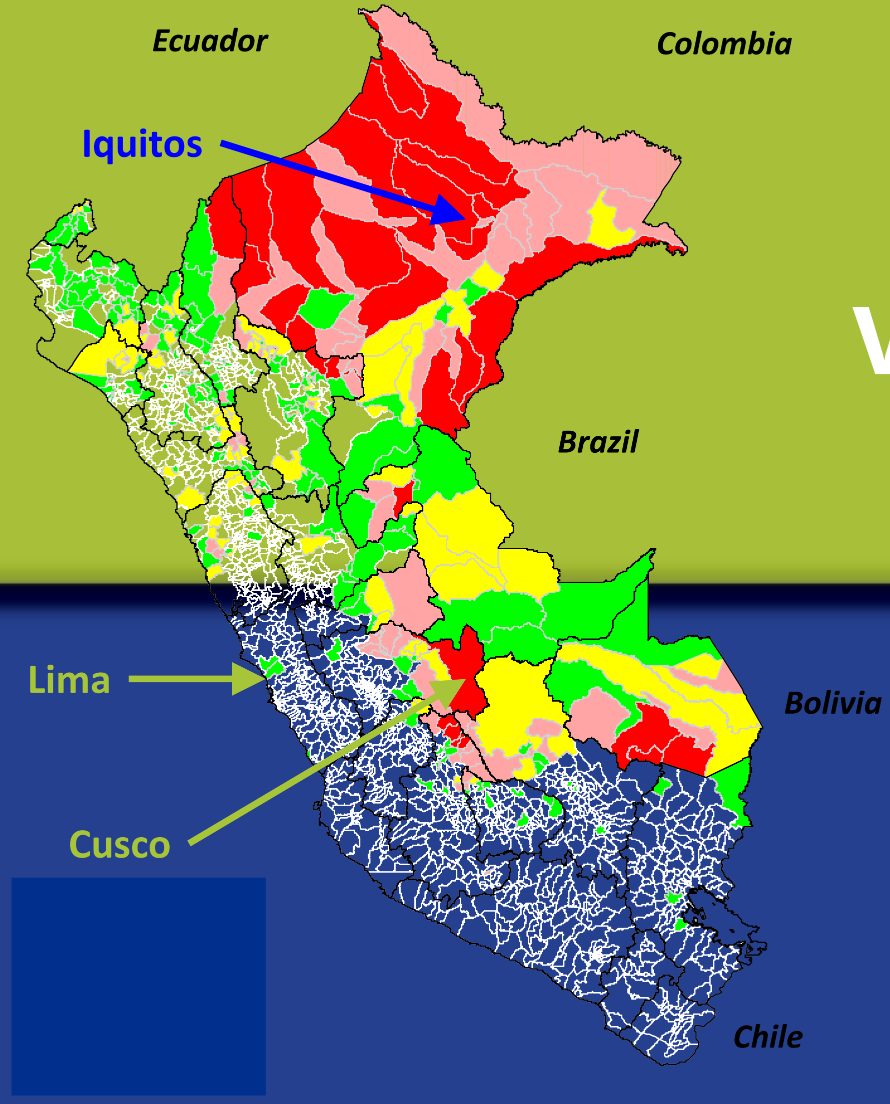

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An Early Warning System for Vector-Borne Disease Risk in the Amazon

NASA Project NNX15AP74G
William Pan, Duke University

Health and Air Quality Applications Programs Review
September 18-19, 2018
Burlington, VT

Project Team

Duke University

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Johns Hopkins University

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Carlos Alvarez, MS	DIRESA-Loreto
Yuri Escajadillo, PhD	SENAMHI
Luis Alfaro, PhD	SENAMHI

Project Summary
NNH13ZDA001N-Health

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OBJECTIVE:

Develop an **early warning system for malaria** in the Peruvian Amazon and evaluate the expansion of the system to other diseases and Amazon regions.

GEOGRAPHIC SCOPE:

Primary : Peru (Loreto), Ecuador (Napo, Orellana, Succumbios)
Secondary locations: Colombia, Western Brazil (Acre)

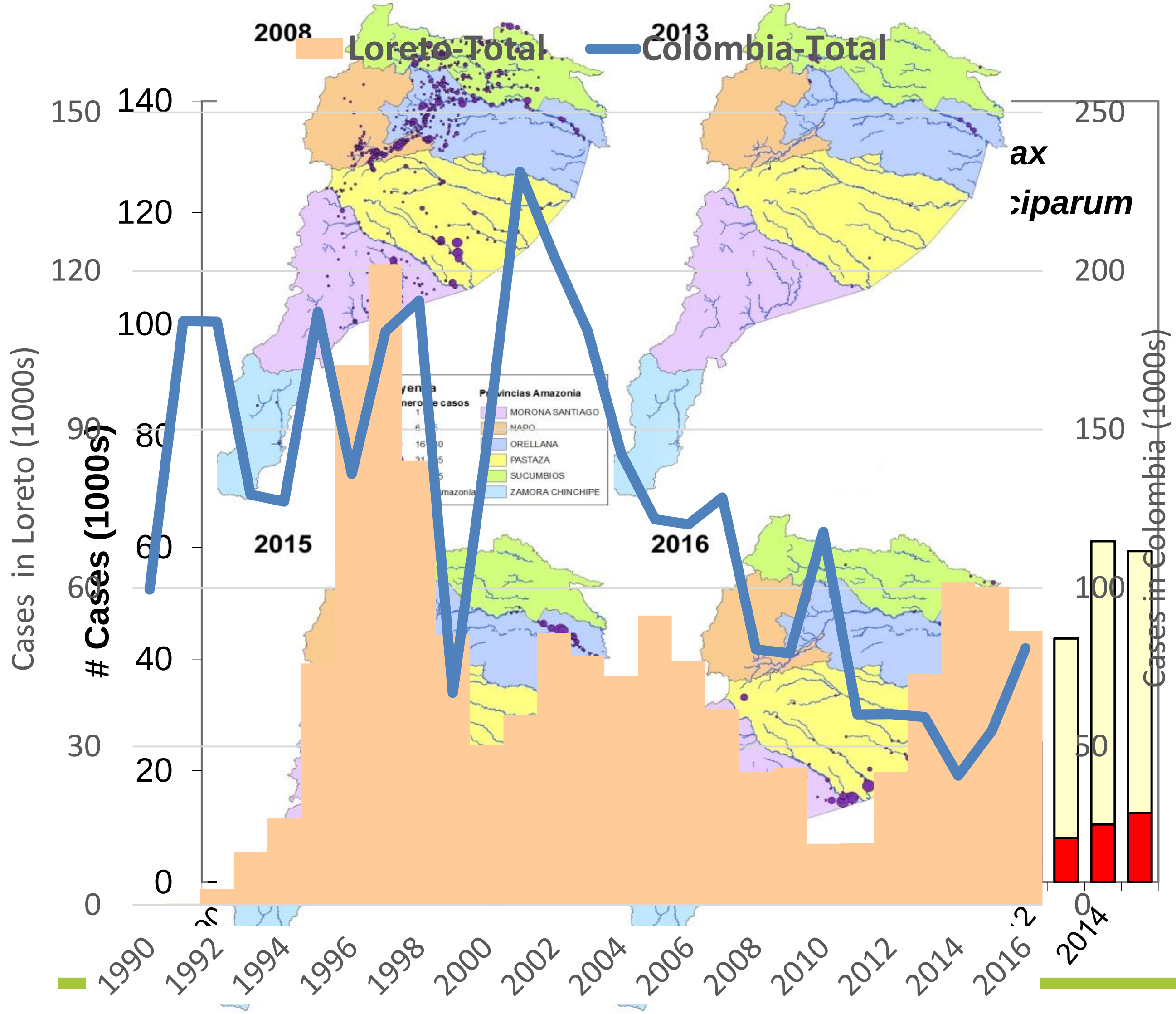
SOCIETAL BENEFIT:

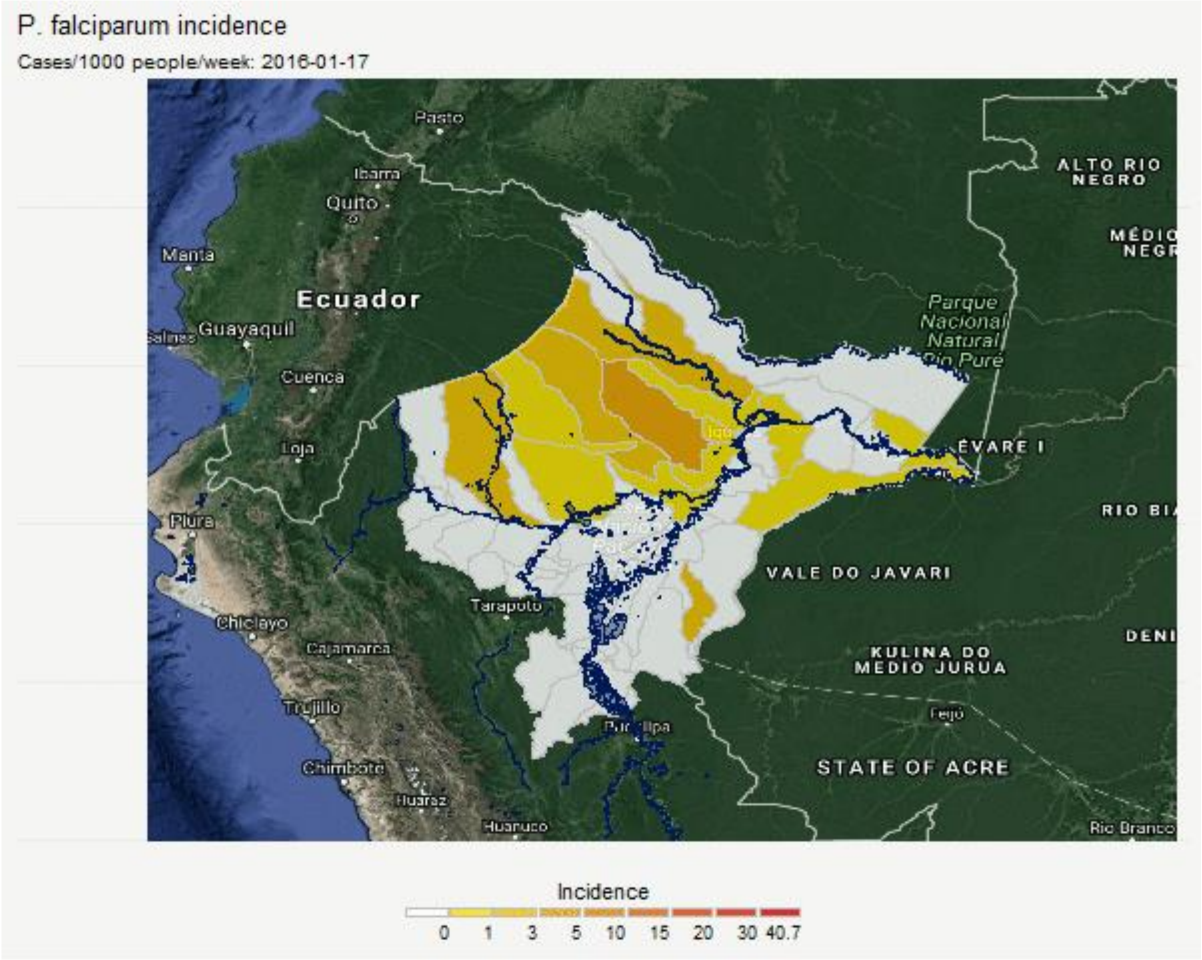
Improved / targeted interventions; Application of components to other diseases and climate events

EARTH OBSERVATIONS / MODELS / TECHNOLOGIES APPLIED:

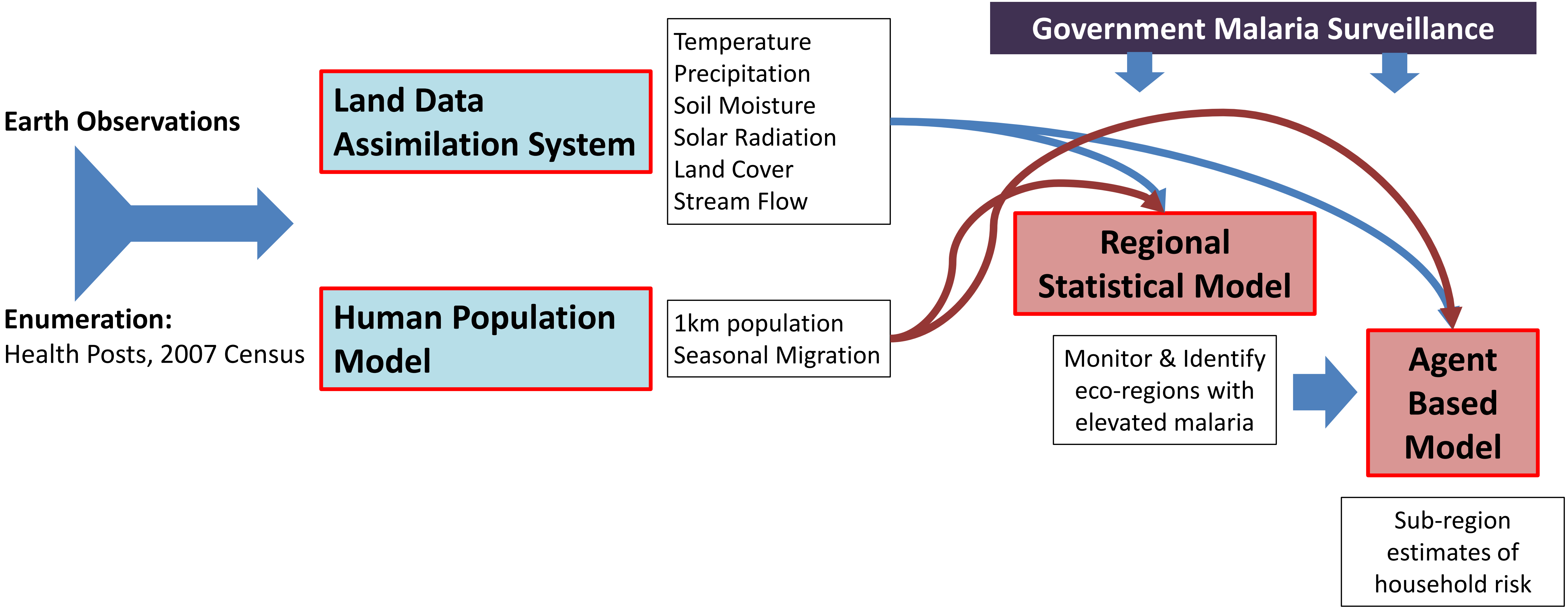
Land Data Assimilation System (LDAS) – MODIS, LandSAT, GRACE, TRMM, GPM, SMAP, GOES

Motivation: Malaria resurgence in the Americas





Overview of our Approach



Summary of Milestones (Year 3)
Administrative

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- **Project Administration:**
  - Monthly conference calls
  - Stakeholder meeting, October 2018 in Quito, Ecuador and Lima, Peru. The main objective is long-term sustainability and technology transfer
  - Data acquisition: updated malaria surveillance data in Peru to February 2018; malaria incidence data in Ecuador related to 2016 outbreak
  - Spin-off grant applications to NOAA, RFF and NASA (not funded), FAO (pending), Ecuador Government (pending)

- **Personnel:**
  - No major changes

Summary of Milestones (Year 3)
Scientific

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- **Progress by Component:**
  - LDAS
    - Performed evaluation of estimated evapotranspiration over the Peruvian & Ecuadorian Amazon
    - Evaluate the impact of Madden-Julian Oscillation (MJO) on rainfall seasonal to sub-seasonal (S2S) climate variability
    - Conducted a preliminary objective climate regionalization analysis using S2S precipitation hindcast
  - Human Population Model
    - Completed assessment of human population model (5KM scale)
  - Statistical Model
    - Completed Socio-environmental regional forecast model and performed forecast error estimates
    - Finalizing Bayesian distributed lag model for district-level forecasting model
  - ABM
    - Published study on local-scale migration effects on malaria transmission
    - Submission of study evaluating long-term migration and asymptomatic malaria effects on malaria incidence

Summary of Milestones (Year 3)
Scientific

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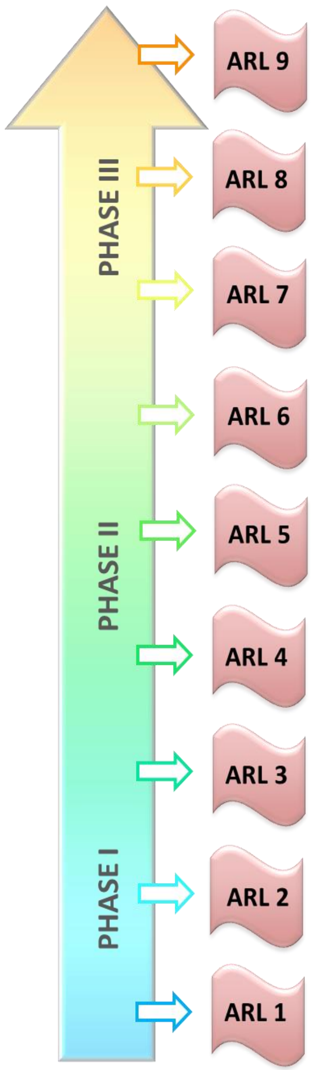
- **Extensions of EWS**
  - Cutaneous Leishmaniosis
    - Completed field study of CL transmission factors, began evaluation of LDAS product in informing transmission
  - Mercury exposure
    - Used LDAS to understand Hg cycling in the environment. Pursuing external funding for extended research
- **Dissemination:**
  - Pan, WK. "An Early Warning System for Malaria in the Amazon" Institute for Disease Modeling Symposium, Session: Malaria in Low-Transmission Settings, Bellevue, WA, April 16-18, 2018
  - Zaitchik, B. (2018) An Environmentally-Informed Malaria Risk Warning System for the Western Amazon. The Malaria Institute. Johns Hopkins University. January 26, 2018.
  - Pizzitutti, F., WK Pan, BF Feingold, B Zaitchik, CA Alvarez and CF Mena (2018) "Out of the net: An Agent-Based Model to study human movement influences on local-scale malaria transmission." PLoS ONE, 13(3): e0193493. https://doi.org/10.1371/journal.pone.0193493
  - Pizzitutti, F., BF Feingold, B Zaitchik, G. Salmon-Mulanovich, CF Mena and WK Pan, "Modeling asymptomatic infections and word-related human circulation as drivers of unstable malaria intransmission in low prevalence rsesd" in review *Acta Tropica*

Challenges & ARL

- Shift Francesco from Duke to JHU
- New President and Ministers of Health (Ecuador & Peru)
- Malaria epidemic (Ecuador, Peru, Colombia)
- Limited intervention data
- Modeling seasonal migration cannot be validated



Starting ARL = 4 *(8/2015)*
- System components have been published and have been shown to work together

ARL by component *(9/2018)*
- LDAS = 7
- Human Pop = 7
- Statistical Model = 7
- ABM = 7

Goal ARL = 8

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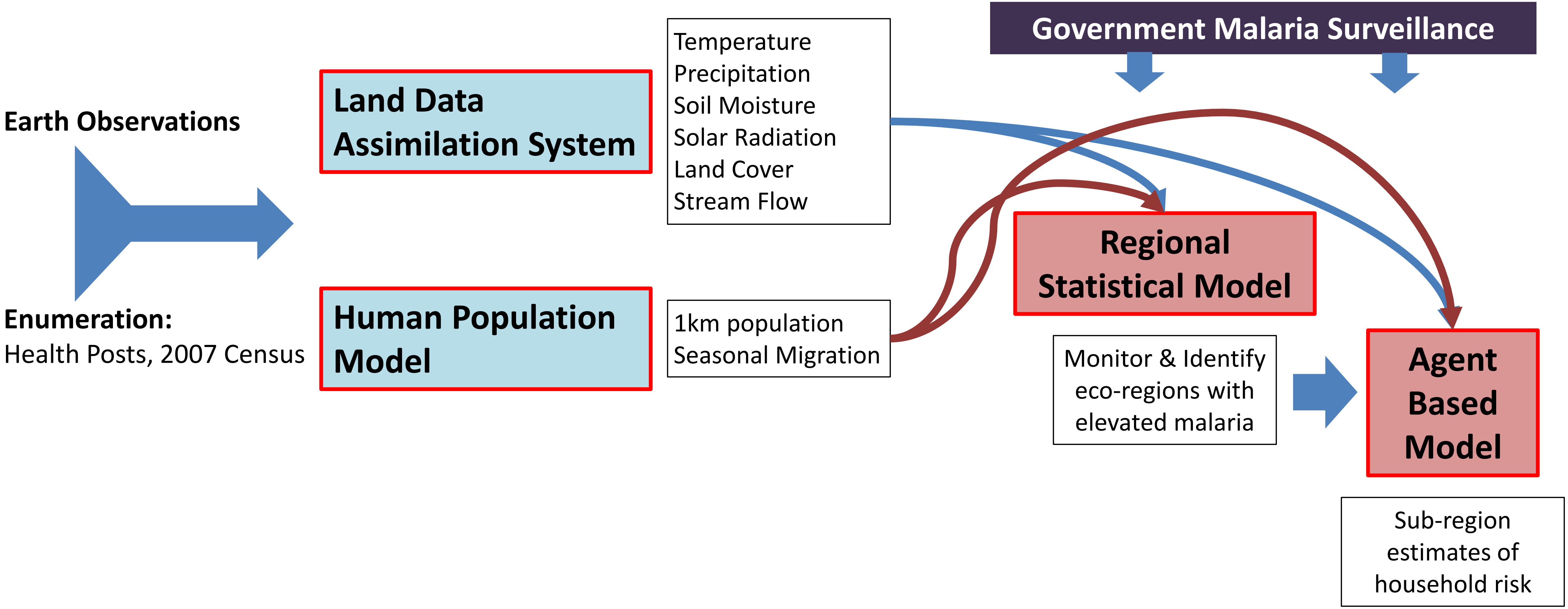
Malaria Early Warning System Component Updates

LDAS

Population

Statistical & ABM

Overview of our Approach

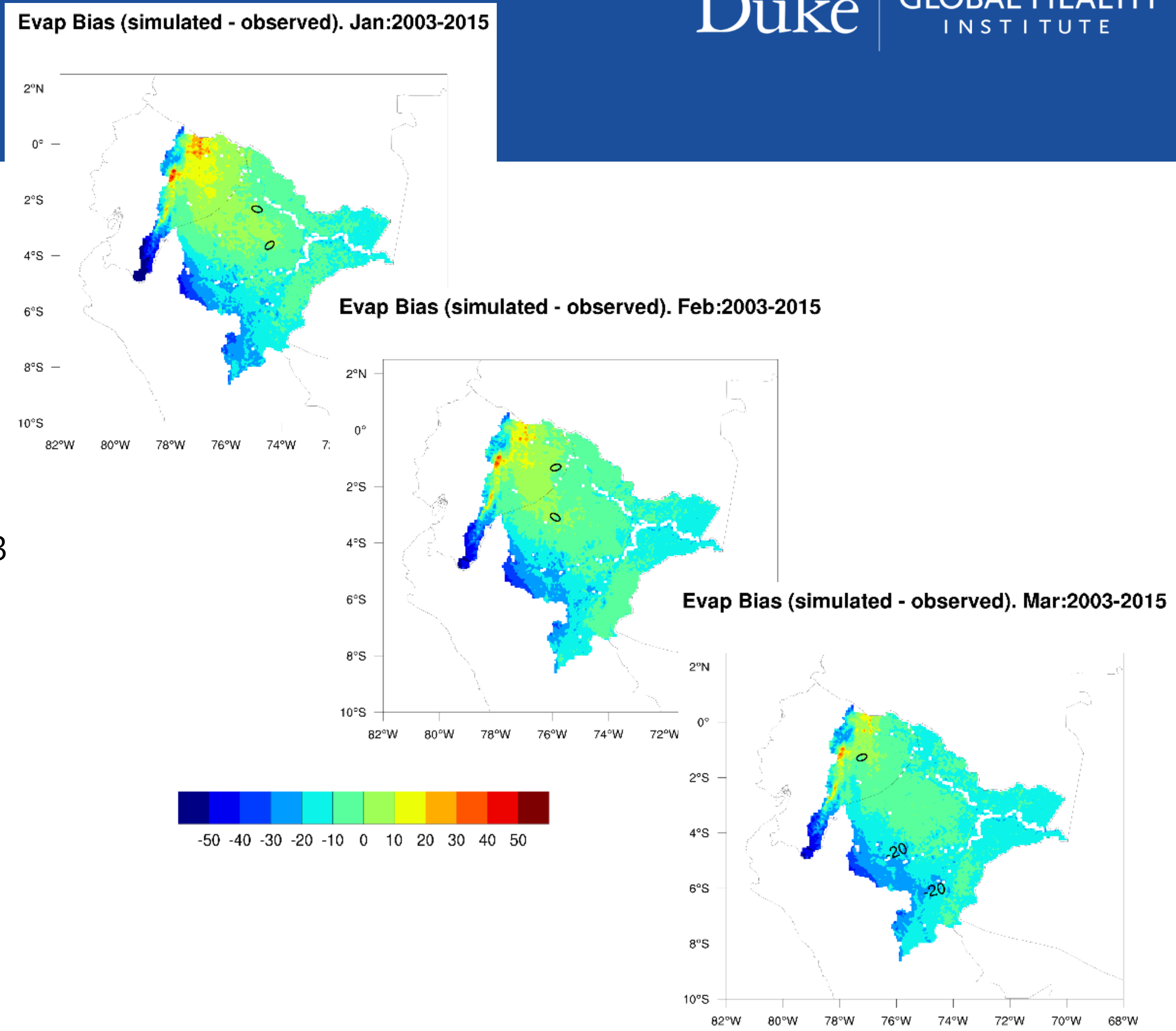


LDAS

LDAS provides environmental descriptors on a daily, 1km scale

UPDATES

- **Compared the estimated evapotranspiration by LDAS to satellite observed evapotranspiration** across the Peruvian and Ecuadorian Amazon (from ALEXI), from 2003 to 2015
- Performed a diagnostic analysis of the relationships between the **activity and phases of the MJO** by using the operational Real-Time Multivariate MJO index (RMM) and a regional index (EOF1)
- Evaluated the skill of selected National Multi-Model Ensemble (NMME) global forecast systems in Northwest South America (NWSA) through an approach designed to address spatial bias



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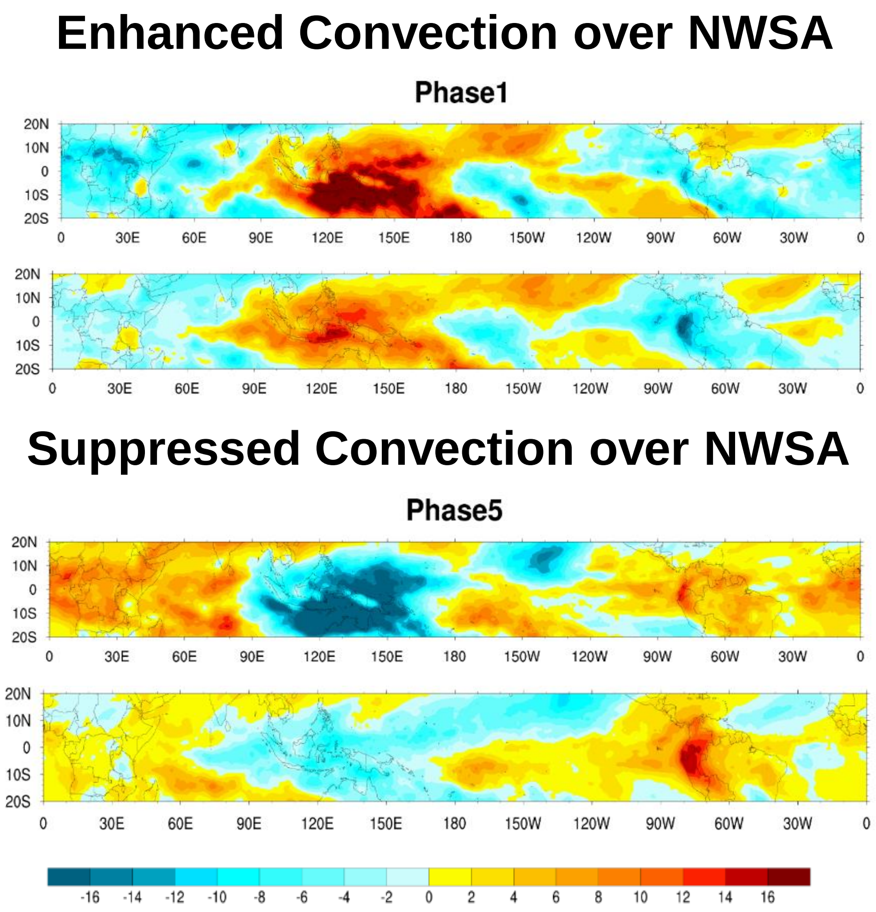


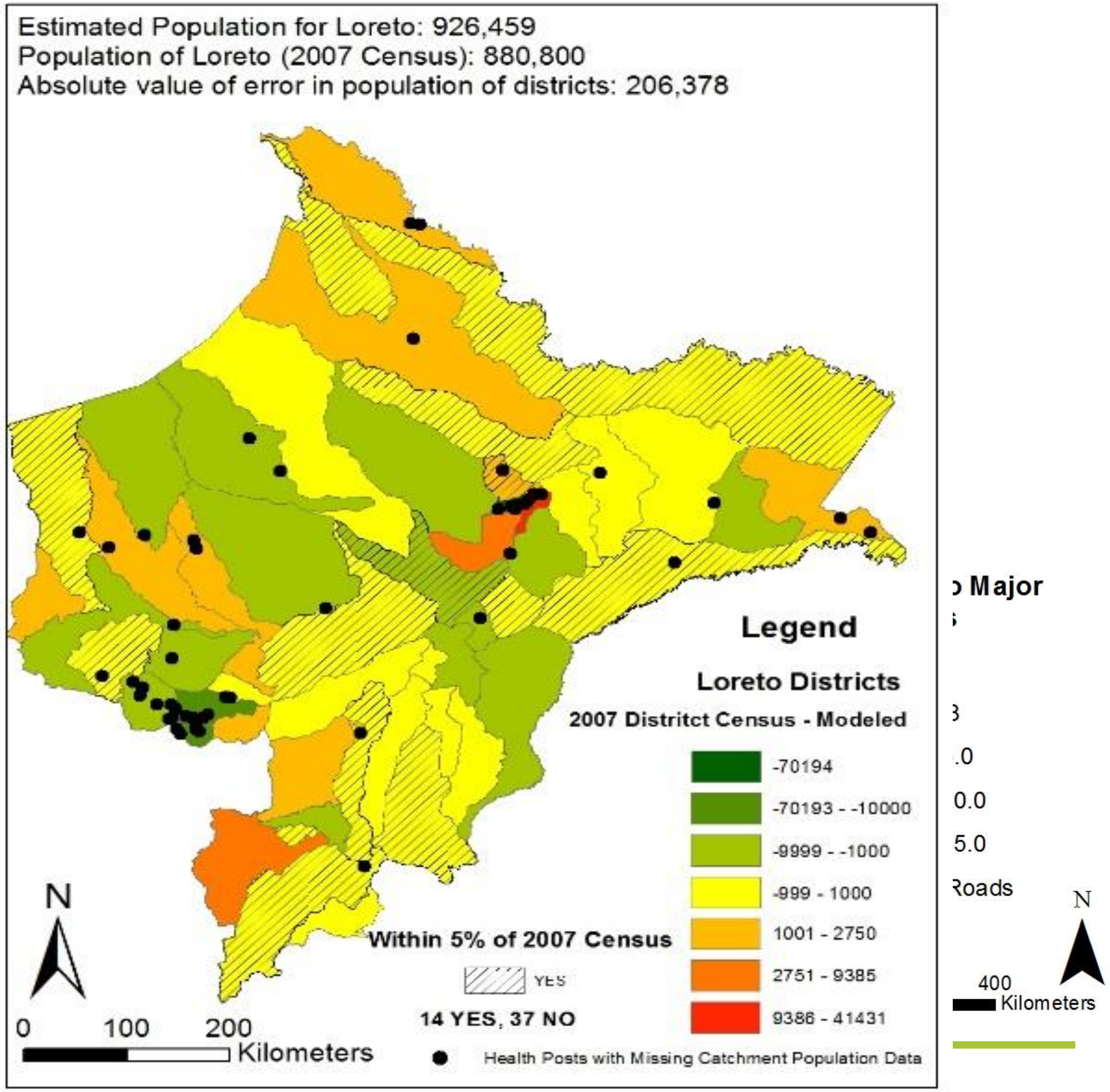
Human Population Model

Provide accurate estimates of population at risk

UPDATE

Modeling health post catchment population with:

- Land cover
  - Percent forest within 5km radius
  - Area classified as water within Theissen polygons
- Location
  - Distance to main roadways and rivers
  - Distance to superior education
- Health post characteristics
  - Health post category 1-3 (health post vs. hospital)
- District Characteristics
  - Number of health posts in the district
  - Number of communities
  - Area



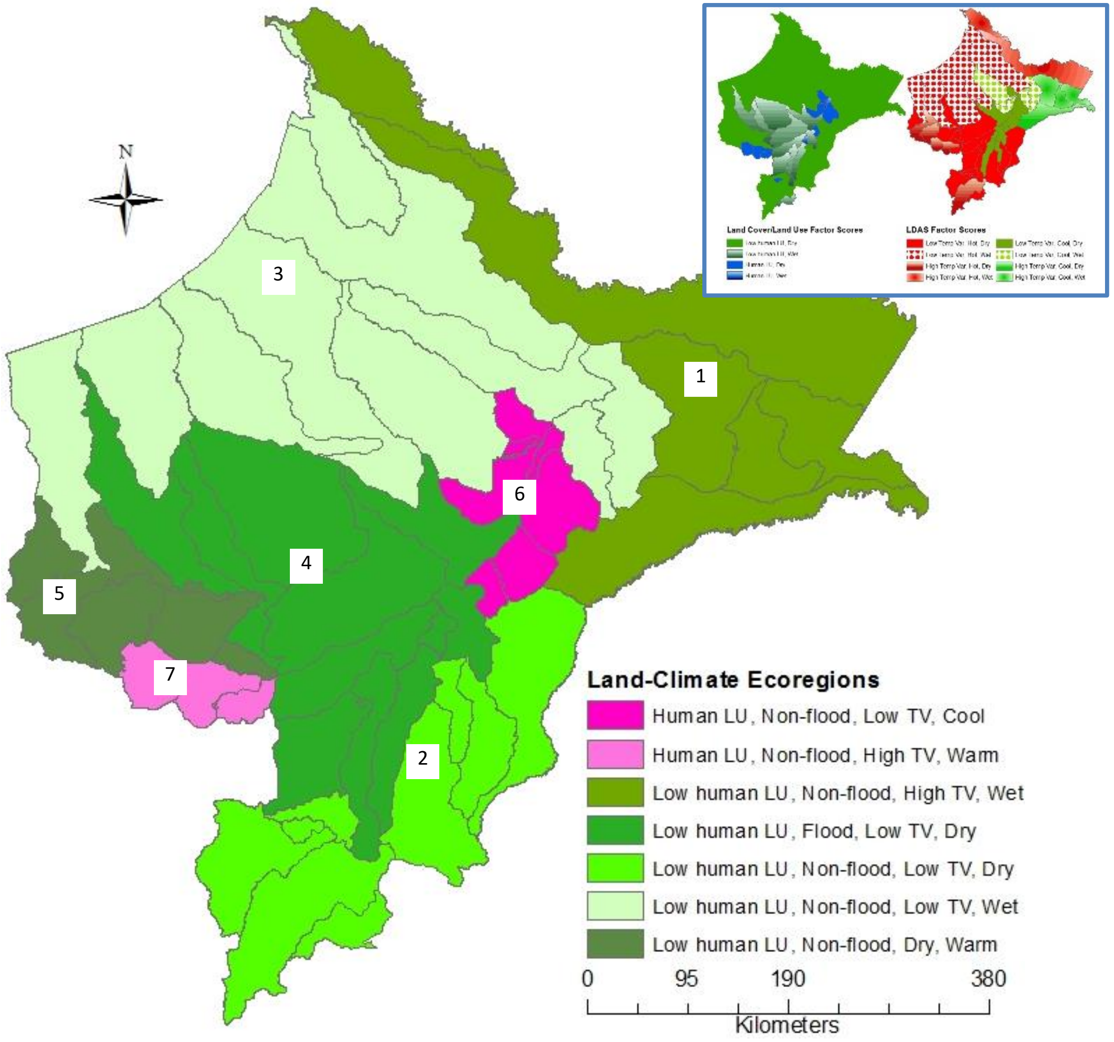
Regional Statistical Model

Approach #1

- Identify unique ecoregions that share similar mean and variance structures by type of land cover, climate parameter(s), and ecological char.
- Fit an Unobserved Components Model to each ecoregion:

$$y_t = \mu_t + \gamma_t + \psi_t + r_t + \sum_{i=1}^{p} \phi_i y_{t-i} + \sum_{j=1}^{m} \beta_j x_{jt} + \varepsilon_t$$

  - Trend (μ_t), cycle (ψ_t), seasonal (γ_t) and autoregressive (r_t) components, including momentum ($\sum_{i=1}^{p} \phi_i y_{t-i}$) and explanatory factors ($\sum_{j=1}^{m} \beta_j x_{jt}$).
- Perform 12-week forecasts



Regional Statistical Model

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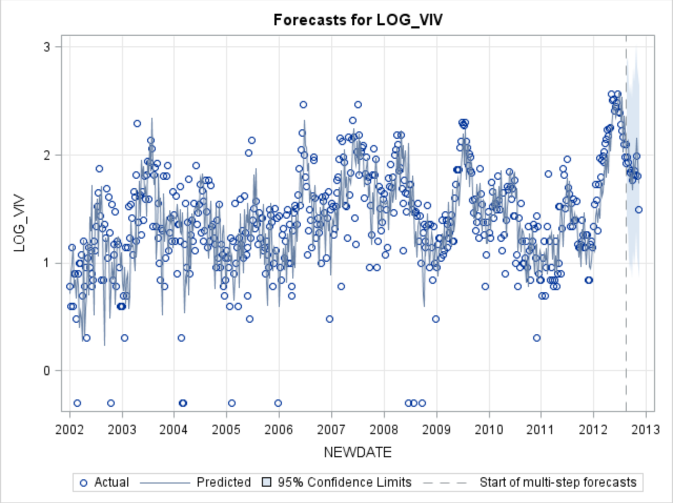
- Perform 12-week forecasts

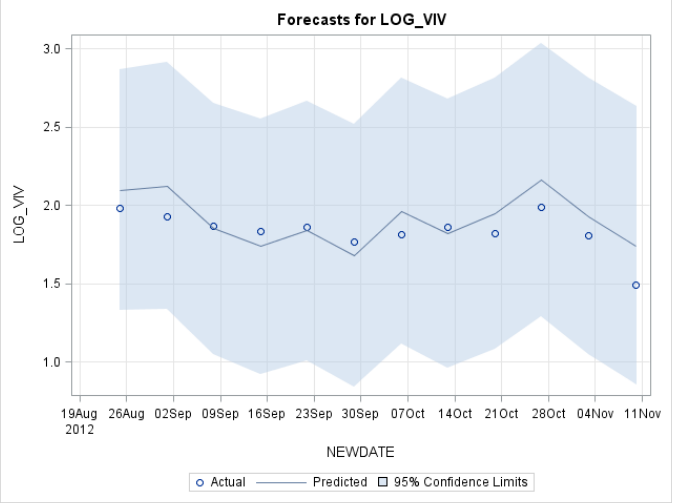
  Left – Model fit

  Right – 12 week forecast

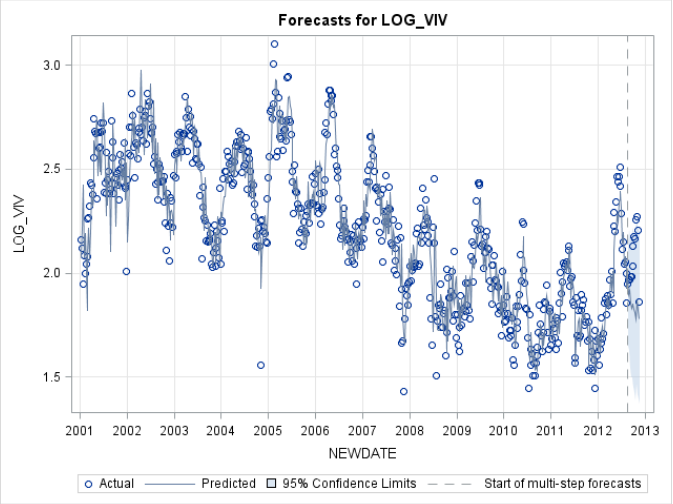
  If observed data exceed 95% CI, outbreak is suspected

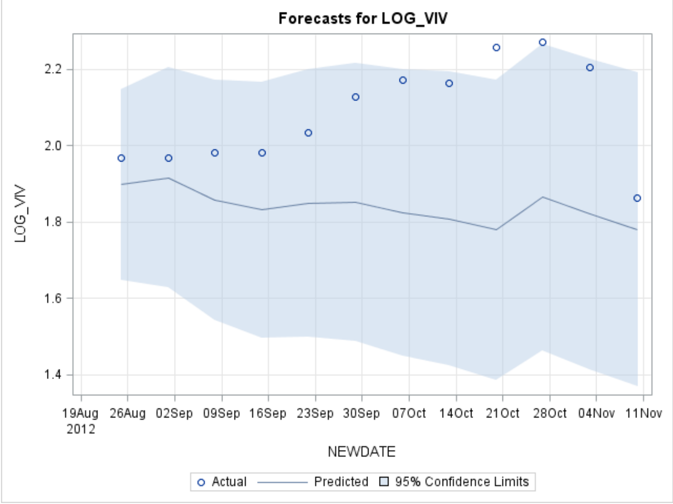
EcoRegion 1





EcoRegion 6 (Iquitos)





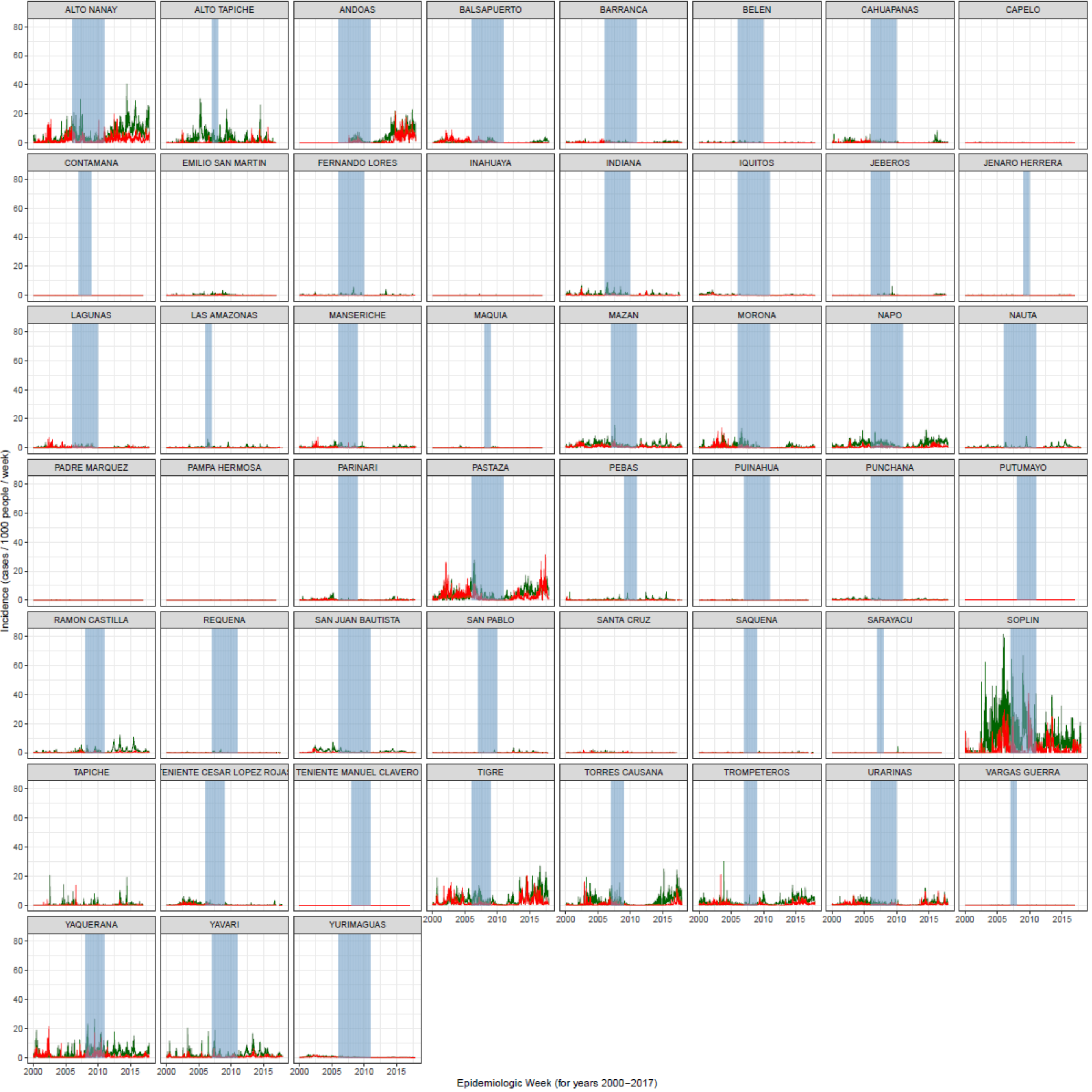
Regional Statistical Model

Approach #2

- Create forecasts by district (original proposal). Evaluate effects of Global Fund interventions (bednet distribution, strengthening malaria diagnostics, environmental management, health worker training)
- **Bayesian Distributed Lag Model**

$$y_t = \boldsymbol{x}_t^T \boldsymbol{\beta} + \boldsymbol{\gamma}_t$$

- y_t is incidence (cases/1000/week) at time t
- $\boldsymbol{x}_t^T$ is vector of environmental covariates at times $t, \ldots, t-36$ (i.e. environmental conditions over the previous 9m)
- $\boldsymbol{\beta}$ is a vector of (distributed lag) regression coefficients linking the environmental covariates to the response
  - $\boldsymbol{\beta_k} | \sigma^2_{\{\beta_k\}}, \phi_k \sim GP\left(0, \sigma^2_{\{\beta_k\}} \boldsymbol{\Sigma}(\phi_k)\right)$
  - Regression coefficients for each of the k environmental predictor vectors are assigned a Gaussian Process prior with an exponential covariance structure
- $\boldsymbol{\gamma_t}$ is a random effect capturing seasonal variation above and beyond the variability captured in $\boldsymbol{x}_t^T \boldsymbol{\beta}$
  - $\boldsymbol{\gamma} | \sigma^2_{\{\gamma\}}, \phi_{\{\gamma\}} \sim GP\left(\boldsymbol{0}, \sigma^2_{\{\gamma\}} \boldsymbol{\Omega}(\phi_{\{\gamma\}})\right)$
  - Random effects $\boldsymbol{\gamma}$ assigned a Gaussian process prior with periodic covariance structure (i.e. residual variability exhibits yearly seasonal patterns



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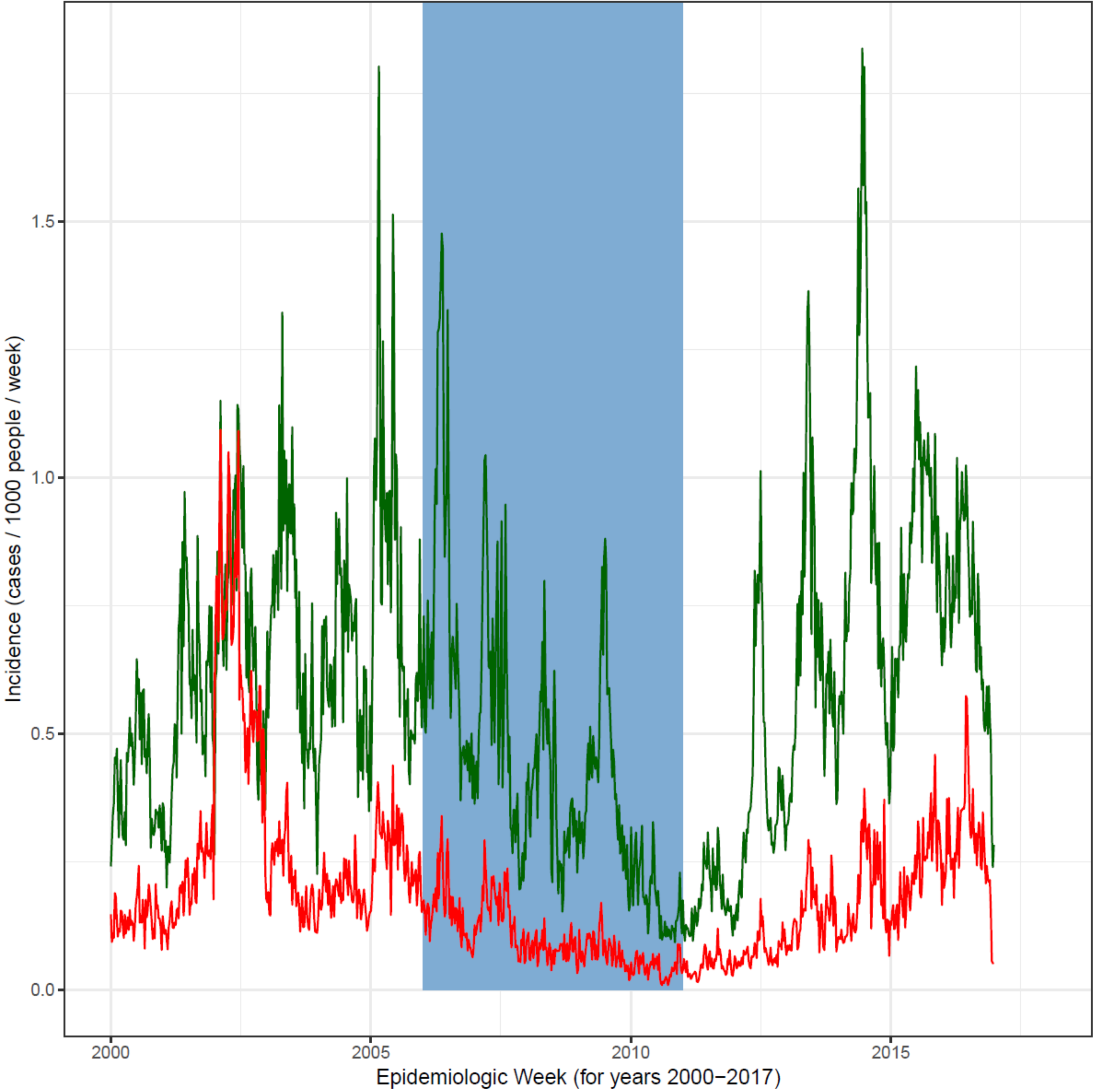
Malaria incidence for each district, (green=vivax; red=falciparum)

Blue Band = Global Fund Intervention Period



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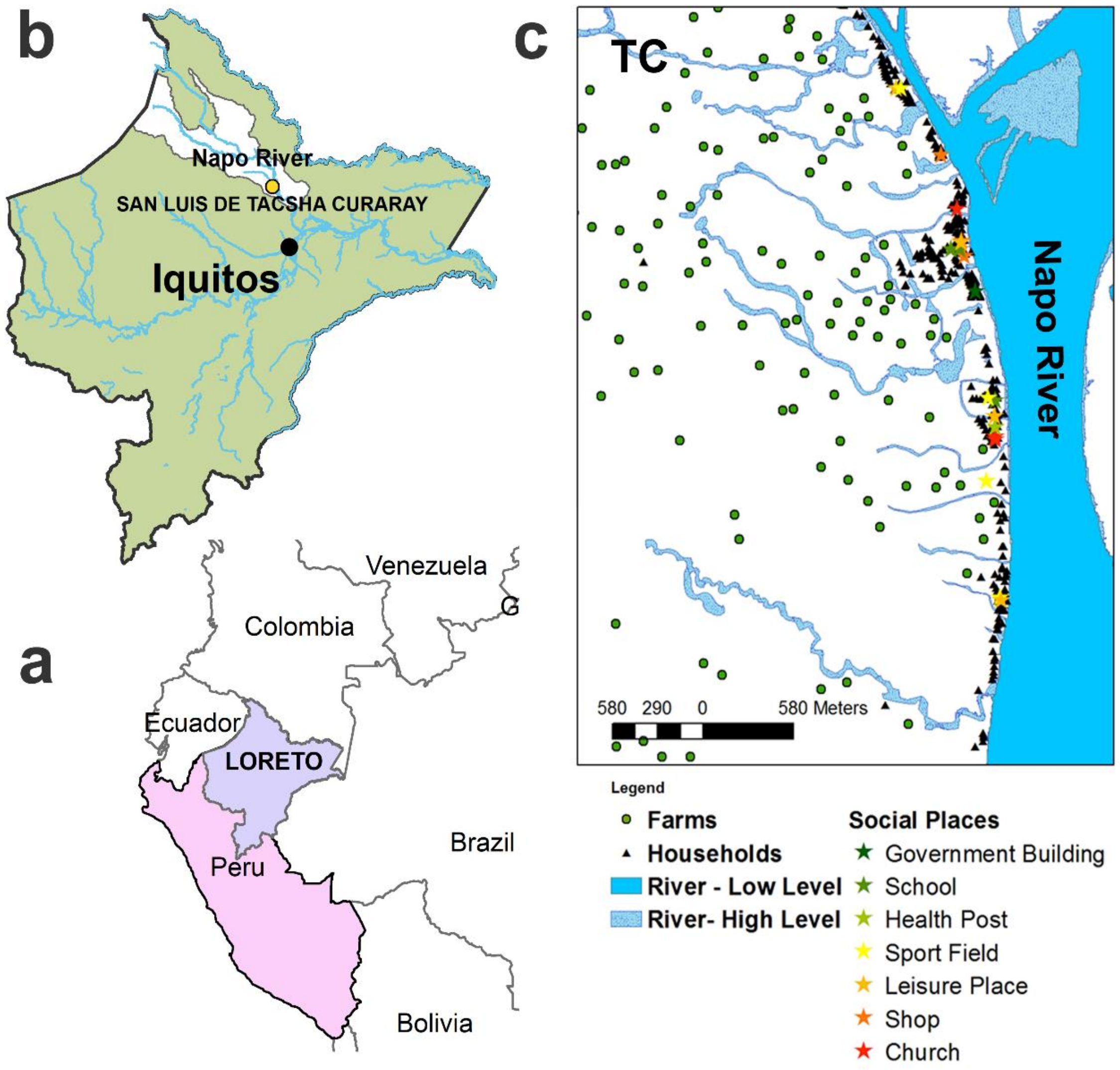
Malaria incidence for each district, (green=vivax; red=falciparum)

Blue Band = Global Fund Intervention Period

Model result from one district – Significant decline in malaria during GF intervention, followed by increase with GF withdrawal

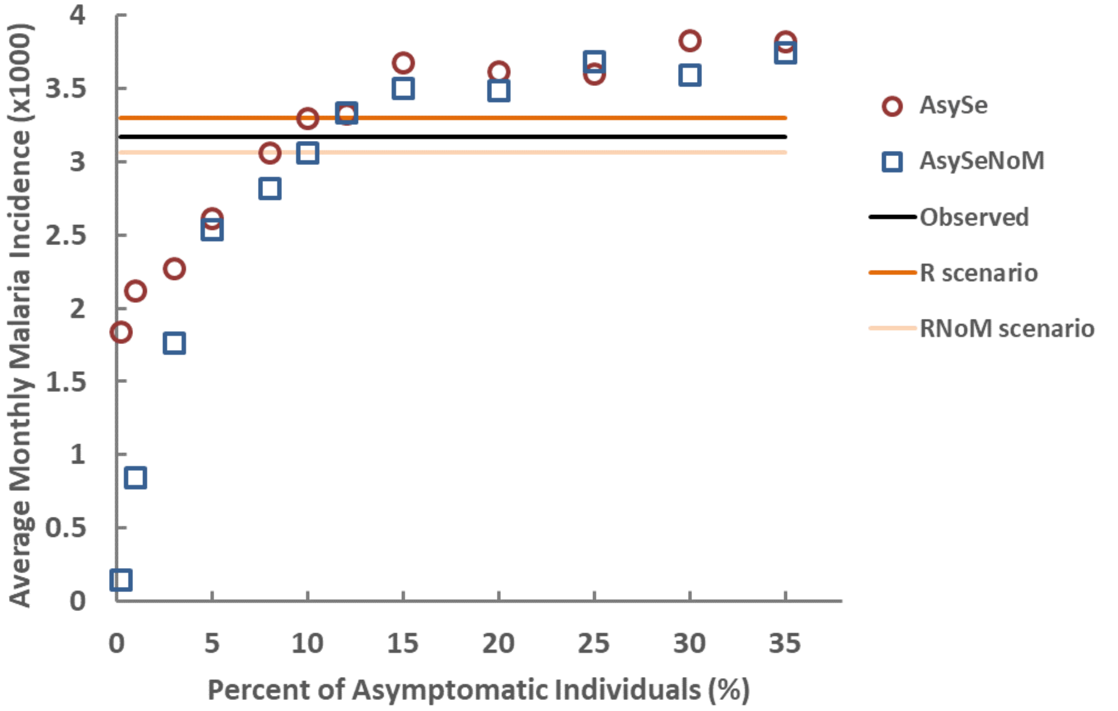
Agent Based Model

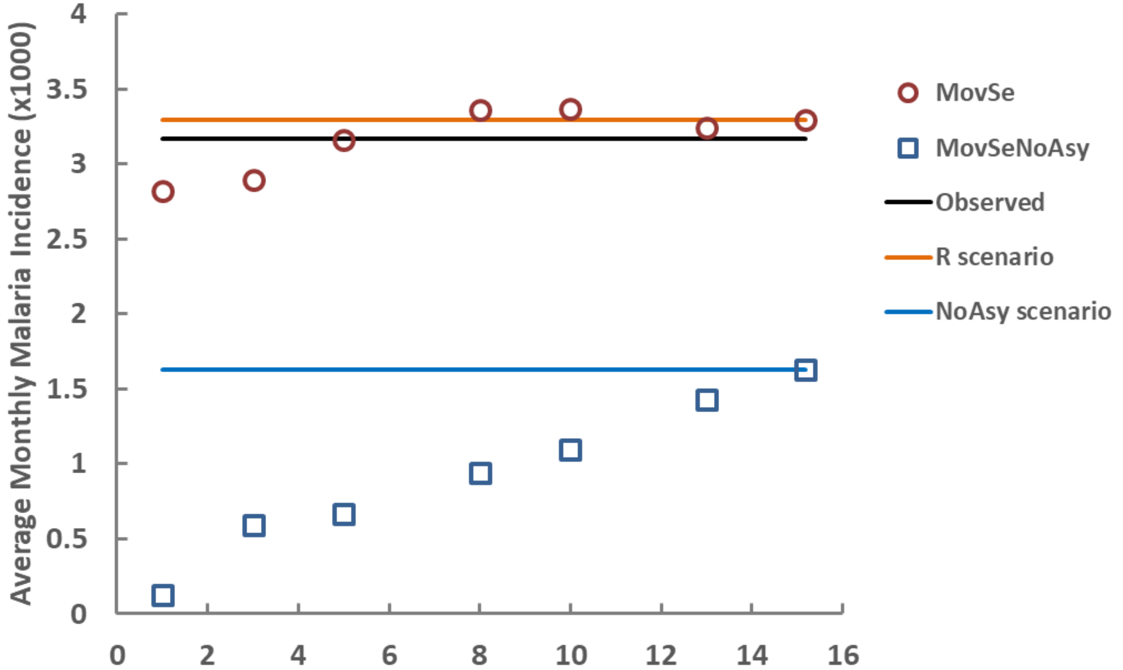
- ABM model was used to test whether infection reservoir represented by asymptomatic carriers combined with circular human (occupational) movement can capture observed hypoendemic malaria transmission
- Results show that ABM reproduces passive case detection surveillance



Agent Based Model

- ABM model was used to test whether infection reservoir represented by asymptomatic carriers combined with circular human (occupational) movement can capture observed hypoendemic malaria transmission
- Results show that ABM reproduces passive case detection surveillance
  - Scenario analysis show that, even if asymptomatic infections are completely eliminated, human movements generate a flow of imported cases that is enough to permit the persistence of transmission
  - Simulation results were verified over a wide range of clinical immunity prevalence values and over a wide range of percentages of people working in remote hyperendemic areas.





NCE Year MAJOR CHALLENGE

- **Sustainability and Technology Transfer**
  - Original goal of our project was to transfer technology to the US Naval Medical Research Unit (NAMRU6)
  - NAMRU6 was replaced by Ministry of Health
    - Political changes in Peru: 2 presidents, 5 Ministers of health in 3.5 years
  - Potential for Government Institutions and local Universities to maintain the system

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Sustainability Plan

• Stakeholder meeting in Quito, Ecuador and Lima, Peru	October 2018
• Follow-up assessment	November 2018

Strong Interest

Technical training & implementation plan with stakeholders	Dec 2018
Technical Training	Mar 2018
Procotol & Software transfer	Apr 2018
Final Training	June 2018

Moderate Interest

Technical training & implementation plan with stakeholders	Dec 2018
Workplan to complete publications	January 2019
Manuscript submissions	May 2019

Low/No Interest

Workplan to complete publications	December 2018
Manuscript submissions	April 2019