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

NASA Project NNX15AP74G
William Pan, Duke University

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# Project Team

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## Johns Hopkins University
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  - Post-doc

## Peruvian Collaborators
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- **Andres Lescano**
  - UPCH
- **Ana Maria Morales**
  - MINSA
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  - DIRESA-Loreto
- **Yuri Escajadillo, PhD**
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- **Luis Alfaro, PhD**
  - SENAMHI
### Project Summary
**NNH13ZDA001N-Health**

<table>
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<th><strong>OBJECTIVE:</strong></th>
<th>Develop an early warning system for malaria in the Peruvian Amazon and evaluate the expansion of the system to other diseases and Amazon regions.</th>
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| **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

- # Cases (1000s)
  - P. vivax
  - P. falciparum

- Cases in Colombia (1000s)
- Cases in Loreto (1000s)

- Loreto-Total
- Colombia-Total

- P. falciparum incidence
  - Cases/1000 people/week: 2010-01-17

- Map showing incidence and distribution of malaria cases in the Americas.
Overview of our Approach

Earth Observations

Land Data Assimilation System
- Temperature
- Precipitation
- Soil Moisture
- Solar Radiation
- Land Cover
- Stream Flow

Human Population Model
- 1km population
- Seasonal Migration

Regional Statistical Model
- Monitor & Identify eco-regions with elevated malaria

Agent Based Model
- Sub-region estimates of household risk

Government Malaria Surveillance

Enumeration:
Health Posts, 2007 Census
Summary of Milestones (Year 3)

Administrative

- **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

- **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

- **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
  - 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 zones” 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
Malaria Early Warning System
Component Updates

LDAS
Population
Statistical & ABM
Overview of our Approach

**Earth Observations**

**Land Data Assimilation System**
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**Human Population Model**
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- Monitor & Identify eco-regions with elevated malaria

**Agent Based Model**
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**Government Malaria Surveillance**
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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**UPDATES**
- Compared the estimated evapotranspiration by LDAS to satellite observed evapotranspiration across the Peruvian and Ecuadorian Amazon (from ALEXI), from 2003 to 2015.
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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

Estimated Population for Loreto: 926,459
Population of Loreto (2007 Census): 880,600
Absolute value of error in population of districts: 206,378
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:
  \[
  y_t = \mu_t + \gamma_t + \psi_t + r_t + \sum_{i=1}^{p} \phi_i y_{t-i} + \sum_{j=1}^{m} \beta_j x_{jt} + \epsilon_t
  \]
  - Trend ($\mu_t$), cycle ($\psi_t$), seasonal ($\gamma_t$) 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
Approach #1

- Unobserved Components Model to each ecoregion:

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

- Perform 12-week forecasts
- Left – Model fit
- Right – 12 week forecast
- If observed data exceed 95% CI, outbreak is suspected
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**

\[ y_t = x_t^T \beta + \gamma_t \]

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