Agent-Based Modeling for Malaria Policy:
Applications, Challenges, and Lessons Learned

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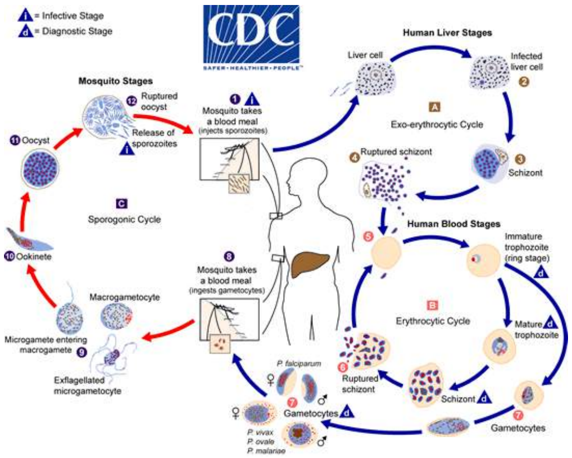
Presentation Outline

- Malaria Basics
- Describe agent-based modeling application
  - Bioko Island Malaria Elimination Program
  - Analytical methodology
  - How we built and used our models
- Four lessons learned about the challenges presented when trying to use agent-based models to make robust policy recommendations

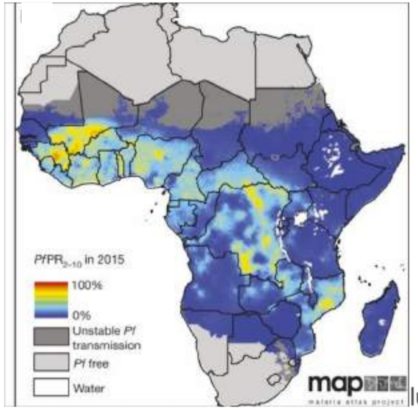
Malaria

- Vector borne parasitic disease
- Transmitted by *Anopheles* mosquitoes
- Tropical climates
- Disease burden
  - Estimated 200 million cases per year
  - Estimated 400,000 deaths per year
  - Disproportionately affecting children
  - Concentrated in sub-Saharan Africa

Parasite Life Cycle



Parasite Distribution, Africa 2015



Heterogeneous Aspects of Malaria

- Malaria dynamics – nonlinear, multicomponent, heterogeneous
- Two examples:
  - Transmission is heavily dependent on mosquito ecology
    - Local mosquito habitats and mosquito activity
    - Seasonal changes to temperature and rainfall
    - Vector control – nets and insecticides
  - Human exposure risk and immunity
    - Immune response and symptoms sensitive to lifetime exposure history
    - Treatment seeking behavior in response to symptoms

Agent-Based Models (ABMs) for Malaria

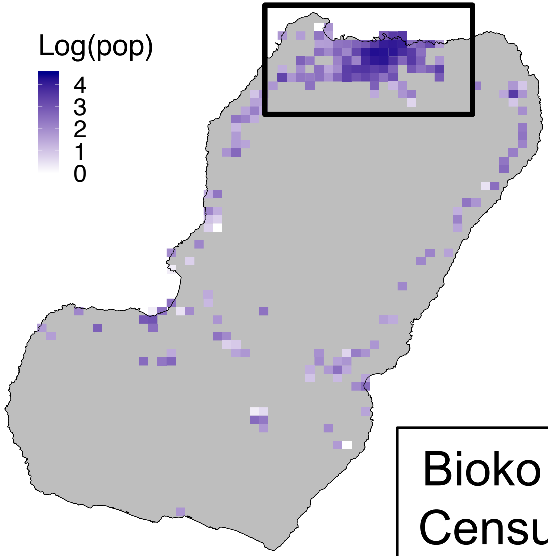
- Possible to write-down simpler mechanistic models
  - e.g. Ross-Macdonald compartmental models
  - Simpler models do not account for heterogeneities
    - Fail to account for heterogeneous exposure
    - Fail to account for immune response variability
- ABMs can capture the many heterogeneities inherent to malaria transmission in ways that other modeling tools cannot
- ABMs are one of the best tools for exploring complicated data sets, and understanding which aspects of the data are most important

Challenges Posed by ABMs for Policy Analysis

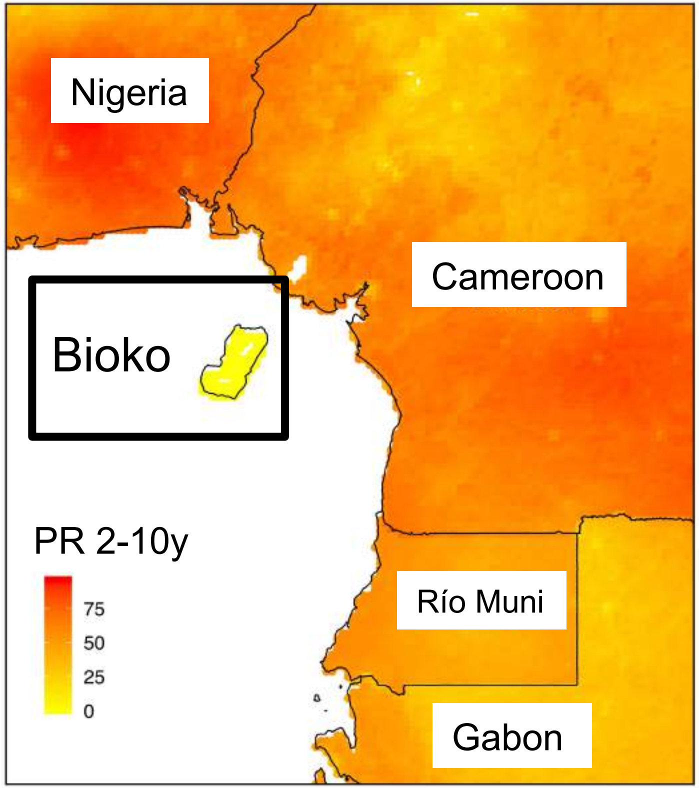
- Robust policy recommendations require characterization of uncertainty
  - Uncertainty reflected in underlying data
  - Uncertainly inherent in choice of mechanistic model
- Made more difficult when using ABMs
  - Extensive and detailed data sets required
  - Enormous parameter space makes it difficult to calibrate
  - Vast set of possible models of individual behavior to choose from
- ABMs can be unwieldy to set up, use, and interpret

An Application: Bioko Island

- Island Population: ~250,000
- Malabo Population: ~190,000

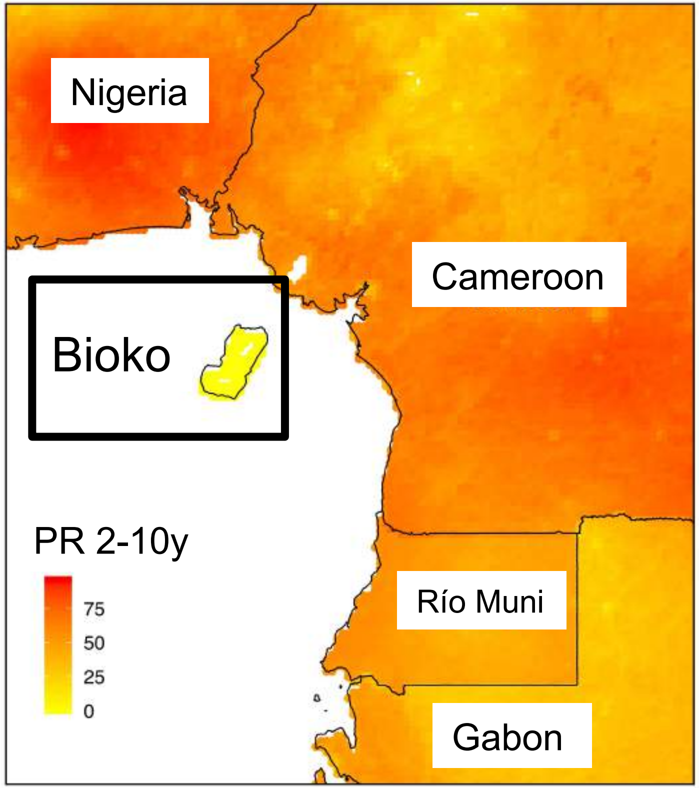


Bioko Island Census Map



Bioko Island Epidemiological History

- PR = Parasite Rate, a measure of prevalence
- High risk region
- 2004 – Bioko PR ~ 40%
- 15-year control program, including:
  - Extensive surveillance
  - Extensive vector control
  - Freely available treatment
  - Capacity building
- Since 2015 – Bioko PR ~ 10%

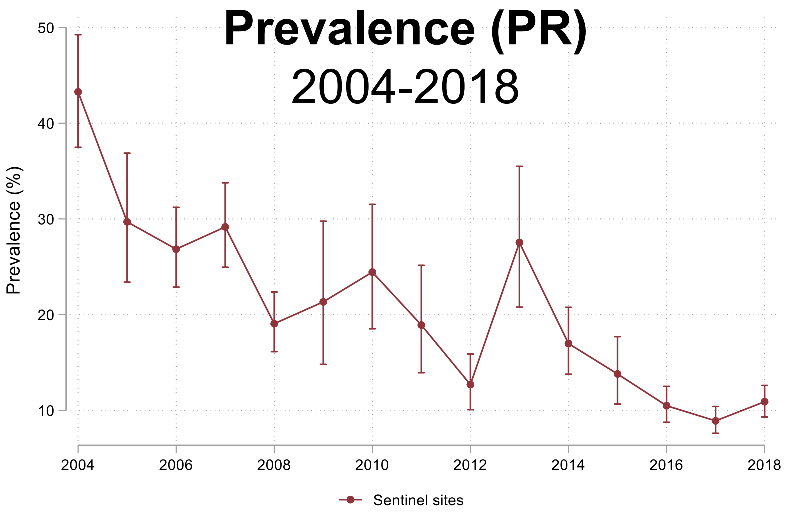


Bioko Island Malaria Elimination Program

- Program managed by MCDI
- Collect data in Malaria Indicator Survey:
  - Annual survey of ~15,000 residents
  - Parasite Rate
  - Travel history
- Close collaboration was crucial for understanding transmission environment

Bioko Island: Key Questions

- No improvements to PR since 2015
- Why has progress stalled?
- What is role of off-island transmission?
- Will adding a vaccine to the current intervention package result in halting transmission on Bioko Island?

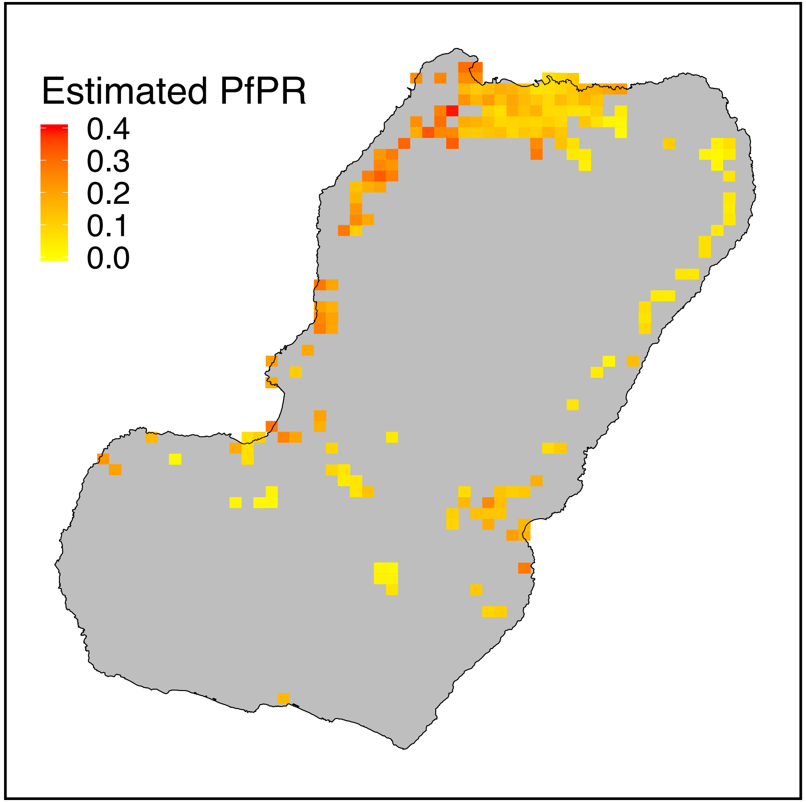


Modeling Methodology

- Create geostatistical map of estimated PR
- Calibrate all mechanistic models to match PR in each map-area
- Analysis:
  - Quantify influence of cases acquired off-island with simple dynamical model
  - Simulate vaccination deployment scenarios with ABM

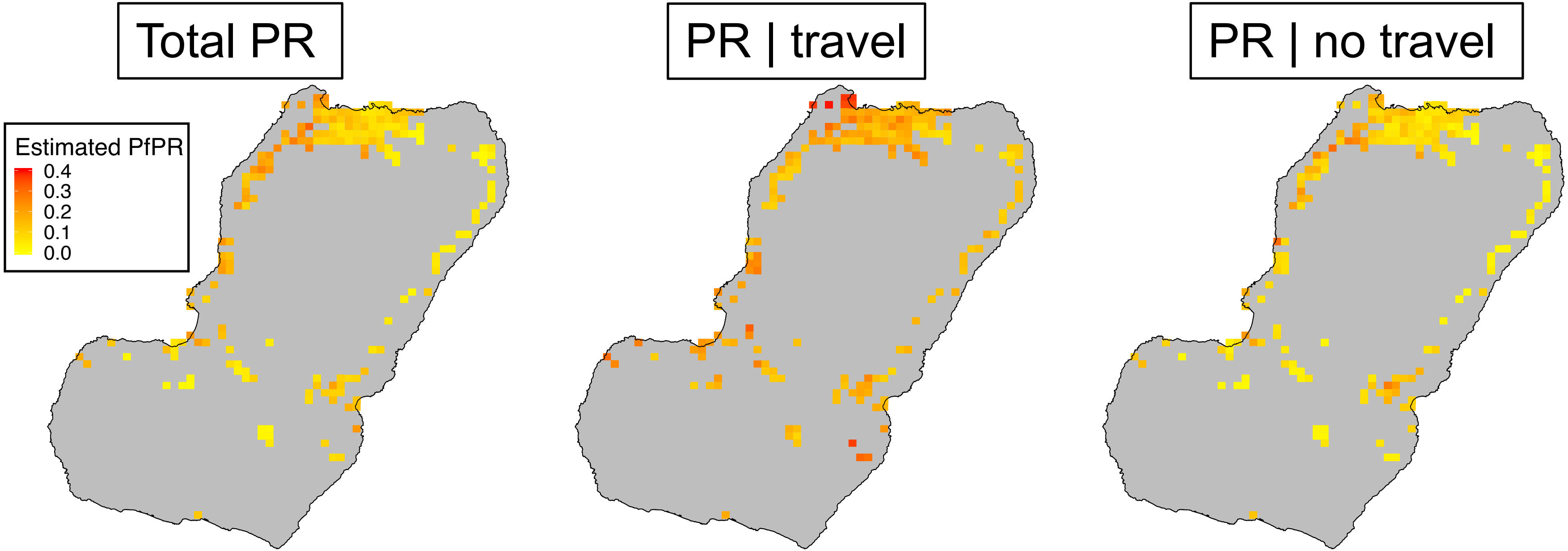
Mapping Malaria Prevalence

- Geostatistical prevalence mapping
  - Census
  - Survey data
  - Environmental covariates
- Estimate prevalence in each map-area
  - Captures km^2-scale variability in PR
  - Highest PR along northwest coast
  - ~10-14% in Malabo



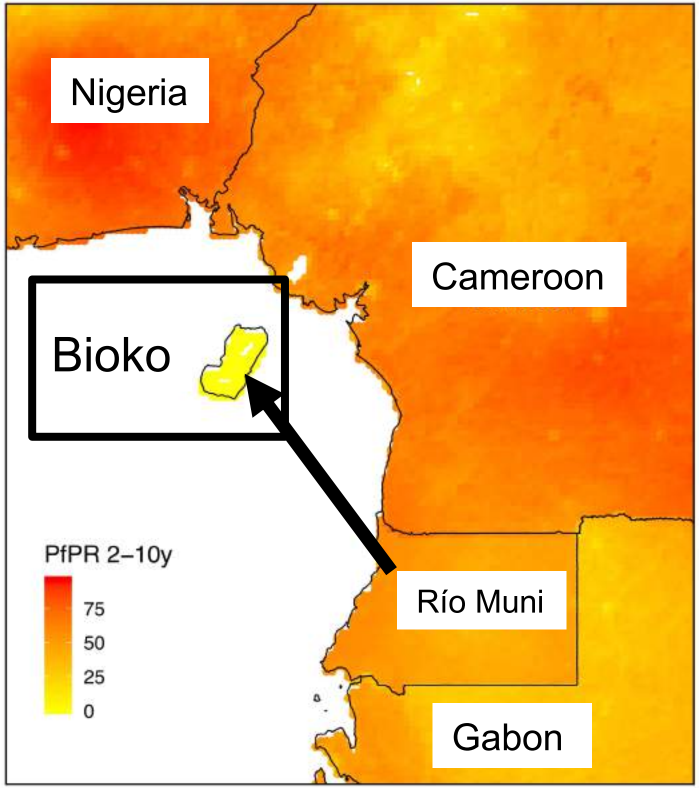
Prevalence Conditioned on Travel History

- Map PR, this time conditioning on recent travel
- Higher risk of malaria among those who traveled off-island



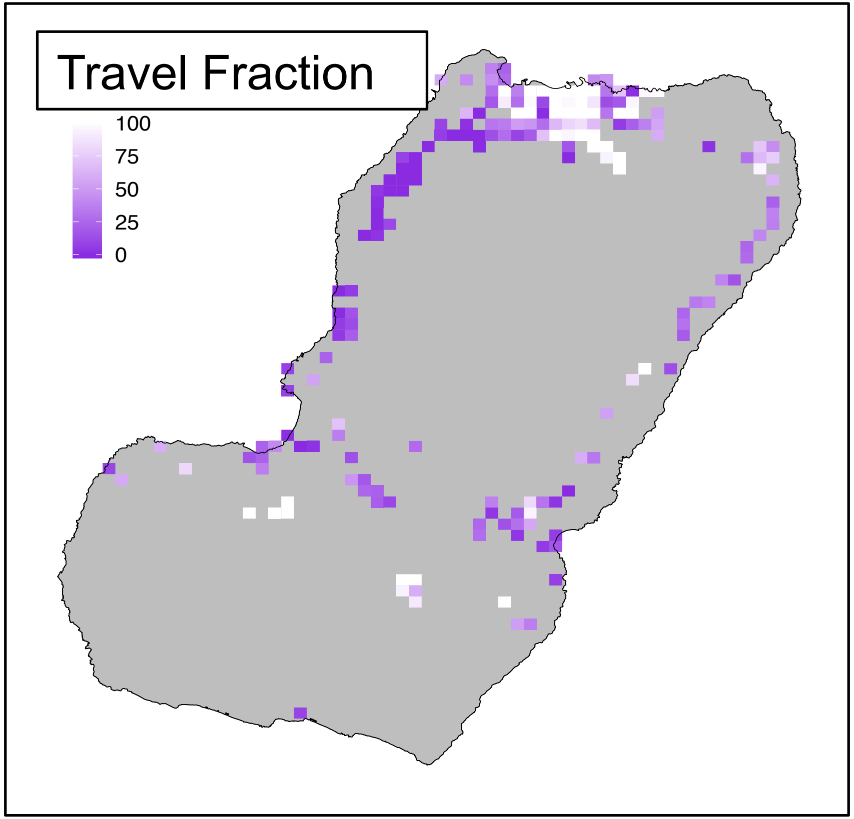
Influence of Off-Island Transmission

- Mainland EG has very high transmission risk
- Frequent off-island travel from Malabo
- How much of the prevalence seen on the island is attributable to travel?
- Use simple dynamical model
  - Ross-Macdonald
  - Include off-island infections
  - Calibrate based on PR + travel survey



Influence of Off-Island Transmission

- Travel Fraction: % cases attributable to off-island transmission
- Malabo
  - High travel fraction (white)
  - Infections not occurring locally
  - Explains high prevalence and few viable vectors in urban area
- Malaria cases acquired off-island maintain prevalence in parts of Bioko



Lesson 1: ABMs Are Not Always Necessary

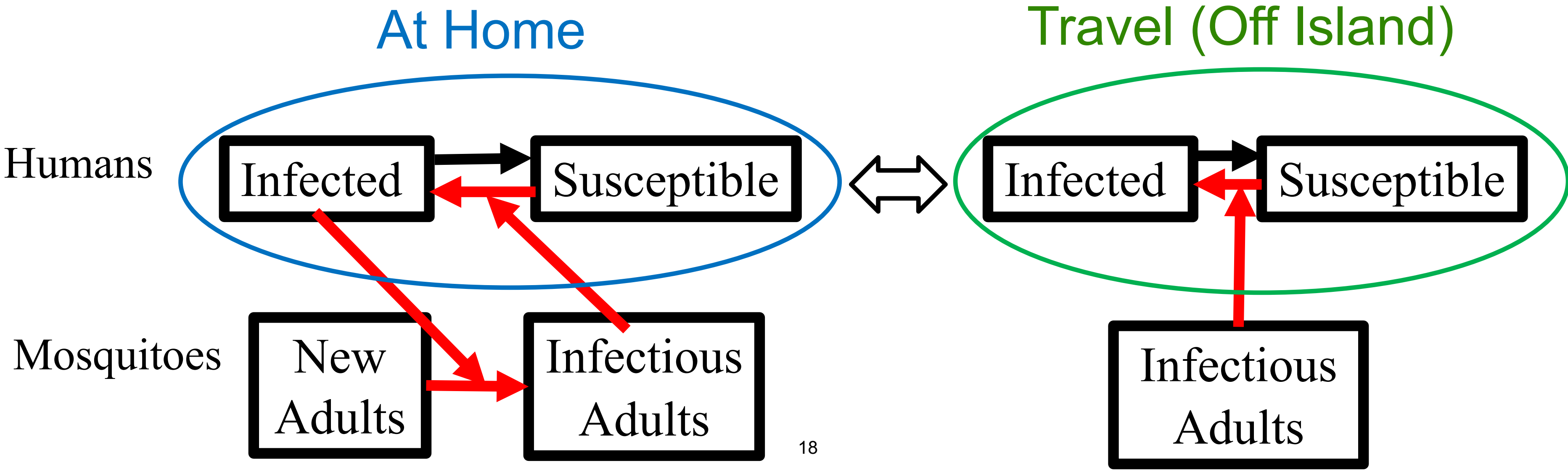
- Using the simple dynamical model we were able to answer important questions about drivers of prevalence on Bioko Island
- Wanted a map of attributable cases – individual-level detail unnecessary:
  - More difficult to build
  - More difficult to calibrate
  - More difficult to interpret
  - Would not give us different results (effect size is very strong)
- ABMs more suited to exploring effects of individual-level heterogeneity

Agent-Based Modeling for Bioko Island

- What would be the impact of deploying a vaccine?
- Modeling vaccination requires individual-level heterogeneity
  - Vaccine coverage and distribution – whether someone receives the vaccine
  - Vaccine efficacy – whether the vaccine lends protection
  - Variable efficacy – fraction of new infections blocked by each individual
- Use simulation to measure population-level effects of protection

MACRO: Our Agent-Based Model

- Humans treated as individual agents
  - Populate island with individuals based on census data
  - Allow individuals to travel, based on travel survey data
  - Individuals in contact with mosquitoes, can become infected



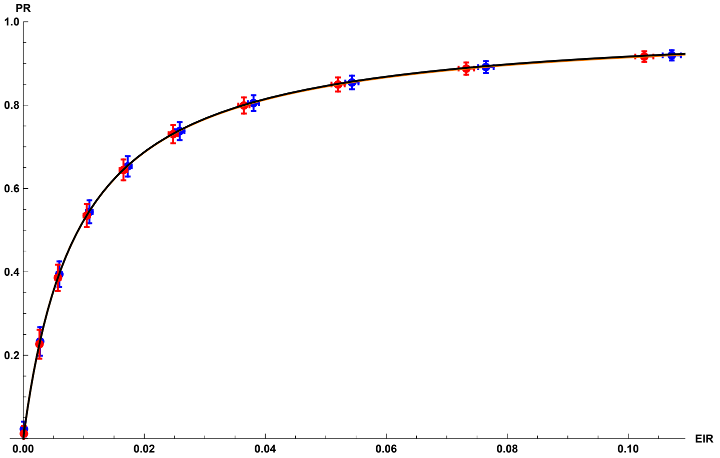
Lesson 2: Challenge of Verifying ABMs

- ABM outputs are very complicated
- How do I know the simulation is doing what I designed it to do?
- No accepted standards for ABM verification
  - Difficult to argue to others whether the model can be trusted

ABM Verification

- Dynamics based on Ross-Macdonald Model
- Can show that ABM aligns with Ross-Macdonald under special circumstances
- Challenges:
  - Time consuming
  - Can only verify without heterogeneity
- Upsides :
  - Not just a theoretical exercise
  - Now can quantify importance of heterogeneity by comparing with non-homogeneous case

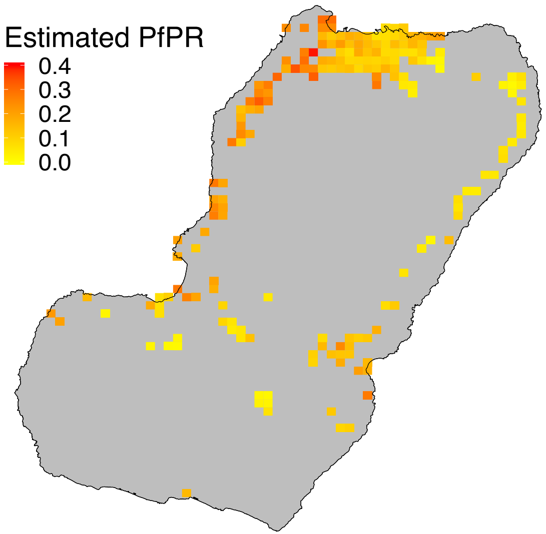
Comparing related models
PR vs EIR



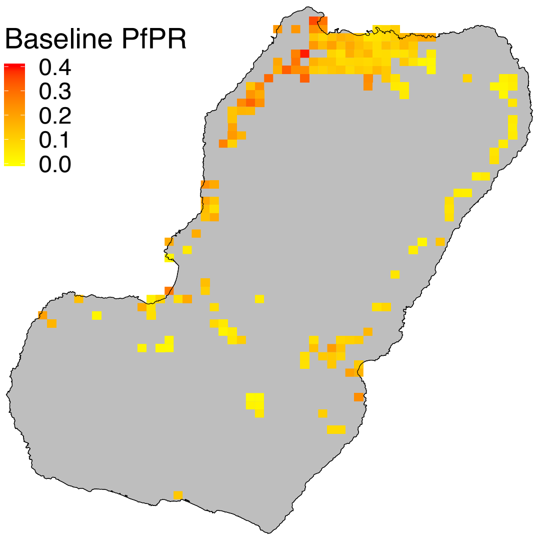
Agent-Based Modeling Results

- Establishing a baseline, calibrating to geostatistical PR map

Geospatial Estimate Mean PR

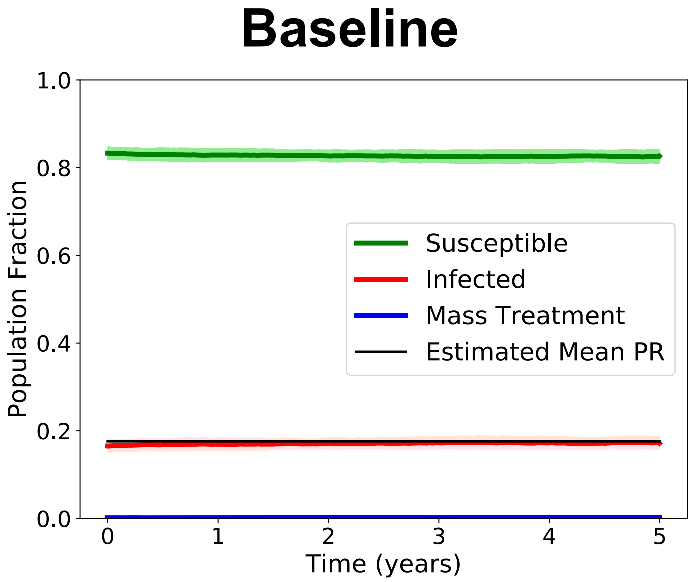


Calibrated Model Mean PR



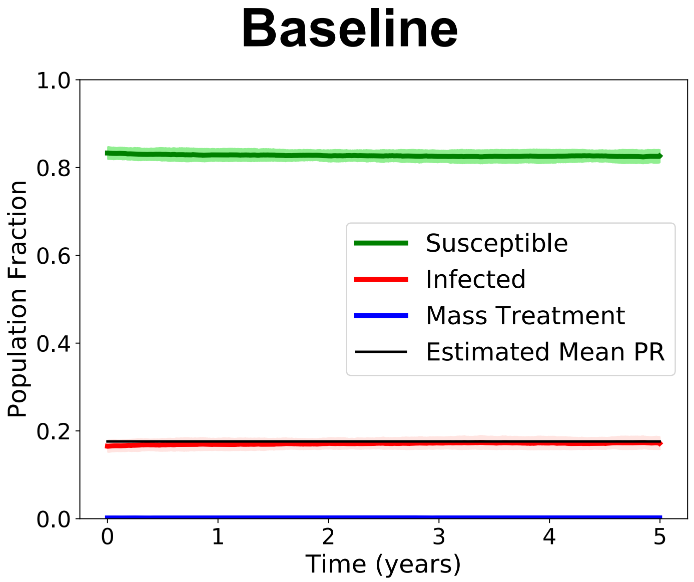
Agent-Based Modeling Results

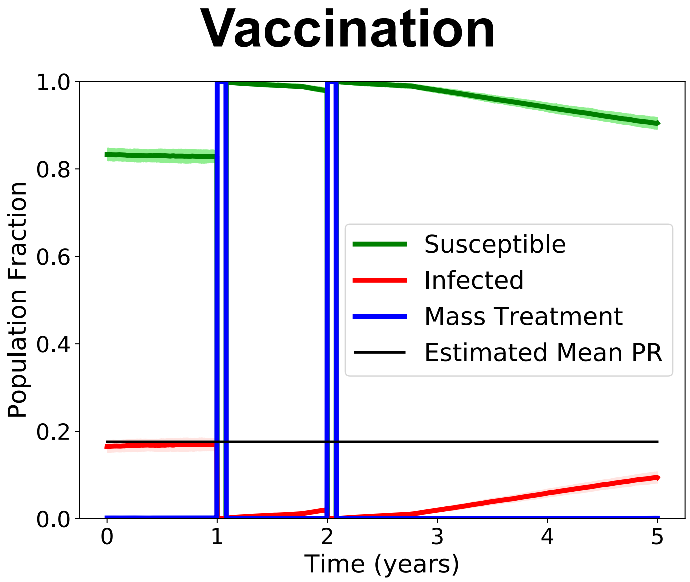
- Baseline: what would happen with no additional interventions
- Red: tracking mean prevalence over time



Agent-Based Modeling Results

- Adding vaccine + treatment, as a best-case scenario
- Malaria returns after a few years – unlikely to eliminate

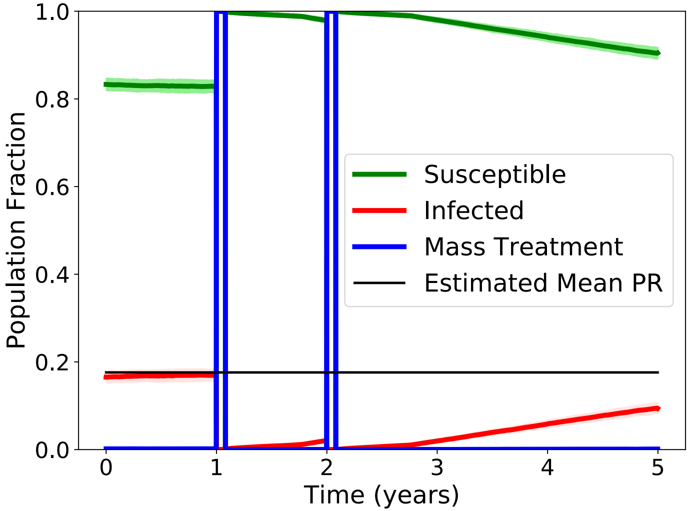




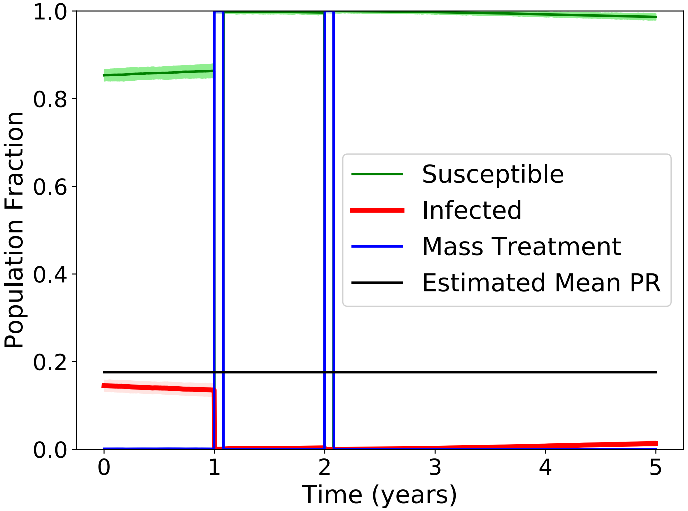
Agent-Based Modeling Results

- Simulated reducing risk of acquiring infections off-island
- Addressing imported cases of malaria may be more effective

Vaccination



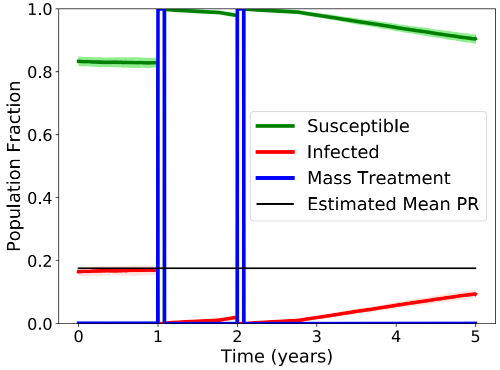
Reduced Off-Island Risk



Lesson 3: Tool for Exploring Data

- ABMs show which features of complicated data sets are important
  - Performed sensitivity analysis on vaccine efficacy and coverage
  - All results the same: malaria resurgence driven by off-island transmission
  - Focus on travel survey data as important for understanding patterns on BI
  - Recommend improvements to future surveys

Vaccination



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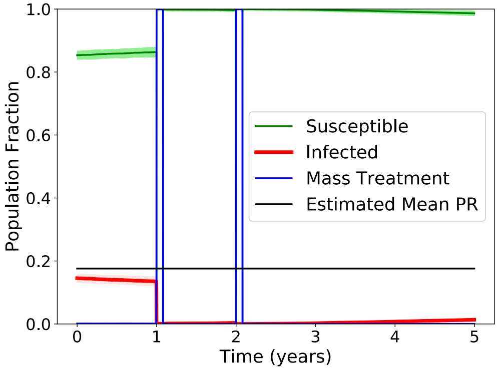

Lesson 4: Communicating with Policy Makers

- Large difference in training/expertise between modelers and policy makers
- When should policy makers trust modeling results?
- What evidence should modelers provide that their model results are useful?
- No standard practices for this

ABMs - Worth the Trouble

- Challenges: how to implement; how to verify; how to communicate
- Why do we keep returning to ABMs?
    - Malaria modeling requires considering many heterogeneous components
    - No other known way of analyzing malaria data
    - No other known way of projecting forward for strategic planning
    - Indispensable for quantifying which aspects of the data matter and which do not
- Just because ABMs can be challenging to work with, does not at all mean we need to avoid them – no other options when dealing with highly complex and heterogeneous problems

Summary

1. ABMs necessary for modeling individual-level heterogeneity
2. Challenging to verify
3. ABMs can help uncover which data are most important
4. Challenging to effectively communicate the results

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