Why a spatial approach?

Transmission has a geographic component

- Global and local

Why a spatial approach?

Evidence from the literature

- 400 BC, Hippocrates – *On Airs, Waters and Place*
- Forgotten during the eradication campaign
- On the agenda now

Targeted interventions for disease control

- Successful and Cost-effective
- Require local knowledge
Research Questions

► What is the local pattern of malaria transmission (spatial and temporal)?
► Does this pattern allow the identification of sub-areas of risk, and how can they be described?
► Which are the local determinants of transmission (behavior, socio-economic, ecology, political, …)?
► How interventions for malaria control could be improved by the knowledge of the spatial variation in risk?

Two case studies

► Opening of new human settlement areas in the tropical forest with accompanying rapid urban development
  • Machadinho-RO - Amazon, Brazil
► Rapid urban expansion of African cities
  • Dar es Salaam, Tanzania

Brazilian Amazon:
Machadinho, Rondônia
Amazon

► Trend
  • Endemic Malaria
  • Vector is naturally found in the tropical forest

► 1970s
  • Opening of roads and settlement projects
    ▶ In 1970 - only 52.5 th. cases of malaria in Brazil
    ▶ In 2000 there were more than 600 th. Cases
      99.9% in the Amazon
      60% in settlement areas

Amazon – Major Highways

Amazon: from forest ...
Case study: Machadinho, RO

► POLONOROESTE (World Bank)
► Road construction was accomplished without delays
► Massive migration
  ▪ From South BR: no immunity & knowledge (malaria)
► Infrastructure → Precarious
  ▪ Very poor houses
  ▪ Only one hospital in the early years of occupation

Case study: Machadinho, RO

► Soil quality was poor, unless high technical inputs were used
► Slash and burn
  ▪ Abandonment and clearing of more areas
  ▪ Human mobility – “carriers”
  ▪ Less than 30% of plots had only one owner
► Deforestation
  ▪ Forest fringe
  ▪ Proliferation of breeding sites
  ▪ Increase in vector density
Malaria in Machadinho

- In 1985:
  - API reached 3,400 positive cases by 1,000 people
  - 65.7% of the population had malaria at least once

- In 1986:
  - 90.1% of the population had malaria at least once
  - 55.9% of people had malaria episodes in more than five months of the year
  - Almost 40% of malaria cases registered in Rondônia were observed in Machadinho
Data

  - The only field survey in the Amazon that follows a colonization project since its inception
  - Questions included migratory history, malaria episodes, knowledge about malaria transmission, socio-demographic characteristics of the settlers, protective behavior against malaria, use of health services, land use, ecological transformations, agricultural production, and housing conditions

- Additional variables created with the aid of GIS (distance, nearest neighbors, buffers)

- Landsat 5 TM images (30m of spatial resolution)
  - Risk factors not available in field survey data

- Ethnographic information

Methodological Approach

A. Spatial Clustering Analysis
B. Spatial Estimation (Kriging) → Sub-areas of risk

- Spatial pattern of malaria transmission
- Possible identification of sub-areas of risk
Methodological Approach

A. Spatial Clustering Analysis
B. Spatial Estimation (Kriging) → Sub-areas of risk
C. Grade of Membership (GoM) → Risk profiles

► Describing sub-areas of risk
► Assessing the most important determinants of transmission
► Targeted interventions for malaria control

A. Spatial Clustering Analysis

► Local Indicators of Spatial Association – LISA
► $G^*(d)$ statistic
  • Identify clusters of high and low values surrounding a particular location $i$ within a distance $d$ from $i$
  • Weights - Tobler’s First Law of Geography: “everything is related to everything else, but near things are more related than distant things” (Tobler, 1979).

$G^*(d)$ Statistic
\( G'(d) \) Statistic

- Multiple and dependent tests
  - Two sources of spatial dependence
    - Geometric
    - Between the values of nearby locations
  - Multiple comparison correction
    - Conservative – Bonferroni, Sidak
      - Probability that a true null hypothesis is incorrectly rejected – Type I error
    - False Discovery Rate
      - Proportion of null hypotheses incorrectly rejected among all those that were rejected

Note: FDR

Unadjusted

Bonferroni

Bonferroni with FDR

Unadjusted

Bonferroni

Bonferroni with FDR
**B. Spatial Estimation (Kriging)**

- Optimal spatial estimation
- 2-step process:
  i. Quantify the spatial structure of the data (semivariogram)
  ii. Produce an estimation

### i. Spatial structure

- **Nugget effect**:
  - A discontinuity at the origin generated by micro-scale variation and/or measurement error.
- **Range**:
  - The distance beyond which the observed points are not correlated anymore.

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**G\'_(d) Statistic**

- Distance = 3,500 meters
- FDR approach to correct for multiple testing

- Significant clusters of low malaria rates
- No significant clusters
- Significant clusters of high malaria rates

Distance = 3,500 meters

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**Distance = 3,500 meters**

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- **Range**:
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ii. **Produce an estimation**

- Weight the surrounding measured values to derive a prediction for each location
  - Weights are obtained from the modeled spatial autocorrelation (semivariogram)

**Kriging**

<table>
<thead>
<tr>
<th>Year</th>
<th>Sub-area 1</th>
<th>Sub-area 2</th>
<th>Sub-area 3</th>
<th>Sub-area 4</th>
<th>Sub-area 5</th>
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<td>35.9</td>
<td>24.8</td>
<td>43.8</td>
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<td>27.9</td>
<td>17.0</td>
<td>43.8</td>
<td>2.9</td>
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<tr>
<td>1987</td>
<td>27.5</td>
<td>24.3</td>
<td>14.9</td>
<td>15.3</td>
<td>35.5</td>
</tr>
<tr>
<td>1995</td>
<td>11.3</td>
<td>2.9</td>
<td>11.8</td>
<td></td>
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</table>
What was learned?

► Determinants of transmission:
  • Vary across space and over time

► 2 scenarios in a settlement area:
  • 1<sup>st</sup> – initial stage; low social and economic diversity; large differences in transmission; natural and man-made environment
  • 2<sup>nd</sup> – later stages; significant social and economic diversity; stable malaria at lower levels; personal characteristics and behavior

What was learned?

► Strategies for control should be targeted in time and space
  • The environment and the habitat conditions should be the focus of interventions in the early years of settlement
    1. Environmental management
    2. Rapid and complete clearance near the house
    3. Good quality housing
    4. Good quality clearing (chainsaw)
    5. Do not leave bare soil exposed for long

What’s being done now?

► In 2000 the Brazilian government started a control program that targeted 32% of the municipalities in the Amazon, which accounted for 93.6% of the cases
  • Reduction of 44.4% in the number of cases was registered between 2000 and 2001
  • Note: This targeting strategy is fixed a priori, and not based on a local surveillance system
  • Areas that experience sudden outbreaks are likely to receive less attention.
African Urban Area:
Dar es Salaam, Tanzania

Dar es Salaam

- Endemic and perennial malaria
- Reduced number of breeding sites
  - Cemented areas, polluted water, etc
- Role of urbanization:
  - Contributes to reduction in transmission (breeding sites and individual exposure)
  - Contributes to increase in transmission (initial process of urban expansion)

Dar es Salaam: urban life
Dar es Salaam: matuta

Urban expansion in Dar es Salaam

Total area = 1,393 km²

<table>
<thead>
<tr>
<th>Year</th>
<th>Area urb. (km²)</th>
<th>Period (years)</th>
<th>Annual growth (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>28</td>
<td>20</td>
<td>2.18</td>
</tr>
<tr>
<td>1997</td>
<td>40</td>
<td>22</td>
<td>7.93</td>
</tr>
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<td>1998</td>
<td>93</td>
<td>11</td>
<td>7.59</td>
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<td>1999</td>
<td>259</td>
<td>14</td>
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</tr>
<tr>
<td>2000</td>
<td>418</td>
<td>5</td>
<td>10.05</td>
</tr>
</tbody>
</table>

Data

► Field survey (on-going)
  • Mapping of breeding sites
  • Adult mosquito catch
  • Household surveys (Longitudinal)
  • Blood test
  • Assessment of drains/ditches
► Remotely sensed imagery

Geostatistical analysis of imagery (RS)

► Describe the spatial structure of the urban area
► Investigate and model the relationship between malaria transmission and the spatial organization of the elements that compose an urban scene

Geostatistical analysis of imagery (RS)

► Semi-variogram
  • Parameters provide information regarding the spatial resolution, the presence of processes that operate at multiple scales, and the size, area, shape and density of objects in the scene
**Target area**

- 15 wards, 5 in each district
- ~4% of total area of Dar es Salaam

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**Dar es Salaam: a quick tour...**

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**Patterns of urban structure**

- Unplanned housing development
- Upper scale housing
- Middle scale housing
- and Peri-urban

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Clusters & Rainfall

1st round – Aug 2004
2nd round – May/Jun 2005

Ward: Ndugumbi
District: Kinondoni

Clusters & Urban Spatial Structure

Variance: 1632.6
Range: 15.4
Partial sill: 802.4

More to come...

►► Evaluation of local interventions for malaria control
  • Analyze data before and after interventions

►► Learn & adapt
  • Identify the main determinants of transmission
  • Adapt interventions
  • Analyze data before and after adaptations

►► Scale-up
One final lesson...

► In 1996, 60% of all malaria cases in the Amazon were concentrated in only 25% of the municipalities

► The same package of interventions was adopted in all municipalities

► 70% of the budget for malaria control was being spent in municipalities with only 3% of the cases