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Research Article

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Land Use and Larval Habitat Increase *Aedes albopictus* (Diptera: Culicidae) and *Culex quinquefasciatus* (Diptera: Culicidae) Abundance in Lowland Hawaii

Katherine M. McClure,[1,2,4] Charlotte Lawrence,[3] and A. Marm Kilpatrick[1]

[1]Department of Ecology and Evolutionary Biology, University of California, Santa Cruz, CA, [2]Current address: Department of Microbiology, Immunology, and Pathology, Colorado State University, Fort Collins, CO, [3]Department of Biology, University of Hawaii, Hilo, HI, and [4]Corresponding author, e-mail: katt.m.mcclure@gmail.com

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Abstract

Vector abundance plays a key role in transmission of mosquito-borne disease. In Hawaii, *Aedes albopictus* (Skuse) (Diptera: Culicidae), the Asian tiger mosquito, has been implicated in locally-transmitted dengue outbreaks, while *Culex quinquefasciatus* Say (Diptera: Culicidae), the southern house mosquito, is the primary vector of avian malaria, a wildlife disease that has contributed to declines and extinctions of native Hawaiian birds. Despite the importance of these introduced species to human and wildlife health, little is known about the local-scale drivers that shape mosquito abundance across lowland Hawaii, where forest, agricultural, and residential land uses are prevalent. We examined landscape, larval habitat, and climate drivers of *Ae. albopictus* and *Cx. quinquefasciatus* abundance in eight lowland wet forest fragments on the Big Island of Hawaii. We found that the abundance of both species increased with the proportion of surrounding developed land and the availability of larval habitat, which were themselves correlated. Our findings suggest that conversion of natural habitats to residential and agricultural land increases mosquito larval habitats, increasing the abundance of *Ae. albopictus* and *Cx. quinquefasciatus* and increasing disease risk to humans and wildlife in Hawaii. Our results further indicate that while source reduction of artificial larval habitats—particularly moderately-sized human-made habitats including abandoned cars and tires—could reduce mosquito abundance, eliminating larval habitat will be challenging because both species utilize both natural and human-made larval habitats in lowland Hawaii.

Key words: *Culex*, *Aedes*, larval survey, land use, avian malaria

Mosquito-borne infectious diseases pose major concerns for human health and the conservation of wildlife, as highlighted by the rapid geographic spread and increasing incidence of mosquito-borne viruses in the past two decades including West Nile, dengue, and Zika viruses (Kilpatrick 2011, Bhatt et al. 2013, Musso et al. 2015, Weaver et al. 2015). Transmission of mosquito-borne pathogens is driven by interactions between the environment, hosts, vectors, and the pathogen, with disease emergence often preceded by the invasion of introduced mosquito species (Lounibos 2002, Weaver and Reisen 2010, Kilpatrick and Randolph 2012). Once established, the distribution and abundance of mosquito vectors play a key role in transmission dynamics, and vector abundance is thus the focus of many vector-borne disease control efforts (Dye 1992, Townson et al. 2005). Determining the ecological factors that influence mosquito abundance can enable mapping of higher risk areas and facilitates efforts to reduce transmission for both human and wildlife pathogens.

In Hawaii, two vector-borne pathogens, dengue virus, and avian malaria, have impacted human and wildlife health, respectively, and are transmitted by several introduced mosquito species, including *Aedes albopictus* (Skuse) (Diptera: Culicidae), the Asian tiger mosquito, and *Culex quinquefasciatus* Say (Diptera: Culicidae), the southern house mosquito (VanRiper et al. 1986, Effler et al. 2005, LaPointe et al. 2005, Adalja et al. 2012). *Ae. albopictus* is an invasive mosquito that is widespread throughout Hawaii. It is a known vector for at least 22 arboviruses including dengue, chikungunya, and Zika virus (Gratz 2004, Burt et al. 2012, Musso and Gubler 2016). In 2001, *Ae. albopictus* was identified as the main vector in the first outbreak of locally-transmitted dengue in Hawaii since World War II on three islands, and again in 2011 on Oahu where *Aedes aegypti* L. (Diptera: Culicidae) was thought to be absent (Effler et al. 2005, Adalja et al. 2012). It likely also contributed to a recent outbreak on the island of Hawaii in 2015–2016 (http://health.hawaii.gov/docd/dengue-outbreak-2015/). Understanding the drivers of *Ae.*

albopictus abundance is critical given the repeated outbreaks of dengue in Hawaii and the repeated introductions of other pathogens including Zika and Chikungunya (http://www.cdc.gov/zika/reporting/2017-case-counts.html; http://www.cdc.gov/chikungunya/geo/united-states-2017.html).

Cx. quinquefasciatus, the southern house mosquito, is a primary vector of several human diseases including lariasis and West Nile virus encephalitis, as well as wildlife diseases such as avian malaria (Bogh et al. 1998, Turell et al. 2002, LaPointe et al. 2005, Kimura et al. 2010). It was the first of six biting mosquito species introduced to Hawaii, and it spread throughout the main Hawaiian Islands following its introduction in 1826 (Hardy 1960). Cx. quinquefasciatus has contributed to the decline or extinction of many susceptible native Hawaiian birds by vectoring two introduced pathogens, avian pox (Poxvirus avium) and avian malaria (Plasmodium relictum; Warner 1968, VanRiper et al. 1986, Van Riper et al. 2002, LaPointe et al. 2005). Avian malaria transmission limits many native bird species to upper elevation forests where cooler temperatures reduce both Cx. quinquefasciatus population growth and avian malaria replication rates (VanRiper et al. 1986, LaPointe et al. 2010). Cx. quinquefasciatus is also a competent vector for West Nile virus, which could be introduced to Hawaii by multiple pathways and could severely impact both human health and native birds (Kilpatrick et al. 2004, LaPointe et al. 2009, Reisen et al. 2009).

Mosquito abundance is generally thought to be driven by interactions between climate, larval habitat, and host availability. Temperature and precipitation both have strong and sometimes nonlinear effects on multiple aspects of mosquito demography (Ciota et al. 2014). Increasing temperature speeds larval development and shortens the gonotrophic cycle in adults but decreases survival rates (Delatte et al. 2009, Ruybal et al. 2016). Precipitation can increase or decrease mosquito populations, depending on the intensity of rainfall, by creating or flushing larval habitats, and can increase adult mortality (Hayes and Downs 1980, Koenraadt and Harrington 2008, Jones et al. 2012). Ae. albopictus and Cx. quinquefasciatus both use container habitats for larval development, and especially human-made containers (Goff and van Riper 1980, Laird 1988, Yee 2008, Bartlett-Healy et al. 2012). In addition, Ae. albopictus often feeds predominantly on humans (Faraji et al. 2014), whereas Cx. quinquefasciatus feeds on a broader set of hosts (Farajollahi et al. 2011).

We examined drivers of Ae. albopictus and Cx. quinquefasciatus abundance in eight lowland forest fragments on the Big Island of Hawaii. We conducted a fine-scale larval habitat availability study, quantified surrounding land use, and obtained estimates of temperature and precipitation data for each site. Because both species are considered human commensals, we hypothesized that their abundance would increase with the proportion of developed land in the surrounding area, and with larval habitat availability. We did not have a priori hypotheses for the directional effects of rainfall or temperature since both can both increase and decrease mosquito abundance, as detailed above.

Methods

Study Sites and Mosquito Capture

We captured mosquitoes at six sites ranging from 18 to 349 m in elevation on the Big Island of Hawaii from July to August in 2011, and sampled those six sites and an additional two sites from May to August in both 2012 and 2013. Sites were located on forest fragments embedded in a landscape matrix of residential development, areas covered by lava from recent volcanic activity, and agricultural lands in and near Hilo, Hawaii (Fig. 1A). Each site consisted of 4–6 mosquito trap locations, and trap locations were located at least 150 m apart from each other. Sites and trap locations were accessed and connected by transects consisting of either hand-cut paths or small roads that traversed the forest. All sites had similar vegetative communities and were composed of relatively homogenous habitat. The plant community was dominated by the native ohia tree, Metrosideros polymorpha, in the overstory, with native and non-native shrubs, small trees, and ferns in the understory. All sites contained numerous invasive plant species including strawberry guava (Psidium cattleianum), melastoma (Melastoma septemnervium), and Coster's curse (Clidemia hirta) (Zimmerman et al. 2008).

Average annual temperatures range from 21.2 to 23.1°C across the study sites, with summer temperatures ranging from 22.5 to 24.2°C (Fick and Hijmans 2017, Fig. 1B). The study area receives substantial rainfall, ranging on average from 2,394 mm to 3,924 mm of precipitation/year (Giambelluca et al. 2013, Fig. 1C). Previous empirical and modeling work suggest that Cx. quinquefasciatus abundance does not exhibit strong seasonality at elevations below ~600 m in Hawaii, and are present and transmitting avian

Fig. 1. Maps of study sites in east Hawaii showing developed land, temperature, and precipitation. (A) Developed land, roads, and residential areas shown. The extent of the study area on the island of Hawaii is depicted in the upper right corner. Full site names are as follows: AIN, Ainako UH-Hilo; KMR, Keaukaha Miltary Reservation; PAN, Panaewa; SHP, W.H. Shipman property; NAN, Nanawale Forest Reserve; MAL, Malama Ki Forest Reserve; BRY, Bryson's Cinder Cone (Pu'u Kali'u); KEA, Keauohana Forest Reserve. (B) Interpolated mean annual temperature in Celsius. Lines are 100 m elevational contours. (C) Interpolated annual cumulative rainfall. Lines are 500 mm rainfall isoclines; the line west of MAL is 2,500 mm.