CIMMID: Climate integrated model of mosquito-borne infectious disease

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Climate Integrated Model of Mosquito Borne Infectious Disease

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- 700 million cases of mosquito-born ID a year globally
- Highly sensitive to both climate change and landscape heterogeneity
- Fundamentally hard to model at large-scale

- Biologically-aware spatial clustering
  - Isolate static landscape effects from secular trend in environmental data
- Locally calibrated climate model

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- Spatially coupled mechanistic models of human risk
- Local systems of non-linear ordinary differential equations

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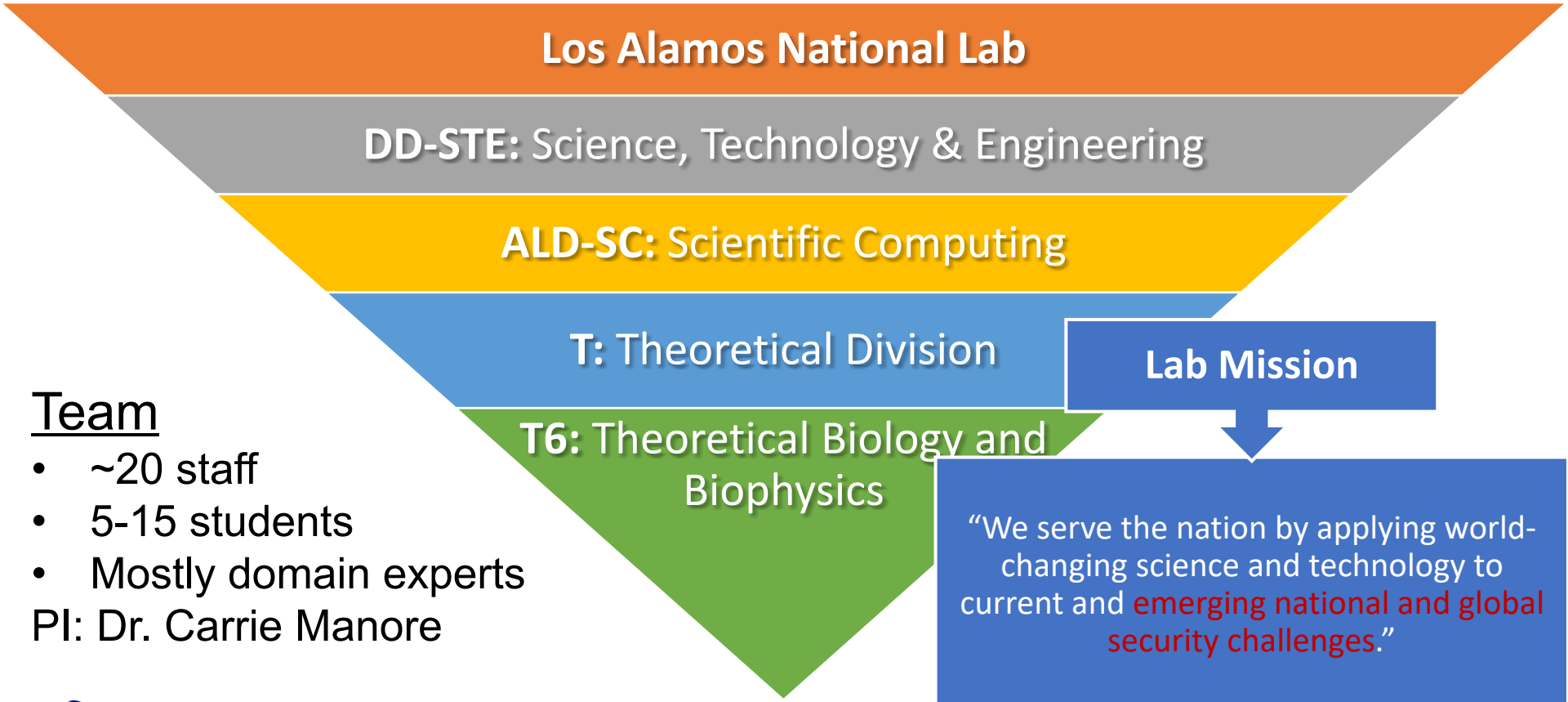


Team

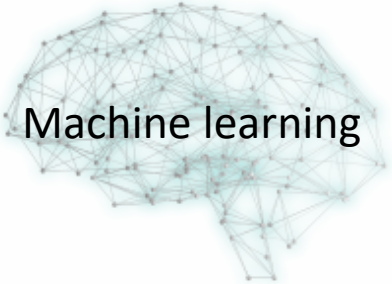
- ~20 staff
- 5-15 students
- Mostly domain experts

PI: Dr. Carrie Manore

Modeling Philosophy

(large scope)

CIMMID



(mechanistic)

(statistical)

SIR-type models

$$\dot{S} = -\beta \frac{I}{S+I}$$

$$\dot{I} = \beta \frac{I}{S+I} + \gamma I$$

Standard regression models

$$y_i = \beta_0 + \beta_1 x_{1,i} + \beta_2 x_{2,i} + e$$

$$e \sim N(0, \sigma)$$

(small scope)

Modeling Philosophy

(large scope)

Physics-informed ML

CIMMID

(mechanistic)

(statistical)

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CIMMID Workflow

CIMMID Modules

1. Select pathogen, region (e.g. North America), and time frame.

2. Divide space into unique, contiguous units based on their potential for supporting relevant mosquitos in (1). ⟵ Hydrological-population units (hydropop units or HU)

3. Calibrate climate model to historical data for each unit in (2) and predict env. data to end of the study period. ⟵ Earth System Model calibration

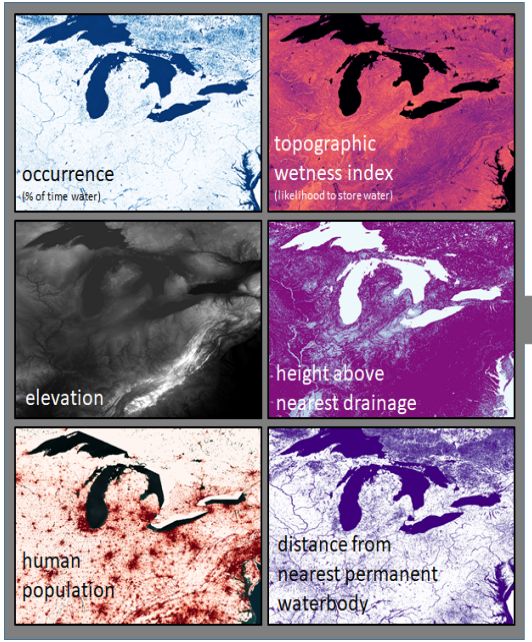
4. Predict mosquito density dynamics over study time frame given (3). ⟵ Process Based Model of mosquito development (PBM)

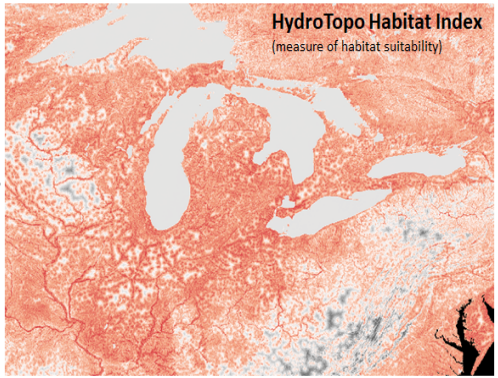
5. Predict human risk given (4). ⟵ Human risk model

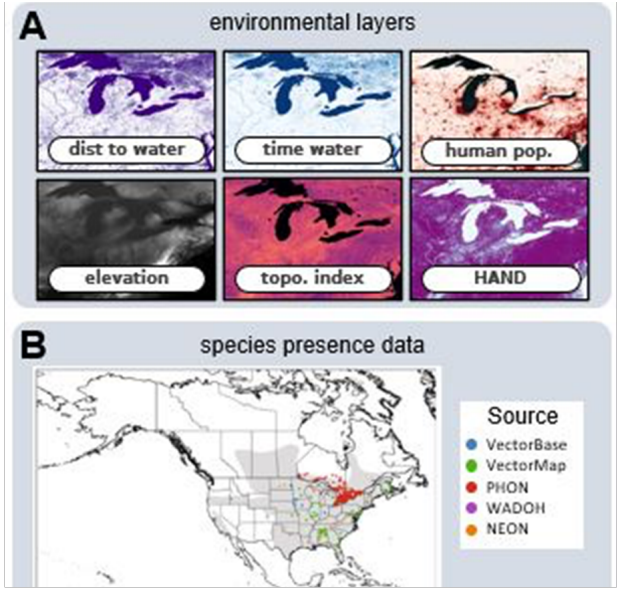
CIMMID core tech: Hydropop units

Mosquito abundance ~ landscape features + environmental variables

(static) (dynamic)





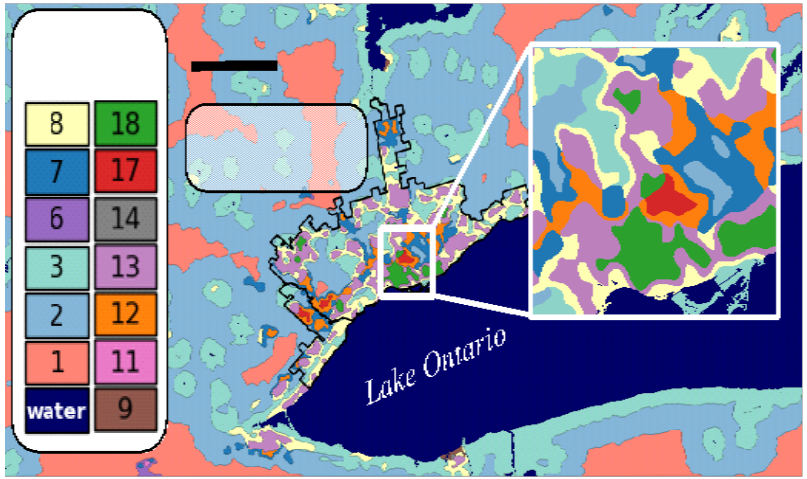


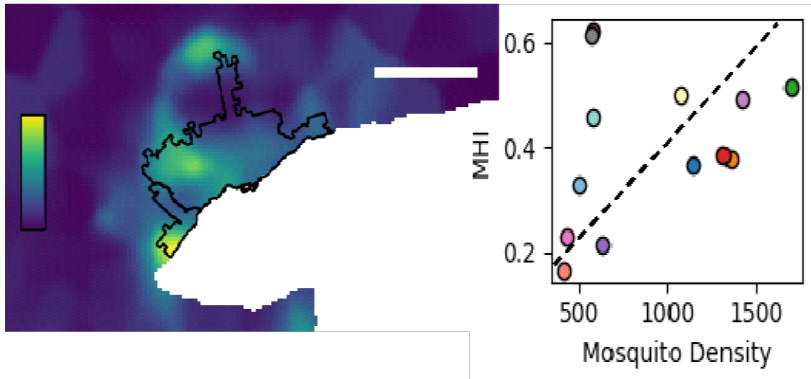
CIMMID core tech: Hydropop units

- Compute spatial Mosquito Habitat Index (MHI)
  - Satellite data: Static landscape features
    - Topology
    - Hydrological properties
    - Elevation
    - …
  - Mosquito presence data

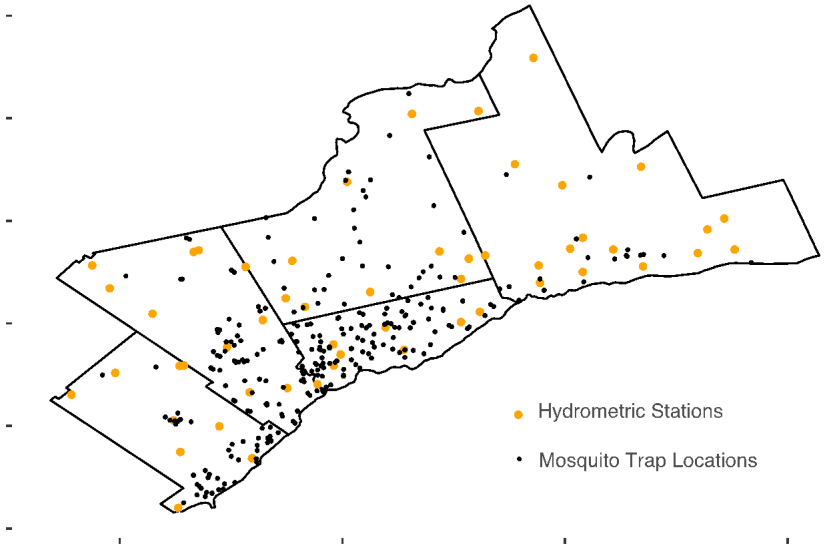
- Cluster values of MHI with human population density to define Hydropop Units (HUs)
  - HUs define long-term stable “homogeneity” regions

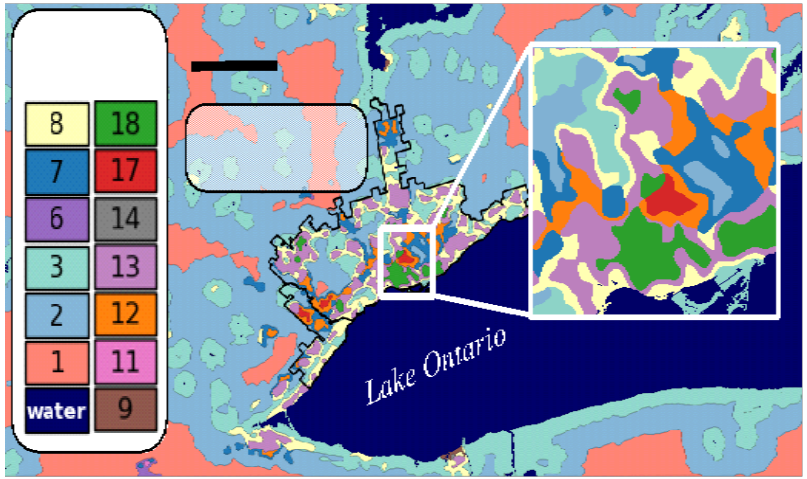
- Find contagious spatial units where MHI are all in the same cluster
  - Additional constraints (e.g. max/min HU area)

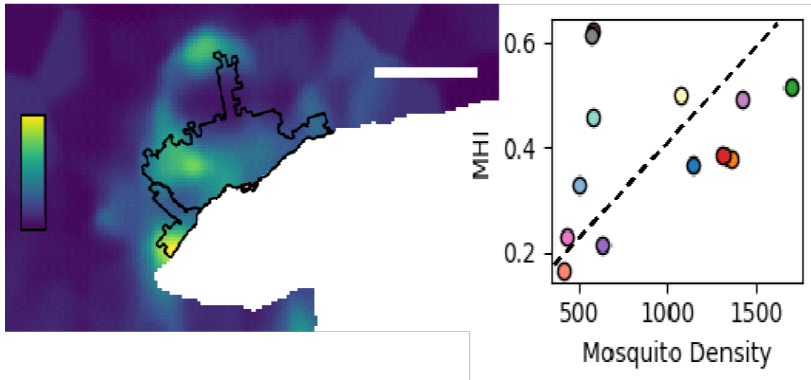




CIMMID core tech: Hydropop units

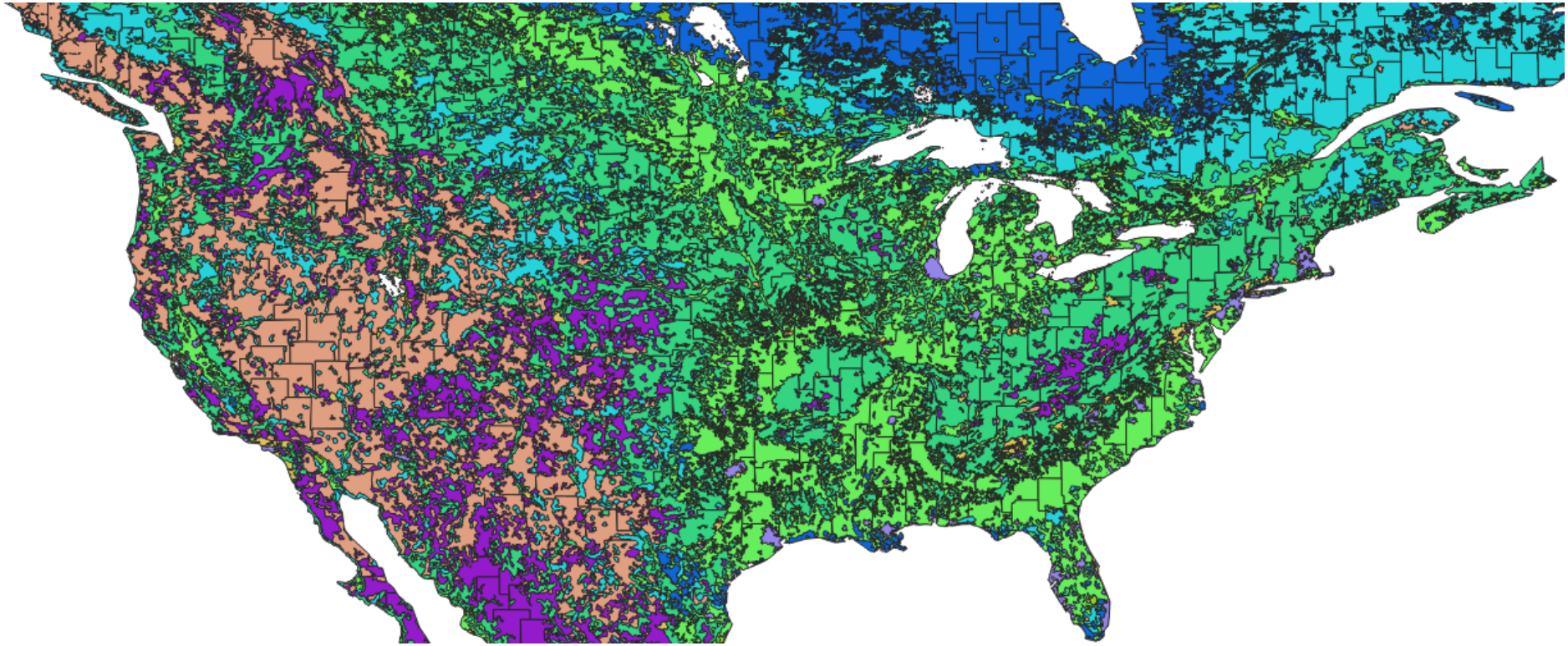




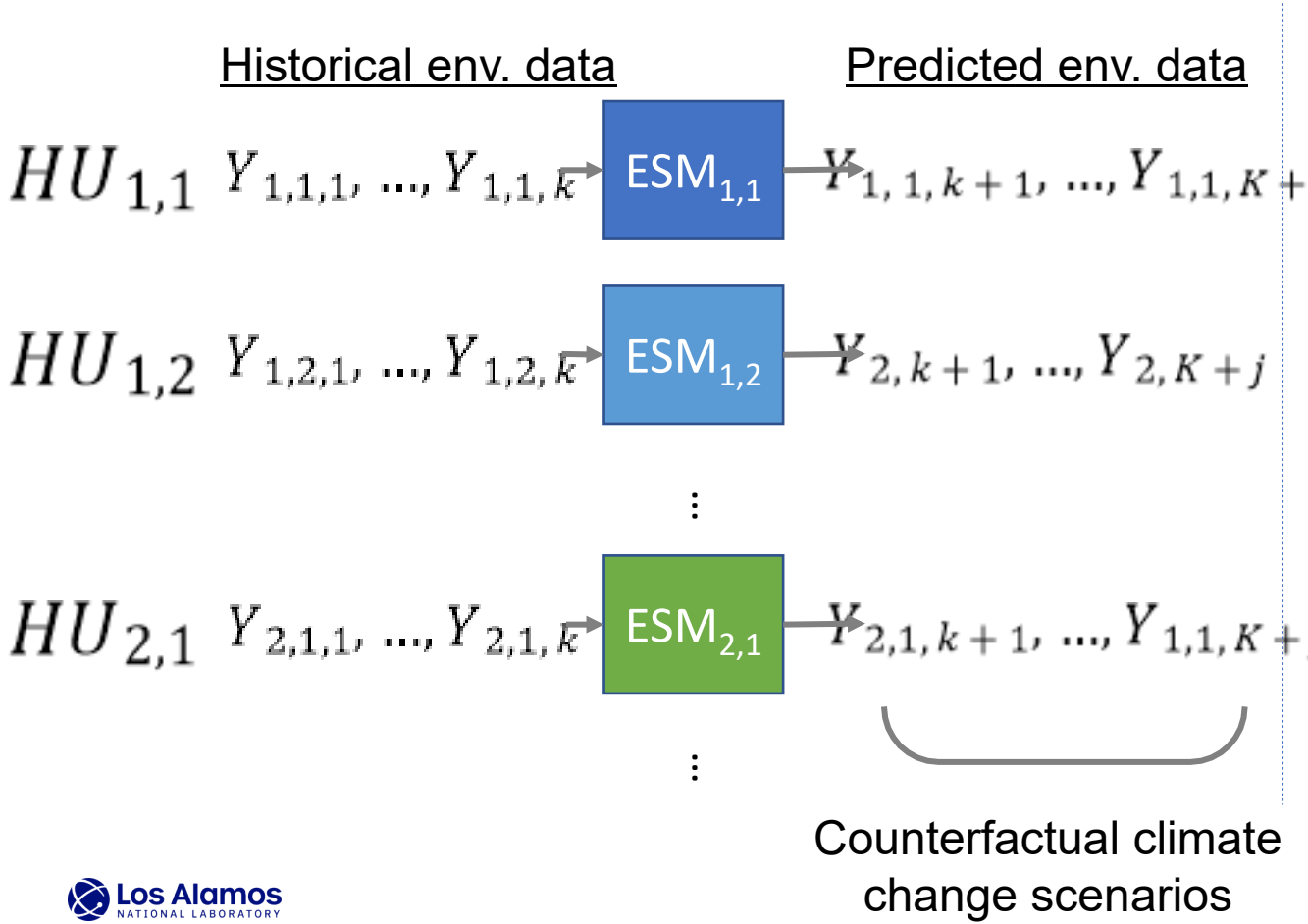


HUs facilitate simulation in regions with limited data

CIMMID core tech: Hydropop units

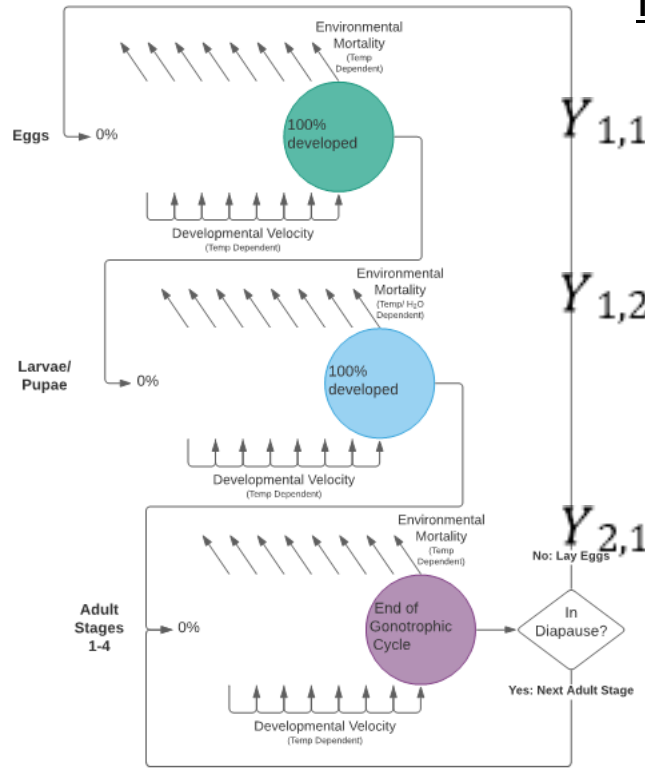


CIMMID core tech: Earth System Model (ESM) calibration



- Computational bottleneck
- Limits spatial resolution of HUs
- Emulator
- Exploit spatial structure
- Hypergraph representation
  - ELM homogeneity regions

CIMMID core tech: Process-Based Model of Mos. Dev.



Historical/predicted env. data

$$Y_{1,1,1}, \ldots, Y_{1,1,k}, \ldots, Y_{1,1,k+j} \rightarrow \text{PBM}_1 \rightarrow \text{Mosquito density over time } HU_{1,1}$$

$$Y_{1,2,1}, \ldots, Y_{1,2,k}, \ldots, Y_{1,2,k+j} \rightarrow \text{PBM}_1 \rightarrow \text{Mosquito density over time } HU_{1,2}$$

$$\vdots$$

$$Y_{2,1,1}, \ldots, Y_{2,1,k}, \ldots, Y_{2,1,k+j} \rightarrow \text{PBM}_2 \rightarrow \text{Mosquito density over time } HU_{2,1}$$

$$\vdots$$

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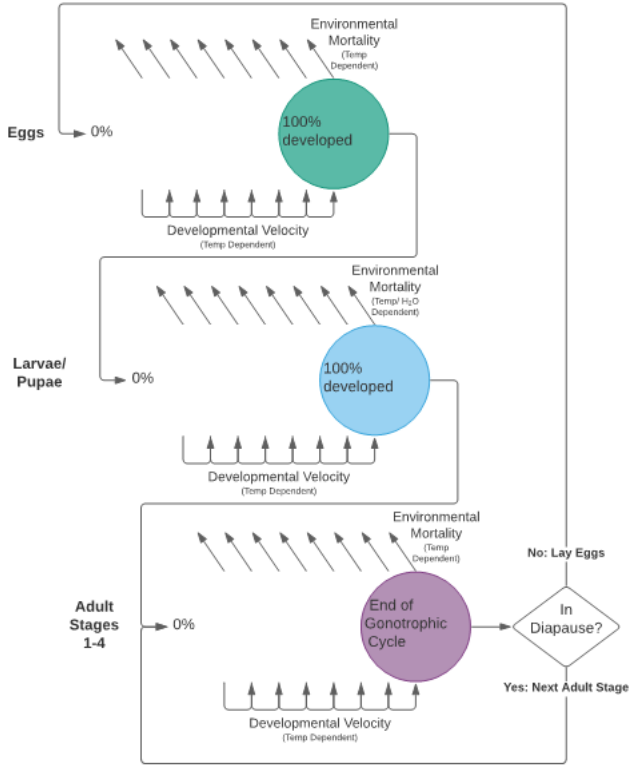
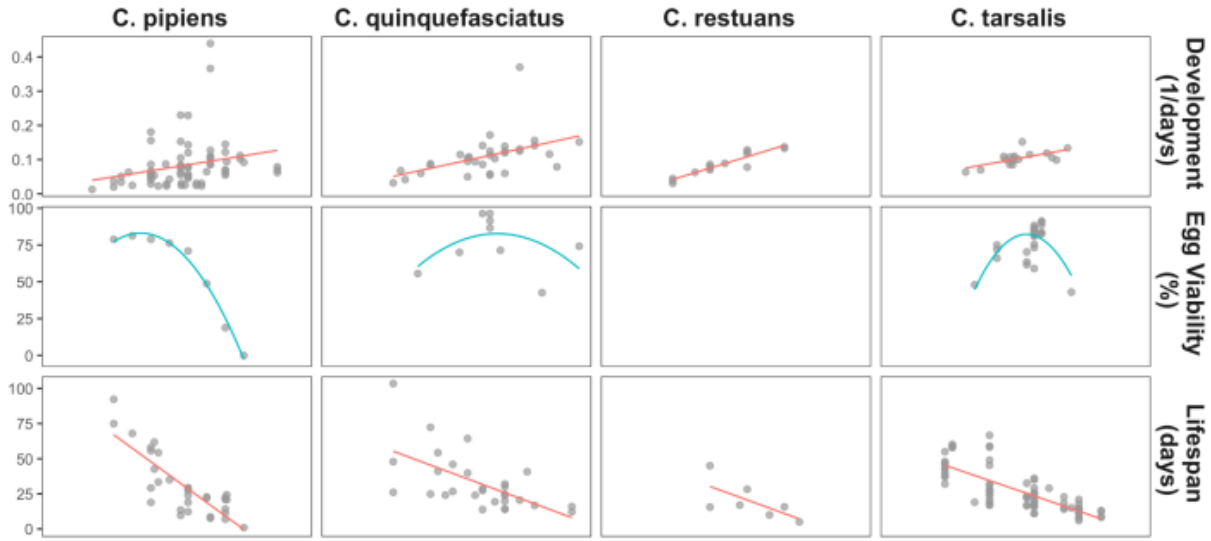
D P Shutt et al., **A Process-based Model with Temperature, Water, and Lab-derived Data Improves Predictions of Daily Culex pipiens/restuans Mosquito Density**, Journal of Medical Entomology, 2022

CIMMID core tech: Process-Based Model of Mos. Dev.





- Integrate experimental constraints
- Reduce model complexity (species clustering)

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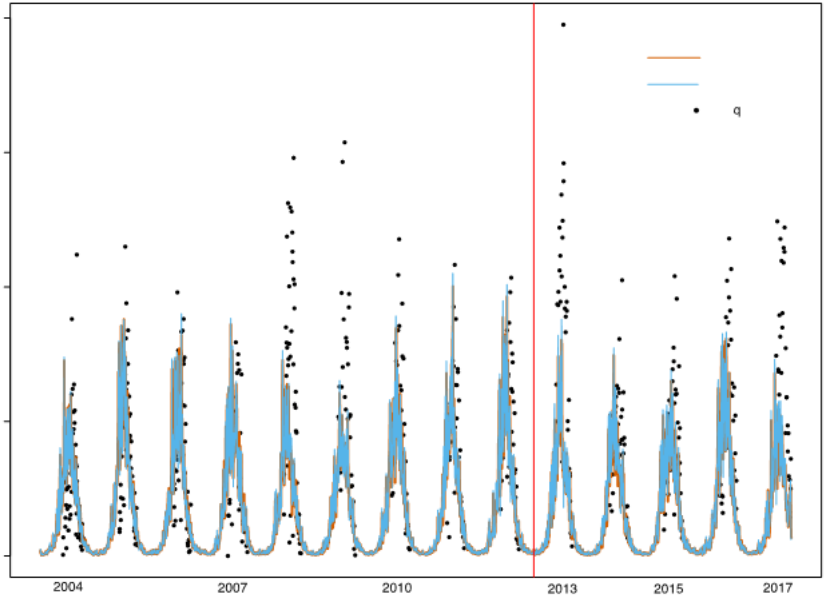
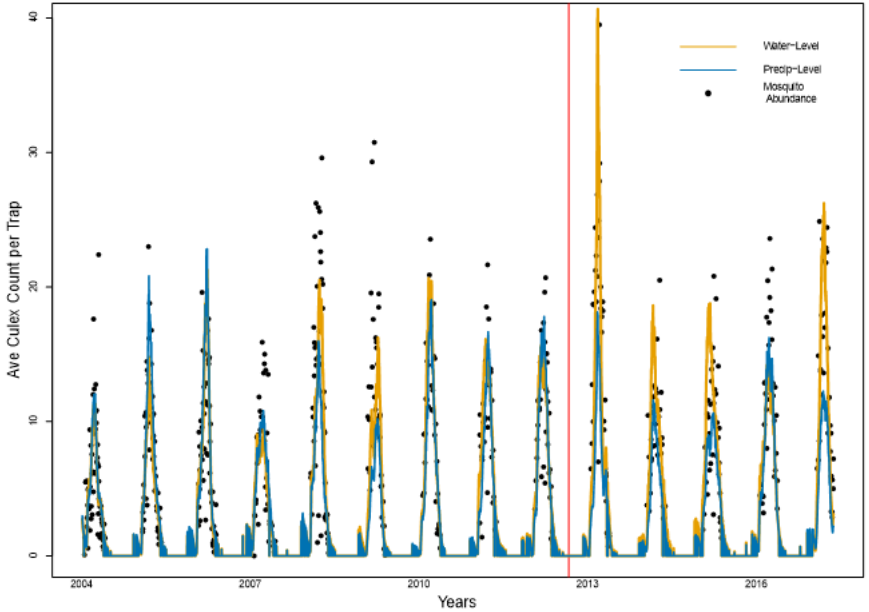
CIMMID core tech: Process-Based Model of Mos. Dev.

Generalized linear model



Process-based model



CIMMID core tech: Human risk model

$$
\begin{aligned}
\frac{dS_h}{dt} &= -\lambda_h(t)S_h \\
\frac{dE_h}{dt} &= \lambda_h(t)S_h - \sigma_h E_h \\
\frac{dI_h}{dt} &= \sigma_h E_h - \gamma_h I_h \\
\frac{dR_h}{dt} &= \gamma_h I_h \\
\frac{dS_v}{dt} &= h_v(N_v)N_v - \lambda_v(t)S_v - \mu_v S_v \\
\frac{dE_v}{dt} &= \lambda_v(t)S_v - \sigma_v E_v - \mu_v E_v \\
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CIMMID core tech: Human risk model

Human risk dynamics

$$\frac{dS_h}{dt} = -\lambda_h(t) S_h$$

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Mosquito risk dynamics

CIMMID core tech: Human risk model

Human risk dynamics

$$\frac{dS_h}{dt} = -\lambda_h(t) S_h$$ ← Human population size estimated from census data

$$\frac{dE_h}{dt} = \lambda_h(t) S_h - \gamma_h E_h$$

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Mosquito risk dynamics

CIMMID core tech: Human risk model

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Mosquito population dynamics given by PBM for given HU

$$\frac{dE_v}{dt} = \lambda_v(t) S_v - \gamma_v E_v - \mu_v E_v$$

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Mosquito risk dynamics

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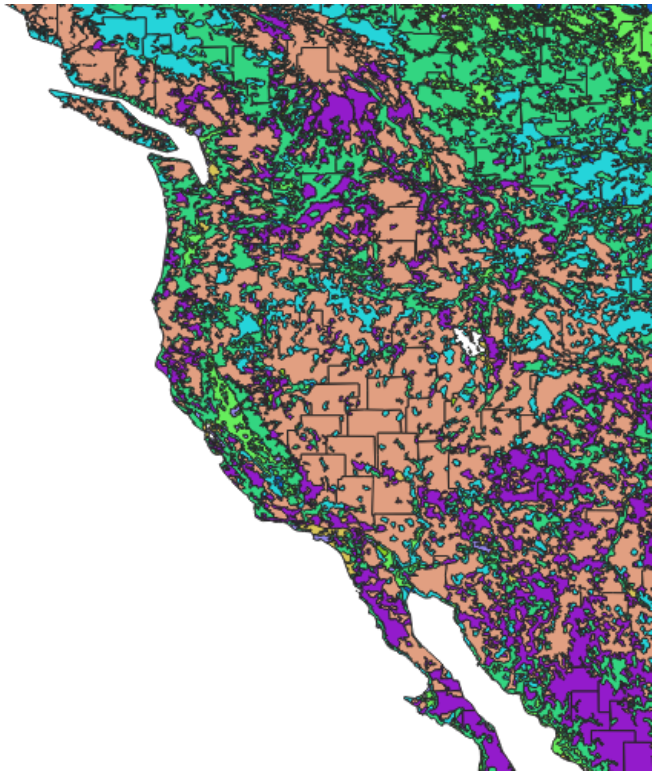
Mosquito risk dynamics

- Force of infection terms
  - Overall biting rate
    - Generally known or constrained
  - Behavioral ecology of biting
    - Periodicity estimated from historical case count data
  - Coupling between HUs
    - Birds for West Nile Virus
    - Infected humans for Dengue

CIMMID: Bringing it all together



Using tons of different data we can

- Define local landscape heterogeneity
- Predict environmental variables under climate change
- Predict mosquito populations
- Predict human risk given human density and infected mosquito populations

Next steps

- Validating large-scale runs of CIMMID for WNV in US and Canada
- Integrating mitigation strategies into models to bring closer to “closed loop”

CIMMID core tech: Development status

Hydropop units	ELM calibration	Mosquito model	Human risk model
Count data	Develop emulator	Implement as partial diff equation	Coupling for prototype WNV model
Broader control parameters	ELM homogeneity regions	Harden random effects model for HU-class specific estimation	Validation of estimation for biting behavior
Automatic cluster detection	Validation on known watershed systems	Validation with A. aegypti	Validation of historical case count predictions
Mature	Developing	Developing	In-progress

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CIMMID Team 2019

National Institutes of Health

CDC CENTERS FOR DISEASE CONTROL AND PREVENTION

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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