Network Analysis of Mosquito Habitats for Controlling Vector-Borne Pathogens

Daniel T. Citron[1], Héctor M. Sánchez C.[2], Sean L. Wu[2], Biyonka Liang[3], John M. Henry[1], David L. Smith[1]

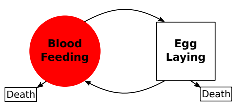
[1] Institute for Health Metrics and Evaluation, University of Washington, USA; [2] Divisions of Epidemiology and Biostatistics, School of Public Health, University of California Berkeley; [3] Department of Statistics, University of California Berkeley

BACKGROUND

The control of malaria and other vector-borne diseases represents a significant challenge to public health worldwide. Sustained transmission of malaria requires mosquitoes to carry parasites from one host to another. Here, we model the movement of mosquitoes, and by consequence the transmission of parasites, as an emergent property of the distribution of resources that mosquitoes need to survive. Mathematical modeling of mosquito ecology and activity enables quantitative assessments of how effective a mosquito population is at sustaining transmission of malaria, and also supports developing strategies for deploying interventions against the vector population.

METHODS

Malaria transmission occurs as a consequence of mosquitoes fulfilling their biological needs. We model the life cycles of mosquitoes as switching between different behaviors – e.g., **egg laying** and **blood feeding** – such that they navigate the landscape looking for places where they can achieve their next objective.



Landscape data: Using simulated geospatial covariate data, we generate synthetic point sets representing sites where mosquitoes seek to lay eggs and blood feed. An exponential movement kernel defines the probabilities of moving from each site to each other site.

Simulations: We simulate mosquito movement using a discrete time Markov chain model with transition probabilities determined by the distribution of resources, a movement kernel, and a behavioral switching model.

RESULTS

Example Simulated Mosquito Life Cycle

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Location	A	B	C	B	A	B	C	B	C	D	B	C	B	C	
Activity	Birth	Blood (F)eeding	(E)gg Laying	F	E	F	E	F	E	F	E	F	E	F	Death

Primary Bite

Parasite Incubation Period

Secondary Bites

Vectorial Capacity (VC): the number of ***infectious secondary bites*** arising from a single host on a single day

VC $\propto$ R_0 – the vector component of the basic reproductive number

The simulation model enables counting the secondary bites delivered by each mosquito at each site. Summing over all sites yields **Total VC**, which quantifies malaria transmission capability on the full landscape.

Vectorial Capacity Network: VC_{ij} = number of secondary bites delivered to site j that originated as a primary bite at site i, quantifying the distribution of secondary bites across the landscape. Essentially, this shows how mosquitoes may mediate parasite flow from one area to another.

Intervention Strategies: Within the model, it is possible to simulate vector control deployment by increasing probability of mosquito death occurring at certain sites. It may be that resources for interventions are limited in practice, but the VC Network suggests a strategy for optimally distributing vector control. Given the resources to only intervene at a limited number of sites, targeting sites based on their exported secondary bites is more effective at reducing VC in the full landscape than choosing sites at random.

DISCUSSION

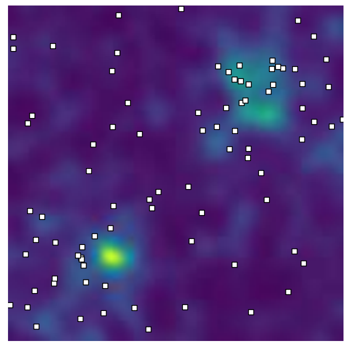
Our model of the mosquito's lifecycle, combined with a movement model and a geographical map of where mosquitoes blood feed and pursue other activities, produces a geographically explicit way to calculate Vectorial Capacity of the area. Additionally, the Vectorial Capacity Network illustrates how mosquitoes potentially transmit parasites from one site to another, and suggests possible quantitative strategies for intervening and reducing malaria transmission.

REFERENCES

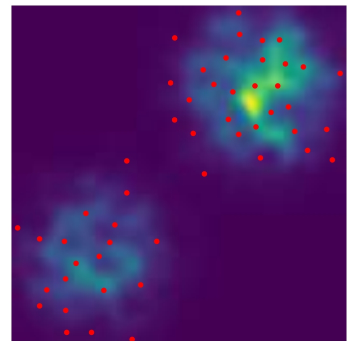
1. T. A Perkins *et al.*, Heterogeneity, Mixing, and the Spatial Scales of Mosquito-Borne Pathogen Transmission. *PLoS Computational Biology* **9,** (2013).
2. D. L. Smith *et al.*, Recasting the theory of mosquito-borne pathogen transmission dynamics and control. *Transactions of the Royal Society of Tropical Medicine and Hygiene* **108** (2014).
3. S.L. Wu *et al.*, Vector bionomics and vectorial capacity as emergent properties of mosquito behavior and ecology. (In preparation)

We acknowledge support from the Bill & Melinda Gates Foundation, Grant OPP1110495

Egg Laying Sites

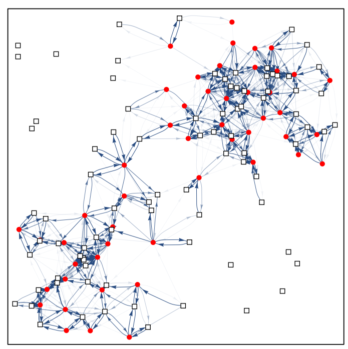


Blood Feeding Sites



Use simulated geospatial covariate data to generate point sets representing different types of mosquito habitats that support mosquito blood feeding or egg laying

Mosquito Movement Network



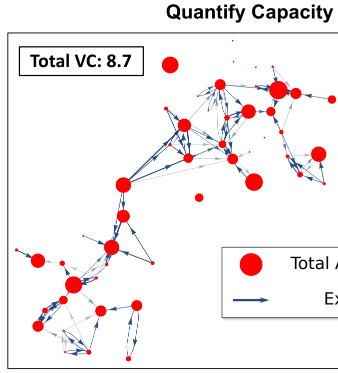
Combine:

- Map of site locations
- Mosquito behavior model
- Mosquito movement kernel

Generate a transition matrix describing how mosquitoes move around the landscape as they engage in different activities.

Blood Feeding Site
Egg Laying Site
Mosquito Movement

Quantify Capacity for Transmitting Malaria

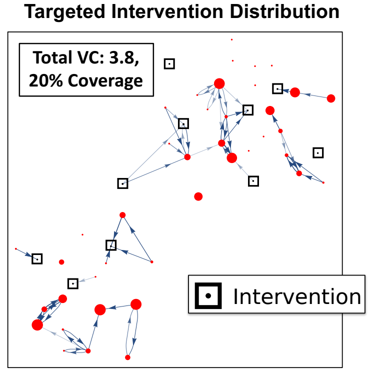


By tracing where mosquitoes blood feed as they traverse the landscape, enumerate the secondary infectious bites that transmit malaria from person to person.

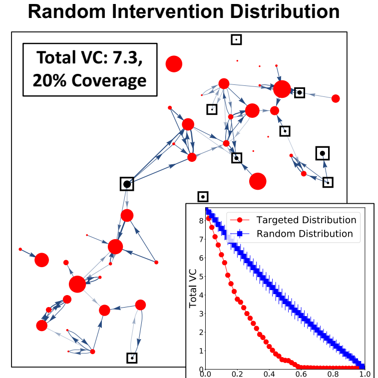
Vectorial Capacity Network: quantify how many secondary bites are exported from each site to each other site.

Total Attributable Secondary Bites
Exported Secondary Bites

Targeted Intervention Distribution



Random Intervention Distribution



Distributing interventions (e.g. spraying with insecticides) to the sites that source the most secondary bites is much more effective at reducing the Vectorial Capacity than distributing interventions at random.