedes	35	231	83	349 (13.65)
Anopheles	61	12	5	78 (3.05)
Culex	427	900	336	**1,663 (65.06)**
Culiseta	0	1	1	2 (0.08)
Eretmapodites	8	169	92	269 (10.52)
Ficalbia	0	1	2	3 (0.12)
Hodgesia	0	11	0	11 (0.43)
Malaya	0	5	0	5 (0.20)
Mimmomyia	1	1	0	2 (0.08)
Toxorhynchites	0	0	1	1 (0.04)
Uranotaenia	28	110	8	146 (5.71)
Unidentified	26	1	0	27 (1.06)
Total (%)*	586 (22.93)	**1,442 (56.42)**	528 (20.66)	2,556

*Significant variation among habitat types according to ANOVA ($p < 0.05$).

forest, and 528 (20.66%) in the young palm plantation with a significant difference of mosquito abundance among habitat types (p<0.05). Interestingly, anthropophilic mosquitoes like *Aedes albopictus* and *Aedes aegypti,* which were absent in forested areas, were found in the young palm plantation (Unpublished data).

Mosquito abundance within the genus *Culex* was the highest (comprising 65.06% of the collections), followed by *Aedes* (13.65%), *Eretmapodites* (10.52%), *Uranotaenia* (5.71%), and *Anopheles* (3.05%) (Figure 2).

Culex species abundance per sampling method and within each subgenus

A total of 1,663 *Culex* mosquitoes (61.03% of females and 38.9% of males) belonging to four subgenera and 38 species was collected (Table 2). The highest number of *Culex* were caught by sweep net (49.3%; 22.2% of females and 27.1% of males) and bird-baited net traps (36.0%; 31.6% of females and 4.4% of males), while the fewest number was caught by resting traps (6.9%; 3.6% of females and 3.3% of males) (Table 2).

Out of 1,663 *Culex* mosquitoes (with 92.1% collected at the adult stage and 7.88% collected at the immature stage), 1,626 were morphologically identified, and the remaining 29 individuals were only identified to genus either because specimens were damaged (most of their scales were completely rubbed off) during the process of collection in the traps or they belonged to cryptic species complexes. Of the subgenera, *Eumelanomyia* was the most abundant (44.2%), followed by *Culiciomyia* (26.76%), *Culex* (24.17%), and *Lutzia* (3.13%) (Table 3). Based on male genitalia examination, new species belonging to *Culiciomyia* and *Eumelanomyia* were found (Unpublished data).

Culex species abundance among habitat types

The highest abundance was found in the selectively logged forest (54.12%) and was mostly represented by *Culex* (*Eumelanomyia*) species (43.22%), while the lowest abundance was recorded in the young palm plantation (20.2%) and was mostly represented by *Culex* (*Culex*) species (9.58%) (Figure 3). The total numbers of *Culex* mosquitoes caught were significantly different among habitats (p<0.05). Tukey's test revealed significant differences in terms of mosquito abundance between unlogged and selectively logged forests (p < 0.05), as well as selectively logged and young palm plantation (p < 0.05), while no significant difference was found between unlogged and young palm plantation (p>0.05).

Diversity and richness of *Culex* mosquitoes among habitat types

The diversity indices for the three habitat types ranged from 1.37 to 2.4 using the Shannon index and from 0.68 to 0.87 with the Simpson index (Table 4). Both indices were high in the selectively logged forest (H = 2.4; DS = 0.84) and low in the unlogged forest (H = 1.37; DS = 0.68) with no species dominance observed in any of the habitats. The highest richness was found in the selectively logged forest (S=33, Chao1=38.6, ACE=40.91), while the lowest richness was found in the unlogged forest (S=13, Chao1=14, ACE=15.99) (Table 4).

Culex species composition differed among habitat types. *Culex argenteopunctatus* was only found in the young palm plantation and accounted for 39.85% of *Culex (Culex)* mosquitoes captured. Another species mosquito belonging to the *Culex* subgenus, *Culex pruina,* was mostly abundant in the young palm plantation (54.14%).

Table 2. Abundance of *Culex* mosquitoes per sampling method among habitat types in the southwest region of Cameroon.

	Unlogged forest	Selectively logged forest	Young palm plantation	Total (%)
Immature stages collection	48 (F=23, M=25)	30 (F=12, M=18)	53 (F=26,M=27)	**131 (7.88)** F=61 (3.66) M=70 (4.22)
Sweep nets	108(F=58, M=50)	554(F=258,M=296)	157(F=53,M=104)	**819 (49.25)** F=369 (22.19) M=450 (27.06)
Resting traps	19 (F=12, M=7)	90 (F=45, M= 45)	5 (F= 2, M=3)	**114 (6.85)** F=59 (3.55) M=55 (3.3)
Bird-baited net traps	252(F=218,M=34)	226 (F=190, M=36)	121(F=118,M=3)	**599 (36.02)** F=526 (31.63) M=73 (4.39)
Total (%)	**427 (25.68)** F= 311 (18.7) M= 116 (6.98)	**900 (54.12)** F= 505 (30.37) M= 395 (23.75)	**336 (20.2)** F=199 (11.96) M=137 (8.24)	**GT=1,663** F=1,015 (61.03) M=648 (38.97)

F= Total number of female mosquitoes; M= Total number of male mosquitoes.

Table 3. Abundance of *Culex* mosquito species among habitat types in the southwest region of Cameroon.

Culex spp.	Unlogged forest	Selectively logged forest	Young palm plantation	Total
Culex (Culiciomyia) spp				
Culex(Culiciomyia) group	8	225	49	282
Culex cinerellus	0	2	3	5
Culex cinereus	0	8	1	9
Culex macfiei	0	27	3	30
Culex muspratti	0	5	0	5
Culex nebulosus	0	82	26	108
Culex semibrunneus	0	3	0	3
Culex subaequalis	0	2	0	2
Culex eouzani	0	1	0	1
Total	8	355	82	445
Culex (Eumelanomyia) spp				
Culex(Eumelanomyia) group	7	12	0	19
Culex albiventris	0	96	81	177
Culex simpliciforceps	161	114	13	288
Culex horridus	0	18	11	29
Culex wigglesworthi	63	145	3	211
Culex sunyaniensis	0	3	0	3
Culex insignis	0	0	2	2
Culex rima	0	1	5	6
Total	231	389	115	735
Culex(Culex) spp				
Culex (Culex) group	3	3	0	6
Culex moucheti	3	5	2	10
Culex duttoni	1	0	0	1
Culex musarum	0	1	0	1
Culex guiarti	0	19	1	20
Culex ornatothoracis	165	45	1	211
Culex philipi	1	3	2	6
Culex pruina	0	5	72	77
Culex thalassius	2	0	0	2
Culex trifoliatus	0	1	0	1
Culex perfidiosus	1	3	0	4
Culex annulioris	0	1	0	1
Culex antennatus	0	1	0	1
Culex perfuscus	2	2	0	4
Culex schwetzi	0	1	0	1
Culex neavei	0	1	2	3
Culex argenteopunctatus	0	0	53	53
Total	178	91	133	402
Culex (Lutzia) spp				
Culex tigripes	8	40	4	52
Culex sp.	2	25	2	29
Grand total n (%)*	427(25.68)	**900(54.12)**	336(20.2)	**1,663**

*Significant variation among habitat types according to ANOVA ($p < 0.05$).

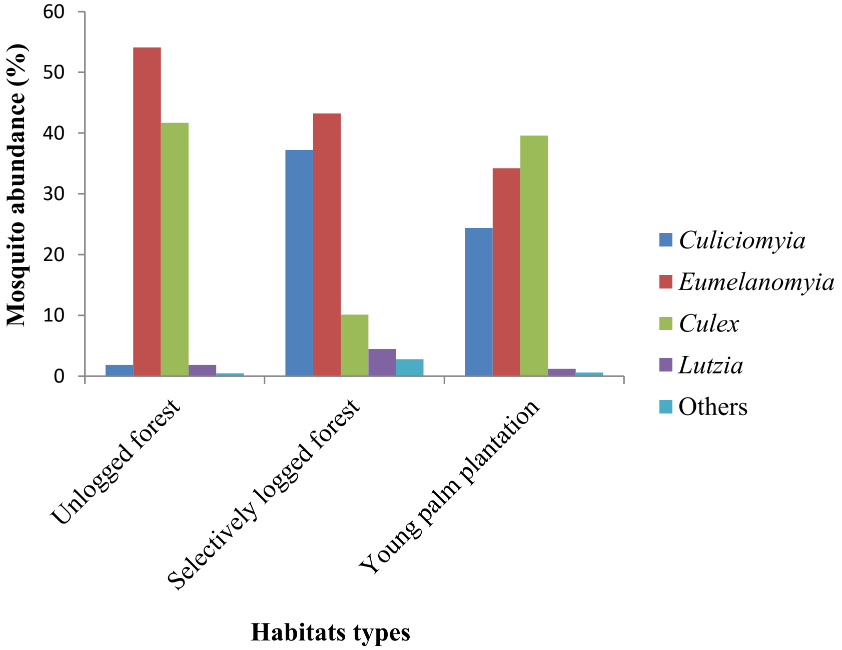

Figure 3. *Culex* mosquito abundance within Subgenera among habitats types in the southwest region of Cameroon (Others: unidentified *Culex* mosquitoes).

Table 4. Diversity and richness of *Culex* mosquito species among habitat types in southwest region of Cameroon.

	Unlogged forest	Selectively logged forest	Young palm plantation
Shannon index (H)*	1.37	2.4	2.14
Simpson's index (DS)*	0.68	0.87	0.84
Observed richness (S)*	13	33	21
Chao1*	14	38.6	22
ACE*	15.99	40.91	23

*Significant variation among habitat types according to ANOVA ($p < 0.05$).

Table 5. Similarity of *Culex* mosquito species among habitat types in the southwest region of Cameroon.

	Unlogged forest	Selectively logged forest
Selectively logged forest	0.62*	
Young palm plantation	0.93	0.67*

*Significant variation among habitat types according to ANOVA ($p < 0.05$).

The ANOVA test revealed that the diversity and richness of *Culex* mosquitoes varied significantly among habitats ($p<0.05$). After the post-hoc analysis, unlogged and selectively logged forests, as well as selectively logged and young palm plantation, were significantly different ($p < 0.05$), while unlogged and young palm plantation were not significantly different in terms of mosquito diversity and richness ($p > 0.05$).

Similarity between habitat types

The similarity index in the three habitat types varies from 0.62 to 0.93, with the highest value found between unlogged forest and young palm plantation (0.93) and the lowest value between unlogged forest and selectively logged (0.62) (Table 5). As such, the proportion of species common to unlogged forest and young palm plantation is higher than species common to the unlogged forest and selectively logged.

DISCUSSION

Mosquito abundance among habitat types

In general, high mosquito abundance and species richness were observed in the study area. This could be due to the heterogeneity of landscapes (unlogged forest, selectively logged forest and young palm plantation) that possibly provided a wide range of larval habitats, resting and mating places, and nectar and blood-food sources (Diallo et al. 2012a, 2012b). Also, this could be explained by the different sampling methods used (immature stages collection, sweep net traps, resting traps, and net traps) that target different development stages. *Culex* was found to be the predominant taxa in the study area, representing more than half of the total collection. This can be explained by the versatile behaviors of mosquitoes of this genus that adapt in a variety of aquatic habitats, both permanent and transient (Ahmad et al. 2011, Edwards 1941, Service 1990).

Culex mosquitoes were collected abundantly in the study area by sweep net traps as in Yaoundé, Cameroon many years ago (Brottes et al. 1966). CDC light traps were not effective in our study area, despite the high efficiency of this method in collecting high number of *Culex* mosquitoes (Nchoutpouen et al. 2019). The efficiency of a sampling method probably depends on the study area and the habitat type. *Culex* were more abundant in the selectively logged forest and less abundant in the young palm plantation. Selectively logged forest was described as a forest slightly fragmented due to selective logging of especially hardwood trees. Such disturbance possibly allows sunlight penetration and accelerates mosquito development and survivorship (Kilpatrick et al. 2006, Tangena et al. 2016, Zahouli et al. 2016). This factor, in combination with the greater number of larval biotopes that are still available to be exploited by different species, may be an important reason for the increase in abundance. That the selectively logged forest was much larger than the plantation should also be taken into consideration. On the other hand, the young palm plantation was characterized by the complete removal of woody vegetation and fewer kinds of aquatic habitats that different mosquito species could exploit. This disturbance of complete deforestation for the establishment of palm plantation could have induced the movement of forest mosquitoes into more suitable areas due to the losses of their larval and adult resting habitats (Afrane et al. 2012, Tuno et al. 2005) and potential hosts (Enayati and Hemingway 2010, Ghazali et al. 2016, Vijay et al. 2016, Kweka et al. 2016). In the young palm plantation, resting places and natural larval sites were rare due to the absence of trees and canopy. Mosquitoes resting on the vegetation were hard to find in the plantation because of too much heat (higher temperature recorded in this habitat as compared to the selectively logged forest), and may have rested in the surrounded remnant forest patches. Larval surveys were less productive in terms of species richness; the most encountered and productive larval habitats were in the standing water created by caterpillar tire prints where only one species of *Culex*, *Culex argenteopunctatus,* was found (Unpublished data).

Diversity and richness of *Culex* mosquitoes among habitat types

The mosquito community in the selectively logged forest recorded the largest number of mosquito species, while the unlogged forest recorded the fewest number of mosquito species with a significant difference among the forest types. Richness and abundance do not always decrease progressively or vary in parallel with increasing habitat modification (Beck et al. 2002, Costa and Magnusson 2002). Forest disturbances might reflect the availability of new habitat features that are not present in undisturbed conditions (Connell 1978) and can cause an increase in the number of species (Connell 1975). This was observed in the selectively logged forest where more larval habitats like pools of water have been created by bulldozer tracks and blocking of streams by fallen trees produced stagnant ponds. This is in accordance with the study of Ribeiro et al. (2012) carried out on mosquitoes in degraded and preserved areas of the Atlantic Forest in Brazil. Their study indicated that the diversity profile of the anthropic environment was characterized by higher richness as compared to the wild environment. According to them, man-modified environments are known to eventually become favorable to greater biological diversity. Yet, although these modifications can compromise vertebrates, they stimulate proliferation of invertebrates such as culicids (Hunter 2007). This is contrary to the study of Ferraguti et al. (2016), who found that mosquito richness was higher in natural areas compared to anthropized areas. More specifically, anthropogenic disturbances alter ecosystem functioning (Dislich et al. 2017) and reduce species richness and abundance compared with forested areas (Savilaakso et al. 2014) due to the loss of habitat and hosts (Ghazali et al. 2016, Vijay et al. 2016).

Furthermore, diversity and richness in the selectively logged forest were significantly different from diversity and richness in the young palm plantation, with the highest values found in the selectively logged forest and the lowest values in the young palm plantation. The fragmented (selectively logged) habitats, in contrast to the plantation, are characterized by the presence of newly created larval habitats and sunlight penetration, and are considered to be ecotones, transition zones between two or more adjacent ecological systems (Odum 1971), and as such, should include an elevated number of species. Thongsripong et al. (2013), when studying mosquito vector diversity among habitats in central Thailand, found that urban/suburban habitats were less diverse in terms of mosquitoes than forest/fragmented forest habitats. Moreover, Zahouli et al. (2017) have reported the greatest species richness of mosquitoes in the rainforest and the lowest abundance and species richness in the oil palm monoculture in southeastern Cote d'Ivoire. Several studies suggest that the decline in biodiversity might lead to a faster rate of emergence and re-emergence of infectious diseases (Kutz et al. 2005) and therefore, an infection risk for a greater proportion of the human population (Keesing et al. 2010, Peixoto and Abramson 2006, Pongsiri et al. 2009, Rueda 2008). However, other studies showed an inverse relationship between the species richness and the increased risk of infections (Confalonieri and Neto 2012).

The presence in deforested habitats (selectively logged forest and young palm plantation) of anthropophilic *Culex* species, such as *Culex antennatus* and *Culex neavei*, could be important as they are vectors of Rift Valley fever (Turell et al. 2008), West Nile fever (Hubalek and Halouzka 1999), and filarial worms. More importantly, *Culex argenteopunctatus* was only found in the young palm plantation and *Culex pruina* was mostly abundant in the young palm plantation despite the harsh environmental conditions. This is the first report of the presence of these species in palm plantations of southwestern Cameroon. *Culex pruina* have been reported in forested and deforested areas of Yaoundé, Cameroon (Brottes et al. 1966) and *Culex argenteopunctatus* in forested areas in Guinea (Baldé et al. 2001). Because of their high sensitivity to environmental changes, mosquitoes have been suggested as bio-indicators of forest degradation level in Brazil (Dorvillé et al. 1996). The presence of these *Culex* species in the young palm plantation can be ecologically significant, given that these species could be associated with degraded environments characterized by the complete absence of woody vegetation except for young palm oil trees. It will therefore be interesting to undertake further research to study the ecology and to determine the roles of these species as vectors through molecular analyses and experimental infections.

Similarity between habitat types

The proportion of species common to the unlogged forest and young palm plantation was high despite the great distance that separated both sites. In addition, no significant difference in terms of mosquito abundance, diversity, and richness was found between these habitats. This can be due to the fact that the young palm plantation was still bordered by patches of forests that were present in the plantation at a closer distance (≤150 m); they likely served as refuges for mosquitoes during the day when it was hot. Thus, a mixture of forest species and anthropophilic species could have easily occurred. This is interesting in terms of interspecies competition that will be worth to observe how this might change with time in the palm plantation. In their study, Zahouli et al. (2017) recorded four species of *Culex* in oil palm-dominated landscapes in southeastern Cote d'Ivoire, of which *Culex nebulosus* from the *Culiciomyia* subgenus were also caught in our study area in both forest and young palm plantations. All these observations confirm that *Culex* species could easily adapt to environmental degradation following complete deforestation. However, each mosquito species has unique life-history characteristics and habitat preferences, and therefore reacts differently to landscape changes (Tucker et al. 2017).

This study, comparing *Culex* mosquito communities before and after deforestation along a gradient of anthropogenic disturbance, showed that deforestation through selective logging and young palm plantation settlement impacts the abundance, diversity, and richness of *Culex* mosquitoes. Therefore, deforestation can have tremendous negative consequences, not only because of impacts on climate, but it can also favor the development or invasion of mosquito vectors of dangerous pathogens. Furthermore, selective logging should be avoided during the deforestation process because it was found to increase the abundance and diversity of mosquitoes. The unlogged forest and the young palm plantation were also found to share common *Culex* species, suggesting that these mosquitoes could easily adapt in clear-cut forests. The presence of the remnant forest patches in the plantation could explain the presence of forest mosquito species found to be common to the plantation and the unlogged forest. Further studies on the dispersion and the possible adaption of forest *Culex* mosquitoes in forest edges and degraded environments will be useful, though. This study also provides useful information for mosquito systematics and ecology, essential for the epidemiology of emerging mosquito-borne diseases. However, further ecological research on other mosquito species in the area is needed. Also, molecular studies on the vector role of these mosquitoes, as well as pathogen isolations from them, are necessary.

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REFERENCES CITED

Afrane, Y.A., B.L. Lawson, R. Brenya, T. Kruppa, and G. Yan. 2012. The ecology of mosquitoes in an irrigated vegetable farm in Kumasi, Ghana: abundance, productivity and survivorship. Parasit. Vectors 15: 223.

Ahmad, W.N.W.M.A., M.N. Zurainee, I. Zamree, A.H. Azahari, N.I. Mohd, and H.L. Lee. 2011. Mapping of mosquito breeding sites in malaria endemic areas in Pos Lenjang, Kuala Lipis, Pahang, Malaysia Rohani. Malar. J. 10: 1-12.

Antonio-Nkondjio, C., F. Simard, P. Awono-Ambene, P. Ngassam, J. Toto, T. Tchuinkam, and D. Fontenille. 2005. Malaria vectors and urbanization in the equatorial forest region of south Cameroon. Trans. R. Soc. Trop. Med. Hyg. 99: 347–354.

Austin, K.G., M. González-Roglich, D. Schaffer-Smith, A.M. Schwantes, and J.J. Swenson. 2017. Trends in size of tropical deforestation events signal increasing dominance of industrial-scale drivers. Environ. Res. Lett. 12: 079601.

Bala, G., K. Caldeira, M. Wickett, T.J. Phillips, D.B. Lobell, C. Delire, and A. Mirin. 2007. Combined climate and carbon-cycle effects of large-scale deforestation. Proc. Natl. Acad. Sci. 104: 6550-6555.

Baldé, M.C., B. Dieng, A. Diallo, S.K. Camara, O.K. Konstantinov, and N.C. Mourzine. 2001. Contribution à l'étude des moustiques (Diptera: Culicidae) de la Guinée. Faune et distribution. Bull. Soc. Pathol. Exot. 94: 199-201.

Bamou, R., L.R. Mbakop, E. Kopya, C. Ndo, P. Awono-Ambene, T. Tchuinkam, M.K. Rono, J. Mwangangi, and C. Antonio-Nkondjio. 2018. Changes in malaria vector bionomics and transmission patterns in the equatorial forest region of Cameroon between 2000 and 2017. Parasit. Vectors 11: 464.

Beck, J., C.H. Schulze, K.E. Linsenmair, and K. Fiedler. 2002. From forest to farmland : diversity of geometrid moths along two habitat gradients on Borneo. J. Trop. Ecol. 18: 33–51.

Becker, N., D. Petric, M. Zgomba, C. Boase, M.B. Madon, C. Dahl, and A. Kaiser. 2010. *Mosquitoes and Their Control.* 2nd ed. Springer Verlag. Berlin, Germany, 608 pp.

Blaser, J., A. Sarre, D. Poore, and S. Johnson. 2011. Status of tropical forest management. ITTO Technical Series. Int. Trop. Tim. Org. Yokohama-Japan 38.

Braack, L.A., P. Gouveia de Almeida, A.J. Cornel, R. Swanepoe, and Christiaan de Jager. 2018. Mosquito-borne arboviruses of African origin: review of key viruses and vectors. Parasit. Vectors 11: 26.

Brottes, H., A. Rickenbach, P. Bres, J-J. Salaun, and L. Ferara. 1966. Les arbovirus au Cameroun: isolements à partir de moustiques. Bull. Org. Mond. Santé 35: 811-825.

Burkett-Cadena, N.D. and A.Y. Vittor. 2018. Deforestation and vector-borne disease: Forest conversion favours important mosquito vectors of human pathogens. Basic Appl. Ecol. 26: 101-110.

Carlson, J.S., E. Walther, R. Trout Fryxell, S. Staley, L.A. Tell, R.N.M. Sehgal, C.M. Barker, and A.J. Cornel. 2015. Identifying avian malaria vectors: sampling methods influence outcomes. Parasit.Vectors 8: 1-16.

Confalonieri, U.E. and C. Costa Neto. 2012. Diversity of mosquito vectors (Diptera: Culicidae) in Caxiuanã, Pará, Brazil. Interdiscip. Perspect. Infect. Dis. 2012: 1-9.

Connell, J.H. 1975. Some mechanisms producing structure in natural communities. In: M.L. Cody and J.M. Diamond (eds.), *Ecology and Evolution of Communities*. Harvard University Press, U.S.A. pp. 460-490.

Connell, J.H. 1978. Diversity in tropical rainforest and coral reefs. Science 199: 1302-1310.

Costa, F. and W. Magnusson. 2002. Selective logging effects on abundance, diversity, and composition of tropical understory herbs. Ecol. Appl. 12: 807-819.

Diallo, D., C. Diagne, K.A. Hanley, A.A. Sall, M. Buenemann, Y. Ba, I. Dia, S.C. Weaver, and M. Diallo. 2012a. Larval ecology of mosquitoes in sylvatic arbovirus foci in southeastern Senegal. Parasit. Vectors 5: 1-17.

Diallo, D., A.A. Sall, M. Buenemann, R. Chen, O. Faye, C.T. Diagne, O. Faye, Y. Ba, I. Dia, D. Watts, S.C. Weaver, K.A. Hanley, and M. Diallo. 2012b. Landscape ecology of sylvatic Chikungunya virus and mosquito vectors in southeastern Senegal. PLoS Negl. Trop. Dis. 6: e1649. doi: 10.1371/journal.pntd.0001649.

Dislich, C., A.C. Keyel, J. Salecker, Y. Kisel, K.M. Meyer, M. Auliya, A.D. Barnes, M.D. Corre, K. Darras, H. Faust, B. Hess, S. Klasen, A. Knohl, H. Kreft, A. Meijide, F. Nurdiansyah, F. Otten, G. Pe'er, S. Steinebach, S. Tarigan, M.H. Tölle, T. Tscharntke, and K. Wiegand. 2017. A review of the ecosystem functions in oil palm plantations, using forests as a reference. Biol. Rev. Camb. Phil. Soc. 92: 1539-1569.

Dorvillé, L.F.M. 1996. Mosquitoes as bioindicators of forest degradation in southeastern Brazil, a statistical evaluation of published data in the literature. Stud. Neotrop. Fauna Environ. 31: 68-78.

Edwards, F.W. 1941. Mosquitoes of the Ethiopian region: III Culicine adults and pupae. London: British Museum (Natural History) 3: 499.

Enayati, A. and J. Hemingway. 2010. Malaria management: Past, present, and future. Annu. Rev. Entomol. 55: 569-591.

Epstein, J.H., H.E. Field, S. Luby, J.R. Pulliam, and P. Daszak. 2006. Nipah virus: impact, origins, and causes of emergence. Curr. Infect. Dis. Rep. 8: 59-65.

Ferraguti, M., J.M. Puente, D. Roiz, S. Ruiz, R. Soriguer, and J. Figuerola. 2016. Effects of landscape anthropization on mosquito community composition and abundance. Sci. Rep. 6: 29002.

Hubalek, Z. and J. Halouzka. 1999. West Nile virus a reemerging mosquito-borne viral disease in Europe. Emerg. Infect. Dis. 5: 643-650.

Hunter, P. 2007. The human impact on biological diversity: How species adapt to urban challenges sheds light on evolution and provides clues about conservation. EMBO Reports 8: 316-318.

Jones, K.E., N.G. Patel, M.A. Levy, A. Storeygard, D. Balk, J.L. Gittleman, and P. Daszak. 2008. Global trends in emerging infectious diseases. Nature 451: 990-993.

Kamdem, C., B. Tene Fossog, F. Simard, J. Etouna, C. Ndo, P. Kengne, P. Boussès, F.X. Etoa, P. Awono-Ambene, D. Fontenille, C. Antonio-Nkondjio, N.J. Besansky, and C. Costantini. 2012. Anthropogenic habitat disturbance and ecological divergence between incipient species of the malaria mosquito *Anopheles gambiae*. PLoS One 7: e39453.

Keesing, F., L.K. Belden, P. Daszak, A. Dobson, C.D. Harvell, R.D. Holt, P. Hudson, A. Jolles, K.E. Jones, C.E. Mitchell, S.S. Myers, T. Bogich, and R.S. Ostfeld. 2010. Impacts of biodiversity on the emergence and transmission of infectious diseases. Nature 468: 647- 652.

Kilpatrick, A.M., L.D. Kramer, M.J. Jones, P.P. Marra, and P. Daszak. 2006. West Nile virus epidemics in North America are driven by shifts in mosquito feeding behavior. PLoS Biol.

4: 606–610.

Komono, B.D. 2012. La fièvre jaune en Côte d'Ivoire. Historique, actualité et perspectives de recherche pour la lutte. Med. Afr. Noire 5910: 459-469.

Kutz, S.J., E.P. Hoberg, L. Polley, and E.J. Jenkins. 2005. Global warming is changing the dynamics of Arctic host–parasite systems. Proc. R. Soc. Biol. 272: 2571-2576.

Kweka, E.J., E.E. Kimaro, and S. Munga. 2016. Effect of deforestation and land use changes on mosquito productivity and development in Western Kenya highlands: implication for Malaria risk. Publ. Hlth. 4: 9.

Lapointe, D.A., M.L. Goff, and C.T. Atkinson. 2005. Comparative susceptibility of introduced forest dwelling mosquitoes in Hawaii to avian malaria, *Plasmodium relictum*. J. Parasitol. 91 : 843–849.

Leisnham, P. and S.A. Juliano. 2012. Impacts of climate, land use, and biological invasion on the ecology of immature *Aedes* mosquitoes: implications for La Crosse emergence. Ecohealth 9: 217–228.

Lewis, S., D. Edwards, and D. Galbraith. 2015. Increasing human dominance of tropical forests. Science 349: 827-832.

Lutomiah, J., J. Bast, J. Clark, J. Richardson, S. Yalwala, D. Oullo, J. Mutisya, F. Mulwa, L. Musila, S. Khamadi, D. Schnabel, E. Wurapa, and R. Sang. 2013. Abundance, diversity, and distribution of mosquito vectors in selected ecological regions of Kenya: public health implications. J. Vector Ecol. 38: 134-142.

Manga, L., J.C. Toto, and P. Carnevale. 1995. Malaria vectors and transmission in an area deforested for a new international airport in Southern Cameroon. Ann. Soc. Belg. Med. Trop. 75: 43-49.

Nchoutpouen, E., A. Talipouo, B. Djiappi-Tchamen, L. Djamouko-Djonkam, E. Kopya, C.S. Ngadjeu, P. Doumbe-Belisse, P. Awono-Ambene, C.S. Wondji, and C. Antonio-Nkondjio. 2019. *Culex* species diversity, susceptibility to insecticides and role as potential vector of Lymphatic fiariasis in the city of Yaoundé, Cameroon. PLoS Negl. Trop. Dis. 13: 1-16.

Njabo, K.Y., A.J. Cornel, C. Bonneaud, E. Toffelmier, R.N.M. Sehgal, G. Valkiūnas, A.F Russell, and T.B. Smith. 2011. Nonspecific patterns of vector, host and avian malaria parasite associations in a central African rainforest. Mol. Ecol. 20: 1049–1061.

Odum, E.P. 1971. *Fundamentals of Ecology*. W.B. Saunders Company, Philadelphia. p. 624.

Peixoto, I.D. and G. Abramson. 2006. The effect of biodiversity on the hantavirus epizootic. Ecology 87: 873–879.

Plowright, R.K., P. Foley, H.E. Field, A.P. Dobson, J.E. Foley, P. Eby, and P. Daszak. 2011. Urban habituation, ecological connectivity and epidemic dampening : the emergence of Hendra virus from fling foxes (Pteropus spp.). Proc. R. Soc. Biol. Sci. 278: 3703-3712.

Pongsiri, M.J., J. Roman, V.O. Ezenwa, T.L. Goldberg, H.S. Koren, S.C. Newbold, R.S. Ostfeld, S.K. Pattanayak, and D.J. Salkeld. 2009. Biodiversity loss affects global disease ecology. Bioscience 59: 945-954

Ribeiro, A.F., P.R. Urbinatti, A.M. Ribeiro de Castro Duarte, M. Bicudo de Paula, D. Mendes Pereira, L.F. Mucci, A. Fernandes, M.H.S. Homem de Mello, M. Otávio de Matos Júnior, R. Correa de Oliveira, D. Natal, and R. dos Santos Malafronte. 2012. Mosquitoes in degraded and preserved areas of the Atlantic Forest and potential for vector-borne disease risk in the municipality of São Paulo, Brazil. J. Vector Ecol. 37: 316-324.

Rueda, L.M. 2008. Global diversity of mosquitoes (Insecta: Diptera: Culicidae) in freshwater. Freshwater Animal Diversity Assessment. Hydrobiologia 595: 477-487.

Savilaakso, S., C. Garcia, J. Garcia-Ulloa, J. Ghazoul, M. Groom, M.R. Guariguata, Y.L. Laumonier, R. Nasi, G. Petrokofsky, J. Snaddon, and M. Zrust. 2014. Systematic review of effects on biodiversity from oil palm production. Environ. Evid. 3: 1-20.

Schmid, S., A. Dinkel, U. Mackenstedt, M.L. Tantely, F.J. Randrianambinintsoa, S. Boyer, and F. Woog. 2017. Avian malaria on Madagascar: bird hosts and putative vector mosquitoes of different Plasmodium lineages. Parasit. Vectors 10: 1-7.

Service, M.W. 1990. *Handbook to the Afrotropical Toxorhynchitine and Culicine Mosquitoes, Excepting Aedes and Culex*. British Museum (Natural History), London.

Shukla, J., C. Nobre, and P. Sellers. 1990. Amazon deforestation and climate change. Science 247: 1322-1324.

Tangena, J.A.A., P. Thammavong, A.L. Wilson, P.T. Brey, and S.W. Lindsay. 2016. Risk and control of mosquito-borne diseases in Southeast Asian rubber plantations. Trends Parasitol. 32: 402-415.

Thongsripong, P., A. Green, P. Kittayapong, D. Kapan, B. Wilcox, and S. Bennett. 2013. Mosquito vector diversity across habitats in central Thailand endemic for dengue and other arthropod borne diseases. PLoS Negl. Trop. Dis. 7: 1-12.

Tucker, L. J.M., A. Vittor, S. Rifai, and D. Valle. 2017. Does deforestation promote or inhibit malaria transmission in the Amazon? A systematic literature review and critical appraisal of current evidence. Philos. Trans. R. Soc. B. 372: 20160125.

Tuno, N., W. Okeka, N. Minakawa, M. Takagi, and G. Yan. 2005. Survivorship of *Anopheles gambiae* sensu stricto (Diptera: Culicidae) larvae in Western Kenya highland forest. J. Med. Entomol. 42: 270-277.

Turell, M.J., K.J. Linthicum, L.A. Patricaan, F.G. Davies, A. Kairo, and C.L. Bailey. 2008. Vector competence of selected African mosquito (Diptera: Culicidae) species for Rif Valley fever virus. J. Med. Entomol. 45: 102-108.

Vijay, V., S.L. Pimm, C.N. Jenkins, and S.J. Smith. 2016. The impacts of oil palm on the recent deforestation and biodiversity loss. PLoS One 7: e0159668.

Yasuoka, J. and R. Levins. 2007. Impact of deforestation and agricultural development on Anopheline ecology and malaria epidemiology. Am. J. Trop. Med. Hyg. 76: 450-460.

Zahouli, J.B.Z., B.G. Koudou, P. Muller, D. Malone, Y. Tano, and J. Utzinger. 2017. Effect of land-use changes on the abundance, distribution, and host-seeking behavior of *Aedes* arbovirus vectors in oil palm-dominated landscapes, Southeastern Cote d'Ivoire. PLoS One 12: 1-26.

Zahouli, J.B.Z., J. Utzinger, M.A. Adja, P. Muller, D. Malone, Y. Tano, and B.G. Koudou. 2016. Oviposition ecology and species composition of *Aedes* spp. and *Aedes aegypti* dynamics in variously urbanized settings in arbovirus foci in southeastern Cote d'Ivoire. Parasit. Vectors 9(523) : 1-14.

Zélé, F., J. Vézilier, G. L'Ambert, A. Nicot, S. Gandon, A. Rivero, and O. Duron. 2014. Dynamics of prevalence and diversity of avian malaria infections in wild *Culex pipiens* mosquitoes: the effects of *Wolbachia*, filarial nematodes and insecticide resistance. Parasit. Vectors 7: 1-16.