Rice planting in Antananarivo, Madagascar

Mobility and Malaria in Madagascar
Amy Wesolowski
Department of Ecology and Evolutionary Biology
Introduction

Quantifying human mobility patterns

Modeling sources and sinks of malaria parasites in Madagascar
Human travel can introduce pathogens into susceptible populations
Human travel can introduce pathogens into susceptible populations.

Cliff and Haggett (2004) BMJ
Why do we care about human travel for malaria control?

| Malaria resurgence | Targeted interventions |
Why do we care about human travel for malaria control?

**Malaria resurgence**

“Reappearance of new infections in significant numbers after malaria has subsided owing to the measured applied to reduce or interrupt its transmission”

Bruce-Chwatt, 1972
Why do we care about human travel for malaria control?

Malaria resurgence

Spain 1936-1943
Russia 1960-
Afghanistan 1970-1978
Azerbaijan 1990-1996
Turkey 1990-1994
Iran 1991-1999
Liberia 1948-1951
Swaziland 1971-1996
Mauritius 1975-1982
Sudan 1981-1993
Uganda 1990

India 1965-1976
Myanmar 1968-2008
Thailand 1970-1981
Bangladesh 1971-1994
Vietnam 1979-1991
Pakistan 1980-1992
Sri Lanka 1982-1987
French Guiana 1975-1990
Peru 1981-1998
Indonesia 1963-1973
Malaysia 1967-1978

Cohen (2012) Malar J
Why do we care about human travel for malaria control?

Malaria resurgence  

Targeted interventions

Why do we care about human travel for malaria control?

Malaria resurgence  
Targeted interventions

Vector control  
working in the forest  
camping in the forest

Why do we care about human travel for malaria control?

Malaria resurgence

Targeted interventions

Vector control

How do we measure human travel patterns?

FIG. 1 MIGRANT LABOUR MOVEMENTS AND AREAS OCCUPIED BY NOMADIC PASTORALISTS IN AFRICA SOUTH OF THE SAHARA

- Direction of migrant labour movements
- Source areas of migrants
- Areas of high population density and pressure of population on the land
- Areas of economic development (Agricultural, mineral and industrial)
- Areas of nomadic pastoralists

0 Miles 1000

Prothero (1961) WHO Report
Measuring mobility patterns
Mobile phone data
<table>
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Trips
Measuring mobility patterns
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Measuring mobility patterns

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Trips
Measuring mobility patterns

Mobile phone data

Day 1  | Tower per day  | Location per day
-------|----------------|------------------
1      | C              | Orange arrow
2      | A              | Green arrow
3      |                |                  
4      |                |                  
5      |                |                  

Trips
Measuring mobility patterns

Mobile phone data

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Trips
Incorporating mobility into transmission models
For a directly-transmitted immunizing infection

\[ P(\text{import}) = \text{Prevalence (FOI) in source} \times \text{Source contact rate} \times P(\text{infect | contact}) \]
For a directly-transmitted immunizing infection

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\[ P(\text{import}) = \text{Prevalence (FOI) in source} \times \text{Source contact rate} \times P(\text{infect | contact}) \]
How can we extend this framework for malaria?

\[ P(\text{import}) = \text{Prevalence (FOI) in source} \times \text{Source contact rate} \times P(\text{infect | contact}) \]
How can we extend this framework for malaria?

Nonlinear relationships between clinical cases, prevalence, force of infection, age and mobility.
Can we identify sources and sinks?

**Upper bound:** Given prevalence (force of infection) and mobility estimates where are importations most likely?

\[
P(\text{import}) = \text{Prevalence (FOI) in source} \times \text{Source contact rate} \times P(\text{infect | contact})
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**Lower bound:** Given cases reported in a location where local transmission is unlikely where are the likely sources?

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Can we identify sources and sinks?

**Upper bound:** Given prevalence (force of infection) and mobility estimates where are importations most likely?

**Lower bound:** Given cases reported in a location where local transmission is unlikely where are the likely sources?
Can we identify sources and sinks?

**Upper bound:** Given prevalence (force of infection) and mobility estimates where are importations most likely?

**[Actual importations]**

**Lower bound:** Given cases reported in a location where local transmission is unlikely where are the likely sources?
Malaria in Madagascar

Felana Ichantamalala

Jean Maurice Rakotondramanga

Institut Pasteur de Madagascar
Malaria in Madagascar

Population: 23 million
Largest city: Antananarivo (Tana) ~ 2M
Area: ~ Kenya, Texas
High ecological diversity
Malaria in Madagascar

Population: 23 million
Largest city: Antananarivo (Tana) ~ 2M
Area: ~ Kenya, Texas
High ecological diversity

Multiple epidemiological zones
Year round, endemic transmission on the East and West Coasts
Central Highlands and South have periodic outbreaks
Malaria in Madagascar

June 15, 1907.] THE JOURNAL OF TROPICAL MEDICINE AND HYGIENE. 207

Correspondence.

MALARIA IN MADAGASCAR.
To the Editors of the Journal of Tropical Medicine and Hygiene.

Malaria—have been made and are already in operation, leaving 123 kilometres still to be traversed by road in carriages and automobiles. The traffic by rail and road is described as enormous. In 1903, the first year of construction, there was an outbreak of malaria in the uplands contiguous to the railway, but, though there were many cases, the fever is described as having been of a benign type. In 1904 there was a further alarming extension and development of the disease; the capital, Antananarivo, became seriously infected, and the type was now that of malignant tertian. In a total population of 40,000, the deaths from malaria, which appear in previous years to have averaged about fifty, rose in 1903 to 137, in 1904 to 277, in 1905 to 688, and for only the first four months of 1906 to no less than 980.

But, coincidently with the construction of a railway from Tamatave towards Antananarivo, of an important canal in the same direction, and of improvements to the high roads to the capital, a change took place. Of the railway, 148 kilometres—to the rail-head at
Malaria in Madagascar

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W. CARNEGIE BROWN.

island. In the low country malaria has always been endemic, the index of infection in the native population equalling that of West Africa. Tamatave, the principal seaport and chief emporium for the trade of the island, has been a byword for sanitary maladministration and unhealthiness. Of a total number of 14,850 French soldiers who formed the military expedition of 1895, and who landed at that port, no fewer than 4,498 lost their lives. Seventy-two per cent. of this appalling mortality was due to malarial fever—less than 1 per cent. of all deaths being the result of wounds. On the other hand, the uplands, until recently, have been exceptionally exempt from endemic disease. Before 1904, Antananarivo, the capital, and the surrounding country, were practically free from malaria. Fever was infrequent and of a mild type, malarial parasites being seldom seen except in those Europeans who had been living on the coast, or who had come from other colonies. The natives, and especially the Hovas, were a healthy and prolific people. In 1902, out of a total admission list of 1,433 to the native wards of the Government hospitals of the interior, there were only eighty fatalities from all causes. In that year also the records show that of 4,430 European sick, treated in the same hospitals, only forty-six died. It is therefore apparent that, whatever the prevalent diseases were, they were not of a malignant type.

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The high railway bridge to Tamatave, which is now in being, and which is expected to accelerate the development of the country, will also eliminate the high roads to the capital, a change that took place. Of the railway, 148 kilometres—to the rail-head at

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W. Carnegie Brown.
## Mobility in Madagascar

<table>
<thead>
<tr>
<th>Volume</th>
<th>Ratio Avg Incoming vs Outgoing Trips</th>
<th>Number of Destinations</th>
</tr>
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</table>

Data over 6 months (Jan - June 2015)

~3.5M subscribers

Mobile phone tower coverage in 102/112 districts
Mobility in Madagascar

Volume

Ratio Avg Incoming vs Outgoing Trips

Number of Destinations
Mobility in Madagascar

Volume

Ratio Avg Incoming vs Outgoing Trips

Number of Destinations
Mobility in Madagascar

- Volume
- Ratio Avg Incoming vs Outgoing Trips
- Number of Destinations
Mobility in Madagascar

Coefficient of Variation of Daily Travel to Other Districts

Path of Tropical Storm Chedza

Hit by cyclone

Avg Number of Trips to Other Communes

Country Avg

Janv Fev Mars Avr Mai Juin Jul

0.0 0.2 0.4 0.6 0.8 1.0

0 20 28 30 32 34 36 38 40

26 28 30 32 34 36 38 40

Path of Tropical Storm Chedza

Hit by cyclone
How can we extend this framework for malaria?

Movement/Connectivity

High malaria risk

Low malaria risk

Reintroduce parasites

Travel experience clinical symptoms Reintroduce parasites
How can we extend this framework for malaria?

\[ P(\text{import}) = \text{Prevalence (FOI) in source} \times \text{Source contact rate} \times P(\text{infect | contact}) \]
Sources (emitters) and sinks (receivers) of travel and parasite importation were identified

Based on daily travel and importation values, communes were assigned source and sink ranks

The great sources were communes that emitted a large amount of parasites.

The great sinks were communes that received a large amount of parasites.
Sources and sinks of malaria parasites

[Map of Madagascar with map points highlighted as sources and sinks]
Sources and sinks of malaria parasites
Sources and sinks of malaria parasites
Sources and sinks of malaria parasites

What is the seasonal variability in travel?
Sources and sinks of malaria parasites

What is the seasonal variability in travel?

Are there locations that are sources only certain times in the year?
Sources and sinks of malaria parasites

Temporal
What is the seasonal variability in travel?

Are there locations that are sources only certain times in the year?

Spatial
Are you well connected to a large number of locations?

Are you a source for many sinks?

Primary Source

Primary Sink
Sources and sinks of malaria parasites

Number of Related Sinks

Neutral
Primary Source
Temporal
Primary Sink
Spatial
Sources and sinks of malaria parasites

Number of Related Sinks

Colored by Region

Neutral

Primary Source

Temporal

Primary Sink

Spatial
Sources and sinks of malaria parasites

Number of Related Sinks

Sized by Temporal Variability

Neutral

Primary Source

Temporal

Primary Source

Primary Sink

Spatial
Sources and sinks of malaria parasites

Number of Related Sinks

Sized by Temporal Variability

Neutral

Primary Source

Temporal

Primary Sink

Spatial
Sources and sinks of malaria parasites

Neutral

Primary Source

Primary Sink

Temporal

Spatial
How can we extend this framework for malaria?

\[
P(\text{import}) = \text{Prevalence (FOI) in source} \times \text{Source contact rate} \times P(\text{infect} | \text{contact})
\]
Importations in Tana District
Sources and sinks of malaria parasites

Spatial Wallinga-Teunis Method

White et al 2013
Sources and sinks of malaria parasites

Spatial Wallinga-Teunis Method
Sources and sinks of malaria parasites

Spatial Wallinga-Teunis Method

White et al 2013

Churcher et al 2015
Sources and sinks of malaria parasites

Spatial Wallinga-Teunis Method

White et al 2013
Sources and sinks of malaria parasites

Tana District

Monthly cases of malaria in Madagascar

Jan 2009 to Dec 2015
Sources and sinks of malaria parasites

Tana District

Monthly cases of malaria in Madagascar

Cases in Tana

Jan 2009

Dec 2015

Travel

Serial Interval

Time
Sources and sinks of malaria parasites

Tana District

Cases in Tana

Jan 2009

Dec 2015
Sources and sinks of malaria parasites

Tana District

Spatial WT

PfPR method

Smallest Source  Largest Source
Sources and sinks of malaria parasites

Tana District

Spatial WT

PfPR method
Mobility patterns vary in space, time, and volume.

These differences can impact estimates of sources and sinks of malaria parasites.

However, in many instances there are consistent (spatially and temporally) sources that can be inferred using multiple methods.
Acknowledgements

Collaborators
Princeton University
  Jess Metcalf
  Bryan Grenfell
  Metcalf and Grenfell labs
Harvard TH Chan School of Public Health
  Caroline Buckee
University of Southampton
  Andy Tatem
Institut Pasteur
  Simon Cauchemez
Institut Pasteur - Madagascar
  Felana Ihantamalala
  Jean-Maurice Rakotondramanga
  Jean Michel Heraud
  Christophe Rogier

Funders
NIH - MIDAS
Wellcome Trust Sustaining Health
James S McDonnell Foundation
Burroughs-Wellcome Career Award
Thanks!
Malaria in Madagascar

Kesteman et al (2014)

- Population size Madagascar = 23 million
- Texas = 27 million / area slightly bigger

- 226,658 mi²
- 268,597 mi²
- 224,445 mi²

- 88% in high transmission >1 case per 1,000 pop
- 12% low transmission 0-1 case per 1,000 pop

- Reported falciparum to vivid:
  - AS:AQ - artesunate-amodiaquine

Kesteman et al (2014)
Basic framework

Low transmission  High transmission

Acquire infection

Introduce infection

Infected individuals from $i$

\[ P(\text{import}) = \lambda_j \times d \times S_i \]

Onward infections?

Susceptible individuals from $i$

\[ P(\text{infect}) = \lambda_j \times d \]

Interact with infected in $j$
Mobile phone data can be used to understand human mobility dynamics across a range of pathogens and countries.
Malaria in Madagascar

Multiple epidemiological zones
Year round, endemic transmission on the East and West Coasts
Central Highlands and South have periodic outbreaks
There is little (no) local transmission in the capital district
Since the French occupation much attention has been rightly devoted to the making of roads and railway, but the natives engaged in this labour have suffered enormously, owing to their contracting malaria in the unhealthy districts in which from time to time they have worked. Many have died, in spite of assiduous treatment by native doctors in the employ of the Government; more, perhaps, have returned to their villages, wrecks from malaria. These are the villages along the rice valleys, where, as I said, mosquitoes abound. The origin of the epidemic is thus fairly easy to conjecture.

The difficulty in dealing with the outbreak is that the rice-fields themselves, which are necessary for the growth of the staple crop, are largely responsible for the keeping up of the disease. Anything radical done to them aims a blow at the chief food source. It is impossible to spread petroleum over miles and miles of rice fields. Such things as eradicating undergrowth in and near the towns have been done, but the long grass, &c., which harbour mosquitoes have not, I believe, been attacked, neither have “mosquito brigades” been formed.

A word or two supply a reason for extent explain the prophylaxis. The broad level streets west, and south. Through this plain the west there courses a large river, and further west, again, are several rivers rising in the mountains in the centre of the island. These irrigate other valleys, also devoted to the cultivation of rice.

Until recently, malaria was not endemic in these valleys. The population along them is by no means dense, but it is fairly large. Along the river-banks is much long grass, and near the margins grow the rushes used largely for thatching. The natives build their huts quite close to the rice-fields. Mosquitoes swarm there, and when one has the opportunity of noting them one finds that, sometimes at any rate, they are practically all Anopheles. Probably these places are actually more infested than formerly with mosquitoes.

I am, Sir,
Yours faithfully,

Medical Mission, Tananarive,
C. F. A. Moss, M.D.

June 28th, 1907.
Utilizing these data for public health requires coordinations across academia, industry, government, and public health.

**Mobile phone operator**
- Privacy compliance office
- Business analytics
- Data warehouse
- Sustainability team
- Public relations

**Academia**
- Mathematical modeler
- Epidemiologists

**Government**
- Telecom regulators

**Public Health**
- Ministry of health
- Epidemiologists

**What is the public health application?**
**What will the data be used for and who will analyze the data?**
**How will the data be analyzed, aggregated, and anonymized?**
Malaria in Madagascar
Malaria in Madagascar

Multiple epidemiological zones
Year round, endemic transmission on the East and West Coasts
Central Highlands and South have periodic outbreaks
The different tribes send out scouts to find out where rain has fallen, and where grazing will be available. On the basis of their information a decision is taken which may involve the movement of a considerable number of people for a distance of even 100 miles in 60 hours. It has been said of these scouts that they "...lie scientifically to try to ensure that their own people get first to the best grazing."

How can we measure mobility patterns?

Prothero (1961) WHO Report
\[ P(\text{import}_i \rightarrow j | T_d) = 1 - (1 + \alpha b E T_d)^{-1/\alpha} \]

\[ P(\text{import}_i \rightarrow j | T_d) = \lambda_i T_d / 200 \]

\[ P(\text{import}_i \rightarrow j | T_d) = P_{fPR2-10}(i) T_d / 200 \]