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Responses of vector and non-vector mosquito communities to a gradient of native forest cover loss in the Cerrado hotspot, Brazil

Adriano Nobre Arcos^{1,3}✉, Philip Teles Soares^{1,2}, Francisco Augusto da Silva Ferreira³, Francisco Valente-Neto⁴, Wanderli Pedro Tadei³ & Fabio de Oliveira Roque^{1,5,6}

This study aimed to investigate the impact of forest cover loss on the composition of vector and non-vector mosquitoes and to identify potential thresholds for some mosquito species across the gradient of forest cover loss. The study was carried out in an area of the Cerrado hotspot in Brazil. We used linear and non-linear models to assess the response of mosquito abundance to forest cover loss. We registered a total of 6910 specimens and detected a positive effect of the amount of forest cover on the total abundance of mosquitoes in the landscapes. In addition, non-vector species are more susceptible to landscapes with low forest cover, which negatively affects the abundance of these species. On the other hand, the high abundance of vector species was associated with a low percentage of native forest cover. The threshold values ranged from 12.5 to 81% of the forest cover and presented different values for the 14 species. We emphasize that as deforestation increases in the region, there is a clear loss of species and an increase in the presence of potential disease vectors for animals and humans, which is associated with potential implications for the emergence of arboviruses and for public health.

Keywords Culicidae, Deforestation, Vector-borne, Landscape change

The dynamics of vectors of diseases, such as mosquitoes, and landscape changes are among the most critical issues in tropical environments^{1–3}. The ecological and environmental conditions that influence the abundance of these vector-borne diseases are of public interest because of their public health importance⁴. The conversion of natural landscapes to anthropogenic landscapes has caused negative effects on biodiversity, including population declines in many species^{5,6}, but a significant increase in the number of some mosquitoes⁷, particularly anthropophilic species^{8,9}.

Deforestation contributes to the displacement of vectors and their etiological agents, providing contact between wild animals, human populations, and their domestic animals^{10–12}. These interactions favor several zoonoses, mainly in settlements and peripheries¹³. Although some studies agree that habitat loss drastically decreases populations of forest-dependent mosquito species^{14–16}, how different mosquito species are affected across gradients of deforestation, from the most preserved environment to the most altered environment, is poorly known¹⁷.

The conversion of natural ecosystems to other uses is highly important in the tropics. The land that is converted is used for animal and agricultural production, particularly cattle^{18–20}, and for vegetal commodities, such as soy, oil palm, and corn. Brazil ranks first as an exporter of grains, meat and other animal and vegetal products²¹, and this demand creates an enormous amount of land for production, resulting from deforestation²². In some regions, such as the Brazilian Cerrado, deforestation is expected to increase dramatically in the coming years, particularly due to the international demand for meat and grains^{21,23,24}. The converted lands may provide the formation of habitats favorable to the proliferation of mosquitoes that transmit human infections²⁵.

¹Programa de Pós-Graduação em Ecologia e Conservação, Universidade Federal de Mato Grosso do Sul (UFMS), Campo Grande, MS, Brazil. ²Laboratório de Biogeografia e Ecologia Aquática, Universidade Estadual de Goiás (UEG), Anápolis, MG, Brazil. ³Laboratório de Malária e Dengue, Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, AM, Brazil. ⁴Departamento de Biologia Animal, Instituto de Biologia, Universidade Estadual de Campinas (UNICAMP), Campinas, SP, Brazil. ⁵Centre for Tropical Environmental and Sustainability Science (TESS) and College of Science and Engineering, James Cook University, Cairns, QLD, Australia. ⁶Knowledge Center for Biodiversity, Belo Horizonte, MG, Brazil. ⁷Wanderli Pedro Tadei: In memoriam. ✉email: adriano.bionobre@gmail.com

Our knowledge is still limited in identifying the levels of transformation that generate critical changes in ecological systems^{26,27}, that is, if the mosquito communities change gradually (following a given trend) or if the changes are drastic and sudden. These ecological systems are vulnerable to irreversible change when the key properties of the system are pushed over thresholds. Perhaps the most important of these predictors is the total amount of native vegetation remaining²⁸.

Many studies have focused on the identification of non-linear responses of biodiversity elements to the proportion of native vegetation, a pattern in which the response variable (e.g., richness or community composition) has a disproportional effect on a certain value of native vegetation (i.e., thresholds)^{27,29–31}. However, not all biodiversity responses to environmental changes exhibit unique thresholds, which apparently occur within certain amounts of the environmental gradient (usually when habitat loss exceeds 60%) and are modulated by the landscape configuration²⁸. In addition, the shape and dynamics of the matrix around the fragments (usually in the form of agricultural areas) and the quantity and type of domestic animals can play important roles in the response of the zoophilic and anthropophilic mosquito community. For example, forest cover loss causes a decrease in mosquito biodiversity and an increase in the abundance of vector species, such as the malaria vector *Anopheles darlingi*^{15,17}. However, the identification of the level of deforestation that causes disproportional changes in mosquito communities or if these changes are gradual (linear) is poorly known.

With successive modifications of habitats, impacts on the dynamics of infectious diseases are expected, especially those associated with vectors and reservoirs in forests, such as malaria, leishmaniasis and arboviruses³². Thus, the behavior of species associated with ecological factors allows for a better characterization of the interrelationships between vector species or potential vectors and human populations and their domestic animals that settle in a region^{33–35}. Therefore, understanding how mosquitoes respond to landscape gradients is a priority for inferring the potential of disease transmission, which is key to planning more sustainable landscapes in the tropics, including reducing disease risk for humans and animals, maintaining biodiversity and agricultural production.

In this research, our primary goals are twofold: i) to discern the impact of forest cover loss on the abundance of both vector and non-vector mosquitoes within a region in the Cerrado hotspot and ii) to identify potential thresholds for each mosquito species. We hypothesize that the richness and abundance of mosquitoes are positively affected by native forest cover, with a positive effect on the abundance of vector species. In addition, considering that mosquito species may have different ecological requirements and levels of dependence on forests (e.g., larval habitats, hosts)³⁶, we expected that each species would respond differently to forest cover gradients and that sylvatic mosquitoes would be negatively affected by forest loss.

Materials and methods

Study area

The study was carried out in the Bodoquena Plateau region, the southwest region of the state of Mato Grosso do Sul, specifically in the area studied by the Long-Term Ecological Research—Planalto da Bodoquena. The region has forested and well-preserved environments, such as Serra da Bodoquena National Park, and fragmented areas, demonstrating landscape complexity and environmental heterogeneity^{37,38}. The vegetation in the region is composed of remnants of the Atlantic Forest and is mostly from the Cerrado biome (Brazilian savanna). The Brazilian Cerrado is characterized by a high level of endemism, with a high number of species^{39,40}; moreover, it is considered a hotspot of biodiversity^{41,42} (Fig. 1). The region has been threatened by anthropogenic land use changes on a large scale, especially with the expansion of agriculture and livestock^{43,44}.

The regional climate is tropical, as determined by the Köppen-Geiger classification, with wet summers and dry winters⁴⁵. The average annual precipitation varies from 1400 to 1600 mm, and the climate has two distinct seasons: rainy (October–March) and dry (April–September). The annual average temperatures vary between 22 and 26 °C, with the relative humidity of the air reaching a maximum of 80%⁴⁶.

Mosquito collection

Mosquitoes were collected between February and July 2019 in 21 landscapes, using CDC and Shannon light traps. For each landscape, a CDC light trap was installed in the tree canopy, a CDC trap was installed near the ground, and a Shannon light trap was installed inside the forest, approximately 200 m away from each other. Castro manual suction and tubes impregnated with ethyl acetate from 4:00 to 10:00 pm in each landscape (performed next to Shannon's trap), with a sampling effort of 6 h in each landscape for the three collection techniques, totaling 126 h of sampling for all landscapes. All the samples were collected with personal protective equipment, minimizing contact between the mosquitoes and the collectors.

The mosquitoes were sent for identification at the Laboratório de Malária e Dengue of the Instituto Nacional de Pesquisas da Amazônia (INPA) and will be deposited in the entomological collection of the Universidade Federal de Mato Grosso do Sul (UFMS) and the Laboratório de Malária e Dengue (INPA). The species names followed the recommendations of Reinert⁸⁵, according to the list of valid species by Harbach⁸⁶. The nomenclature of species of the genus *Aedes* followed the taxonomic classification recommended by⁸⁷. Collections were authorized under SISBIO permit 58,866 and mosquitoes were identified using specialized dichotomous Keys^{47,48}. The species collected were deposited in the Zoological Reference Collection of the Federal University of Mato Grosso do Sul (ZUFMS) (ZUFMS-DIP01532 to ZUFMS-DIP01595).

Landscape analysis

We defined circular concentric buffers with a radius of 500 m around each sampling point to estimate the percentage of native vegetation. This buffer represents an approximate area of dispersion movement per day for some genera (e.g., *Anopheles*, *Aedes*, *Culex*, *Haemagogus*, *Sabethes*)^{49,50}. To classify land use, we used 2019 images from the Sentinel-2 Level-1C sensor with a 10-m spatial resolution⁵¹. After the images were processed, bands

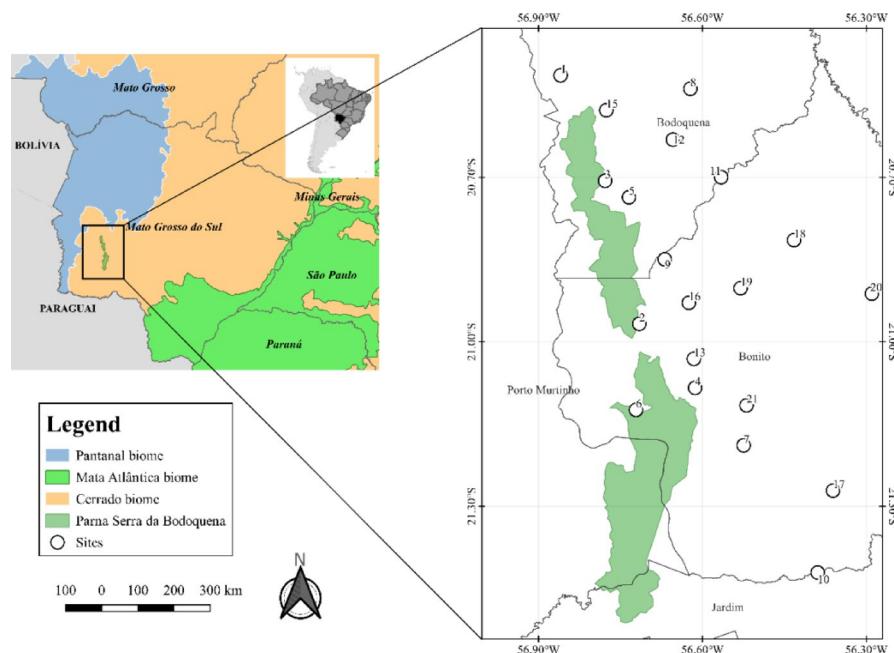


Fig. 1. Spatial distribution of the 21 landscapes in the Bodoquena Plateau, Cerrado hotspot in Mato Grosso do Sul, Brazil. The map was created via QGIS 3.16.5 (<https://download.qgis.org>).

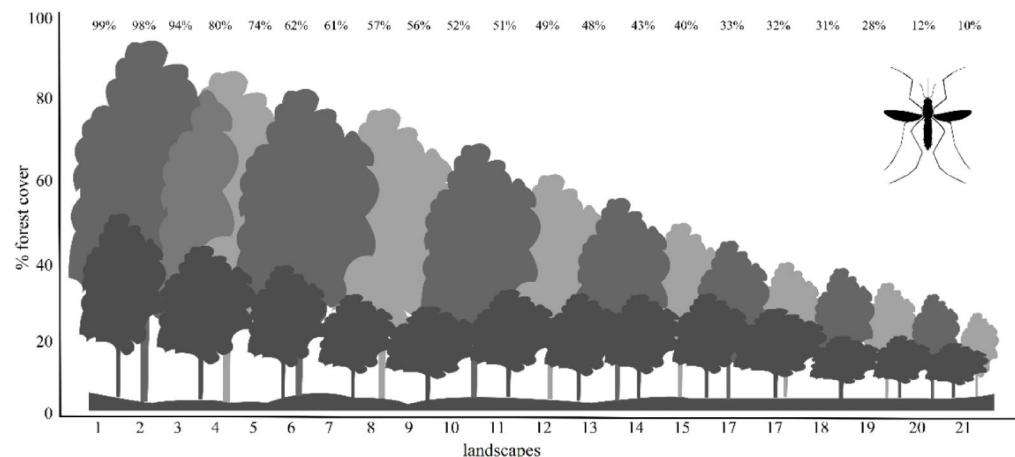


Fig. 2. The forest cover gradient ranged from 99 to 10% around 21 points on the Bodoquena Plateau, which is a Cerrado hotspot in Mato Grosso do Sul, Brazil. The image was created using Adobe Illustrator 2020 (<https://www.adobe.com/br/products/illustrator/>).

3, 4 and 8 (green, red and near infrared, respectively) were merged to perform a semiautomatic classification in Quantum GIS version 3.4.13—Madeira—using the Plugin SCP (semiautomatic classification plugin) version 6.4.0 Greenbelt. The classification resulted in binary data (e.g., forest or non-forest) and the classification accuracy was tested via the SCP plugin in Quantum GIS using Google Earth images as references (Fig. 2, Supplementary Table S1).

Abiotic variables

We characterized the areas of each sampling locally in terms of relative humidity and air temperature, using a digital thermohygrometer model 7663 Incoterm. In addition, we also measured the distance (meters) between the traps and the nearest water body. These lotic water bodies, consisting of streams, canals, and small rivers, had flowing water and intersected the landscapes studied. Although not as accurate, daily precipitation amounts (mm) were obtained from automatic weather stations in the cities of Bonito and Bodoquena, available in the Meteorological Database for Teaching and Research (BDMEP) of the National Institute of Meteorology⁵². All these variables served to characterize our study area in terms of abiotic variables and were not necessarily used in

our models of richness and abundance in relation to vegetation cover itself. Data available in the supplementary material.

Data analyses

Canonical correspondence analysis (CCA) was performed using the vegan package⁵³ as an exploratory analysis to elucidate the relationships between environmental variables (forest cover, distance of the water body and air temperature) and mosquito composition.

To test our hypothesis, we applied different models that assess whether the response of total abundance and the abundance of vector and non-vector species to forest cover (predictor variable) is linear (GLM with Poisson distribution), non-linear (segmented linear regression model—piecewise) or null. The effects of the predictor variable (forest cover gradient) on the abundance of some species were evaluated through a GLM with a Poisson distribution. Although we detected some degree of overdispersion in the data, the Poisson models were retained because they still provided robust and consistent estimates of ecological trends, and model diagnostics indicated that the general patterns remained reliable. We used segmented regression analysis to identify possible species thresholds along a gradient of loss of native forest cover. The analysis divides explanatory variables into two or more linear regressions, seeking to locate the points where there is a relationship of linear change. The identification of thresholds (breakpoints) is estimated using different starting points and identifying regressions with higher R² values⁵⁴. The null model represents the absence of effects. The classification of species as vectors or non-vectors was based on evidence reported in the literature.

To compare the best model for the richness and abundance of each species, we use the corrected Akaike information criterion (AICc) for small sample sizes. We considered models with $\Delta\text{AICc} < 2$ as having the strongest empirical support⁵⁵. The models were generated using specimens identified at the species level, and for all the models, we used the native forest cover (500 m radius) as a predictor variable. Analyses were conducted using the packages “bbmle”⁵⁶ and “segmented”⁵⁷. All plots were made with the package “ggplot2”⁵⁸ in R⁵⁹.

Results

We registered a total of 6910 mosquito specimens, belonging to 12 mosquito genera, representing 33 species. The genus *Aedes* presented the greatest number of specimens (4,447 mosquitoes), with the occurrence of seven species, followed by *Chagasia* (636), with a single species, and *Anopheles* (517), with seven species. The genera *Culex* (361), *Psorophora* (311) and *Haemagogus* (290) were represented by three, four and two species, respectively. *Ae. scapularis* was the most abundant and frequently captured species in all landscapes (3,637 individuals, representing 52% of the specimens identified), followed by *Ae. fulvus* (724), *Ch. bonneae* (636), *Cx. sp.* (348) and *An. triannulatus*, with 310 specimens (Table 1, Supplementary Table 1). The species richness decreased with the loss of forest cover along the gradient (Fig. 3). Overall, few specimens were collected in the traps installed in the tree canopy; among them, the most frequent genera were *Haemagogus* and *Sabettus*.

We identified 28 species of mosquitoes, with the occurrence of twelve vector species of medical importance in the Neotropical region. Among them, *An. darlingi* (Malaria), *Ae. aegypti* (Dengue, Zika, Chikungunya), *Cx. quinquefasciatus* (Filariose, Oropouche fever), *Hg. leucocelaenus* (Sylvatic yellow fever), *Hg. janthinomys* (Sylvatic yellow fever), *Ma. titillans* (Venezuelan Equine Encephalitis virus), *Ae. scapularis* (Rocio Encephalitis virus, Dirofiliariose, Filariose), *Ae. serratus* (Oropouche fever, secondary vector of sylvatic yellow fever), *Ps. ferox* (Rocio virus), *Sa. belisarioi* (Saint Louis Encephalitis Virus—SLEV) (Table 2), are important species with vector competence in Brazil^{1,34,48,66–68,104}.

The relative air humidity in the landscapes ranged from 47.9 to 73.7% (mean = $64.1 \pm 6.4\%$ standard deviation), and the air temperature ranged from 24.0 to 27.9 °C, with a mean of $26.0 \pm 0.9\%$ standard deviation. The average rainfall was $7.7 \text{ mm} \pm 12.3 \text{ mm}$ standard deviation, ranging from 0.0 to 47.6 mm (Supplementary Table S1).

The first axis of the CCA captured 80.0% of the constrained inertia, the second axis captured 15.0%, and the two generated axes explained 95.0%. The CCA ordination clearly revealed a separation between the three groups, with greater associations of species in group 1 (e.g., *Ae. fulvus*, *Sa. glaucopteron*, *Hg. leucocelaenus*) with respect to the percentage of forest. In addition, the species in group 3 (e.g., *Cx. quinquefasciatus*, *Ae. aegypti*, *An. evansae*) were more related to the temperature and distance from the water body; however, the group of species 2 was not associated with the environmental variables addressed (Fig. 4).

The best fit model for total abundance, the abundance of vectors and non-vector species was the generalized linear model. Species abundance was positively related to forest cover. On the other hand, the abundance of vector species was negatively associated with forest cover, and the abundance of non-vector species was positively related to forest cover. The variation in species abundance was strongly explained by the percentage of forest cover (Fig. 5, Supplementary Table 2).

The best fit model for a group of species was the piecewise regression model. We detected thresholds for 14 species along the gradient of forest cover. The *Ma. titillans* change threshold was 81% forest cover. The threshold for *Ae. scapularis* and *Ae. fulvus* was 12% of forest cover. The thresholds for *Ch. bonneae*, *Hg. leucocelaenus*, *Ae. fulvithorax*, *An. darlingi* were between 61 and 62%, and the *Ps. albigena*, *Hg. janthinomys*, *An. triannulatus*, *Wy. aporronoma*, *Sa. glaucopteron*, we observed a threshold between 48 and 54% native forest cover. For *An. albitalis*, a threshold of 30% forest cover was found, and for *Cx. quinquefasciatus* and *Ae. aegypti*, the threshold was approximately 12% forest cover. The null model was the best fit for the other species (*An. rangeli*, *An. evansae*, *Ae. serratus*, *Ps. cingulata*, *Ps. ferox*, *Ma. humeralis*) (Fig. 6, Supplementary Table 2).

Discussion

We identified a positive effect of forest cover on the total abundance of mosquitoes and the abundance of non-vector species. On the other hand, forest cover negatively influences the abundance of vector species. The

Mosquito species	Abundance	%
<i>Aedeomyia (Aed.) squamipennis</i> (Lynch Arribalzaga, 1878)	1	0.01
<i>Anopheles (Nys.) albitalis</i> s.l Lynch Arribálzaga, 1878	1	0.01
<i>Anopheles (Nys.) benarrochi</i> Gabaldon, Cova-García & Lopez, 1941	2	0.02
<i>Anopheles (Nys.) darlingi</i> Root, 1926	216	3.12
<i>Anopheles (Nys.) evansae</i> (Brèthes, 1926)	9	0.13
<i>Anopheles (Nys.) rangeli</i> Gabaldon, Cova García & Lopez, 1940	4	0.05
<i>Anopheles (Nys.) triannulatus</i> s.l (Neiva & Pinto, 1922)	310	4.48
<i>Anopheles</i> sp.	29	0.41
<i>Chagasia bonneae</i> Root, 1927	636	9.20
<i>Coquillettidia (Rhy.) albicosta</i> (Perryassú, 1908)	1	0.01
<i>Culex (Cx.) quinquefasciatus</i> Say, 1823	10	0.14
<i>Culex (Cx.)</i> sp.	3	0.04
<i>Culex (Mel.)</i> sp.	348	5.03
<i>Haemagogus (Hag.) janthinomys</i> Dyar, 1921	48	0.69
<i>Haemagogus (Con.) leucocelaenus</i> (Dyar & Shannon, 1924)	242	3.50
<i>Mansonia (Man.) humeralis</i> Dyar & Knab, 1916	3	0.04
<i>Mansonia (Man.) titillans</i> (Walker, 1848)	147	2.12
<i>Mansonia (Man.)</i> sp.	42	0.60
<i>Aedes (Stg.) aegypti</i> (Linnaeus, 1762)	3	0.04
<i>Aedes (How.) fulvithorax</i> Lutz, 1904	57	0.82
<i>Aedes (Och.) fulvus</i> (Wiedemann, 1828)	724	10.47
<i>Aedes (Och.) scapularis</i> Rondani, 1848	3.637	52.63
<i>Aedes (Och.) serratus</i> (Theobald, 1901)	8	0.11
<i>Aedes (Och.)</i> sp.	21	0.30
<i>Psorophora (Jan.) albigena</i> (Perryassú, 1908)	301	4.35
<i>Psorophora (Gra.) cingulata</i> (Fabricius, 1805)	3	0.04
<i>Psorophora (Jan.) ferox</i> (von Humboldt, 1819)	5	0.07
<i>Psorophora</i> sp.	2	0.02
<i>Sabethes (Sab.) belisarioi</i> Neiva, 1908	1	0.01
<i>Sabethes (Sob.) glaucodaemon</i> (Dyar & Shannon, 1925)	9	0.13
<i>Uranotaenia</i> sp.	1	0.01
<i>Wyeomyia (Den.) aporonoma</i> Dyar & Knab, 1906	85	0.23
<i>Wyeomyia (Den.)</i> sp.	1	0.01
Total	6,910	100

Table 1. Mosquito species collected across a forest cover gradient on the Bodoquena Plateau, Cerrado hotspot in Mato Grosso do Sul, Brazil.

threshold values ranged from 12.5 to 81% of the forest cover and presented different values for the 14 species evaluated. When looking at the total abundance, we detected a clear pattern of forest cover by sylvatic species (approximately 60%) and low threshold values (less than 30%) for urban and anthropophilic species, such as *Ae. aegypti* (approximately 12%). Our results add further evidence that deforestation favors anthropophilic species in tropical regions³⁶ and further demonstrate that species responses are not linear and that forest cover loss of approximately 30–40% already benefits some vector species (such as *Ae. scapularis*, *Ma. titillans* and *An. darlingi*), which has serious implications for public health in rapidly changing landscapes, such as the Cerrado hotspot in Brazil. In deforested and anthropized areas, the loss of natural habitats is compensated by the proliferation of artificial breeding sites, which accumulate rainwater and organic matter (e.g., fish tanks, dams, clay pits, artificial ponds). These microhabitats offer ideal conditions (new habitats for colonization, high temperature, and high nutrient availability) for the reproduction of vector mosquitoes, significantly increasing the risk of outbreaks of vector-borne diseases in ecologically disturbed areas^{17,33–35}. Such environmental changes bring mosquitoes closer to humans, making them more efficient at transmitting diseases, increasing the spread of vector-borne diseases, resulting in a growing number of cases, and posing a public health problem^{3,10,12,15,25,36}.

Forest cover is an important predictor of the composition, distribution, and abundance of several species, especially mosquitoes, which are vectors of diseases^{15,17,60}. Mosquitoes have been used as important bioindicators of environmental degradation⁶¹, helping to assess the degree of environmental changes in a given area⁶² in response to changes in the landscape with drastic changes in its density or local extinction of certain species^{63,64}. Studies have shown positive and negative effects of forest cover on the occurrence of key species for public health, such as *An. darlingi*, *Cx. quinquefasciatus*, *Ae. aegypti*, *Ae. scapularis*^{9,15}. Our results revealed that forest cover affects the abundance of 25 species, revealing a strong relationship between sylvatic vector

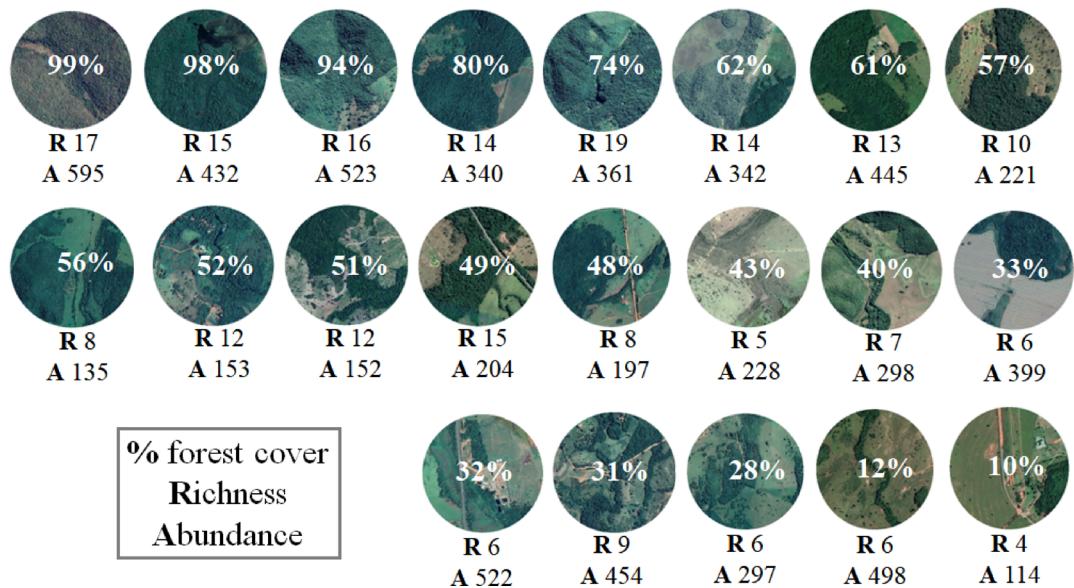


Fig. 3. Landscapes with their respective values of forest cover, richness and abundance of mosquito species on the Bodoquena Plateau, Cerrado hotspot in Mato Grosso do Sul, Brazil.

Species	Pathogen	Evidence of vector status	References
<i>An. darlingi</i>	<i>Plasmodium vivax</i>	Experimental infection	88,89
	<i>Plasmodium falciparum</i>	Experimental infection	88,89
<i>An. albitalis</i> s.l*	<i>Plasmodium vivax</i>	Experimental infection	88,89
	<i>Plasmodium falciparum</i>	Experimental infection	88,89
<i>Ae. aegypti</i>	Dengue virus—DENV	Experimental infection	90
	Zika virus—ZIKV	Natural infection	91
	Chikungunya virus—CHIKV	Natural infection	92
<i>Ae. scapularis</i>	Rocio virus—ROCV	Experimental infection	93
	<i>Dirofilaria immitis</i>	Experimental infection	94
<i>Ae. serratus</i>	Oropouche virus—OROV	Natural infection	95
	Yellow fever virus—YFV	Natural infection	96
<i>Cx. quinquefasciatus</i>	<i>Wuchereria bancrofti</i>	Experimental infection	97,98
	Oropouche virus—OROV	Natural infection	99
<i>Hg. leucocelaenus</i>	Yellow fever—YFV	Natural infection	96,100
<i>Hg. janthinomys</i>	Yellow fever—YFV	Natural infection	100
<i>Ma. titillans</i>	Venezuelan Equine Encephalitis Virus—VEEV	Natural infection	101
<i>Ma. humeralis</i>	Mayaro virus—MAYV	Natural infection	102
<i>Ps. ferox</i>	Rocio virus -ROCV	Experimental infection	103
<i>Sa. belisarioi</i>	Saint Louis Encephalitis Virus—SLEV	Natural infection	104

Table 2. Mosquito species collected on the Bodoquena Plateau, Cerrado hotspot in Mato Grosso do Sul, Brazil, associated with pathogen transmission to humans. * Species complex.

species in landscapes with high values of forest cover (e.g., *Hg. leucocelaenus*, *Hg. janthinomys*, *An. darlingi*), and species with greater adaptability to urban regions and anthropogenic areas with less native forest cover (e.g., *Ae. scapularis*, *Ae. aegypti*, *Ma. titillans*, *Cx. quinquefasciatus*). These results show that forest cover is an important driver of the total abundance of mosquitoes. Moreover, the deconstruction of the community data for vector and non-vector species helped us reveal important patterns that are usually masked when all species are pooled⁶⁵.

We emphasize that the analyses used to relate the percentage of vegetation cover and the occurrence of vector mosquito species have some limitations. The main one is the existence of a species complex in the mosquito samples collected, especially involving *Anopheles albitalis*, which has five formally named species and five unnamed ones¹⁰⁵. Biological problems in species delimitation were a limiting factor that may have influenced our results.

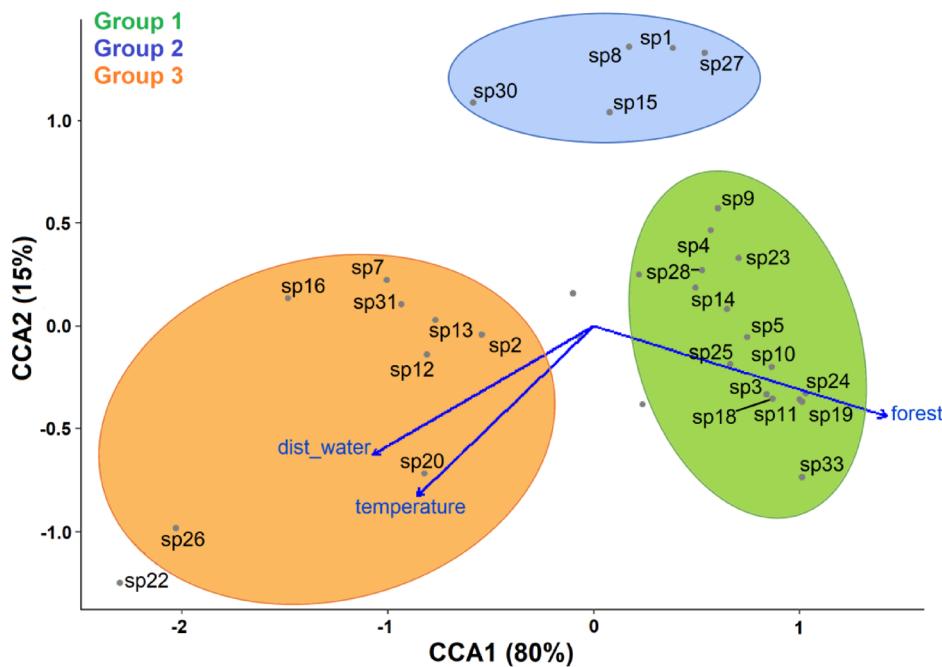


Fig. 4. Ordering diagram of the canonical correlation analysis (CCA) of the relationships between the environmental factors (air temperature, % forest cover, and distance of water) and the abundance of mosquitoes. Group 1 (sp3: *Ae. fulvus*, sp4: *Ae. fulvithorax*, sp5: *Ae. sp*, sp6: *Ps. albigena*, sp9: *Ps. sp*, sp10: *Hg. leucocelaenus*, sp11: *Hg. janthinomys*, sp14: *Ma. sp*, sp17: *An. benarrochi*, sp18: *An. triannulatus*, sp19: *An. rangeli*, sp21: *An. sp*, sp23: *Ch. bornae*, sp24: *Wy. aporonyma*, sp25: *Wy. sp*, sp28: *Cx. (Mel.) sp*, sp29: *Cq. albicosta*, sp32: *Sa. belisarioi*, sp33: *Sa. glaucodaemon*); Group 2 (sp1: *Ae. serratus*, sp8: *Ps. ferox*, sp15: *An. darlingi*, sp27: *Cx. (Cx.) sp*, sp30: *Ad. squamipennis*); Group 3 (sp2: *Ae. scapularis*, sp7: *Ps. cingulata*, sp12: *Ma. titillans*, sp13: *Ma. humeralis*, sp16: *An. albitalis*, sp20: *An. evansae*, sp22: *Ae. aegypti*, sp26: *Cx. quinquefasciatus*, sp31: *Ur. sp*).

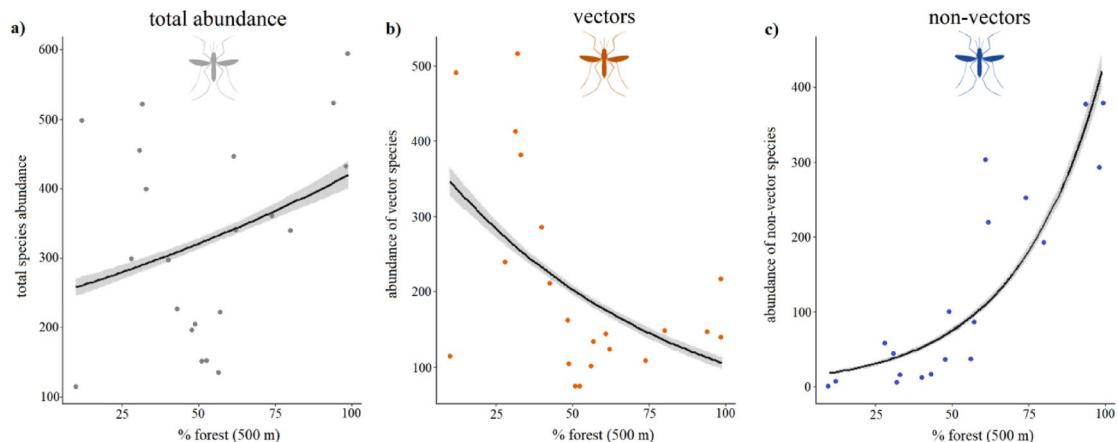


Fig. 5. Relationships between mosquito abundance—gray color (a), vector species—orange color (b), non-vector species—blue color (c) and percentage of forest cover at a radius of 500 m, modeled by generalized linear models. The gray shading represents the confidence interval (95%) for the generalized linear model fitted.

Although these species have already been reported in forest remnants and riparian forests in Mato Grosso do Sul⁶⁹, their occurrence throughout the landscapes on the Bodoquena Plateau is relevant from an epidemiological point of view. This region attract people from Brazil and other countries due to its ecotouristic activities, including snorkeling in clear waters, visits to rivers and streams with clear waters and waterfalls, and cave visits^{70,71}.

In our study, the loss of forest cover favored the emergence of potential vector species (Fig. 3, Supplementary Table 1). This relationship can also explain the strong link between the loss of culicid species and the increased risk of pathogen transmission in urban landscapes⁸. Moreover, the urbanization process positively affects the

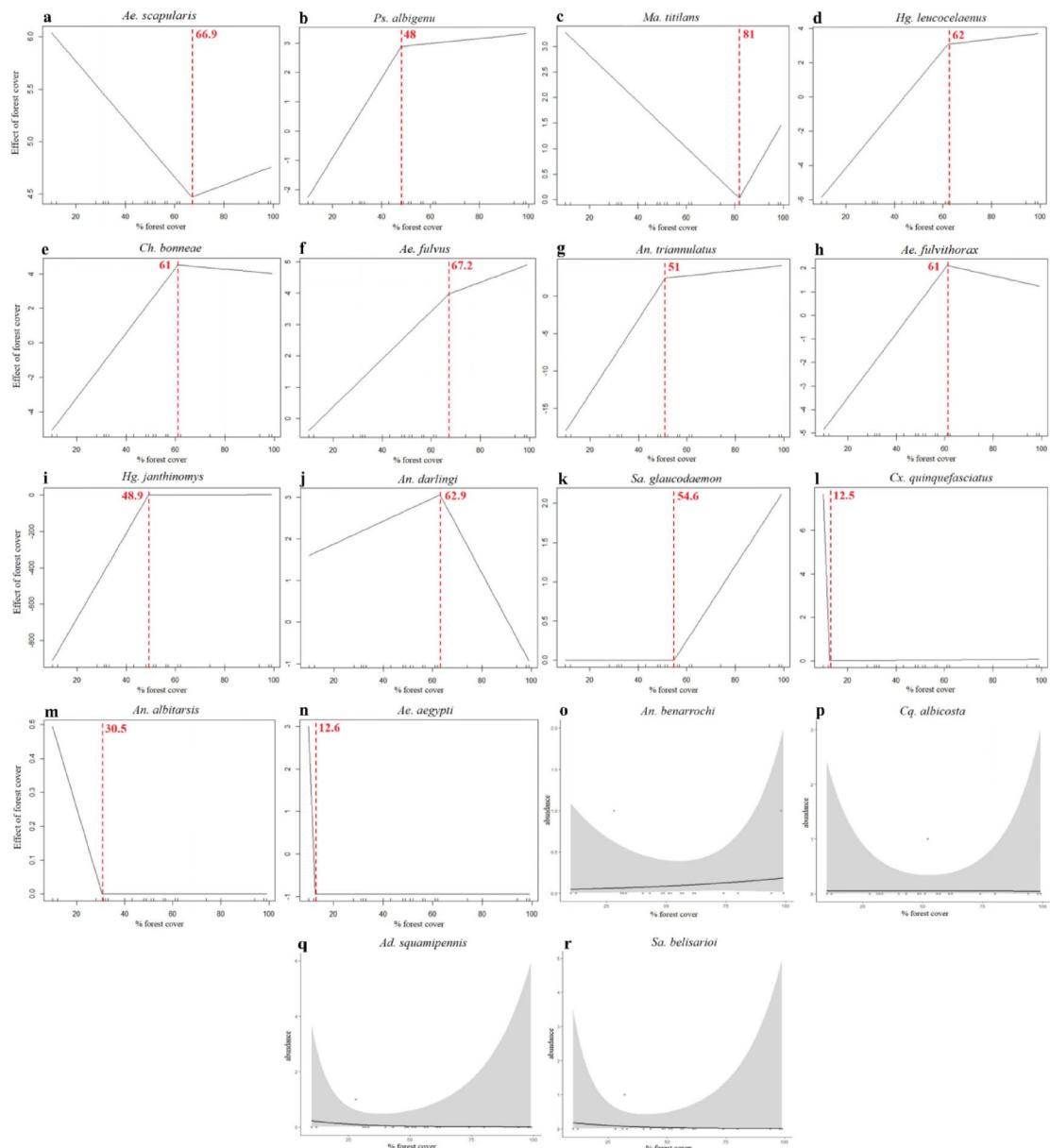


Fig. 6. Relationships between the abundance of each mosquito species and the percentage of native forest cover across landscape gradients on the Bodoquena Plateau, Cerrado hotspot in Mato Grosso do Sul, Brazil. The dashed red line indicates the threshold of forest cover of the species. The gray shading represents the confidence interval (95%) for the generalized linear model fitted. Letters (a) to (n) are the best fits for the piecewise regression model, and letters (m) to (r) are the best fits for the generalized linear model.

abundance of mosquitoes of medical importance⁹, and changes in land use and anthropogenic activities are highlighted as potential drivers of the emergence of viruses and arboviruses^{72,73}. The response of some species to forest cover may be related to the biological and ecological characteristics of mosquitoes, such as their preference for blood meals (zoophilic and anthropophilic), the availability of aquatic habitats for oviposition, the presence of animals and humans and microclimate factors^{36,74}.

Most studies on mosquitoes have detected the effects of forest cover on mosquito biodiversity, with an indication of potential impacts on the abundance of vector species and the risk of disease emergence^{68,75,76}. Studies on tropical biodiversity have shown that the loss of forests can cause non-linear responses in different groups, such as mammals, fish, amphibians, and aquatic insects^{30,31,77–79}. However, for mosquitoes, evidence of a non-linear response to gradients of native vegetation is still scarce^{9,80}. From this perspective, our study assessed the response of abundance (including total abundance and the abundance of vectors and non-vectors of different species) and detected thresholds for vector and non-vector species. We found that 46% of the species presented thresholds between 61 and 81%, 40% of the species presented thresholds between 54 and 30%, and 13% presented thresholds of approximately 12% forest cover. The vector species presented low to moderate forest cover

thresholds, demonstrating their versatility and ability to adapt to altered areas, which has potential implications for the emergence of arboviruses. For example, altered environments can force these species to migrate and, consequently, to change hosts and increase the contact of vectors with humans and domestic animals^{68,81}. With the remodeling of existing ecosystem boundaries, the dynamics between the environment–vector–human triad are altered, leading to the emergence of vector-borne zoonotic diseases³. Additionally, “pathogenic landscapes” serve as early warnings of environments prone to mosquito-borne disease transmission².

When the percentage of forest cover exceeds the threshold values, some aquatic and terrestrial organisms (e.g., dragonflies) are affected at the same time³¹. This congruent effect can be extrapolated to several mosquito species that use both environments during their life cycle, especially sylvatic species. On the other hand, the relationship between land use and habitat loss has increased the abundance of arboviral vectors, which occur in landscapes with medium and high degrees of anthropization⁷⁶. Two urban vector species were rare in this study (*Ae. aegypti* and *Cx. quinquefasciatus*), presenting thresholds of approximately 12% forest cover, being more abundant in landscapes with a high degree of human modification, demonstrating their relationship with altered and urban environments. In addition, six vector species were more likely to occur in landscapes with a medium to high degree of human modification, with thresholds ranging from 12 to 60% forest cover. We emphasize that as deforestation increases in the Cerrado hotspot, there is a clear loss of species and an increase in the presence of potential disease vectors for animals and humans.

In general, when the forest cover of mosquito species is less than 48%, it is negatively affected; in contrast, many vector species ultimately benefit from a decrease in native forest cover (e.g., *Ae. scapularis*, *Ma. titillans*, *An. darlingi*, *An. albitalis*, *Ae. aegypti*, *Cx. quinquefasciatus*). This main result has implications for public health because if a landscape loses more than ~ 50% of its forest cover, it can favor species that transmit diseases. Furthermore, maintaining the integrity of forest ecosystems, especially reducing deforestation, helps (1) maintain biodiversity, (2) maintain the natural balance between wild animals and their own pathogens, (3) decrease contact between vectors and domestic animals and humans, and (3) decrease the transmission of diseases, favoring the maintenance of human health^{82–84}.

In summary, we found strong evidence of the influence of forest cover on the abundance of mosquito species in the Cerrado hotspot. The relationships between increased forest cover and the total abundance of species and non-vector species can be clearly observed. On the other hand, vector species were associated with landscapes that presented a loss of forest cover. Information about mosquito distribution, particularly from this poorly studied region, is necessary to contribute to local and national vector surveillance strategies, including possible monitoring and risk assessment programs for the emergence of arboviruses and other diseases transmitted by mosquito vectors in Brazil.

Data availability

All data supporting the findings of this study are included within the article, supplementary material and available from the corresponding author, A.N.A. No datasets were generated or analysed during the current study.

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Author contributions

A.N.A.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft, Writing—review and editing. P.T.S.: Assisted in data analysis, Formal analysis, Writing—review and editing. F.A.S.F.: Conceptualization, Methodology, Visualization, Writing—review and editing. F.V.N.: Assisted in data analysis, Formal analysis, Writing—review and editing. W.P.T.: Conceptualization, Supervision. F.O.R.: Conceptualization, Methodology, Visualization, Supervision, Writing—review & editing.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to A.N.A.

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