Geographical models in epidemiology

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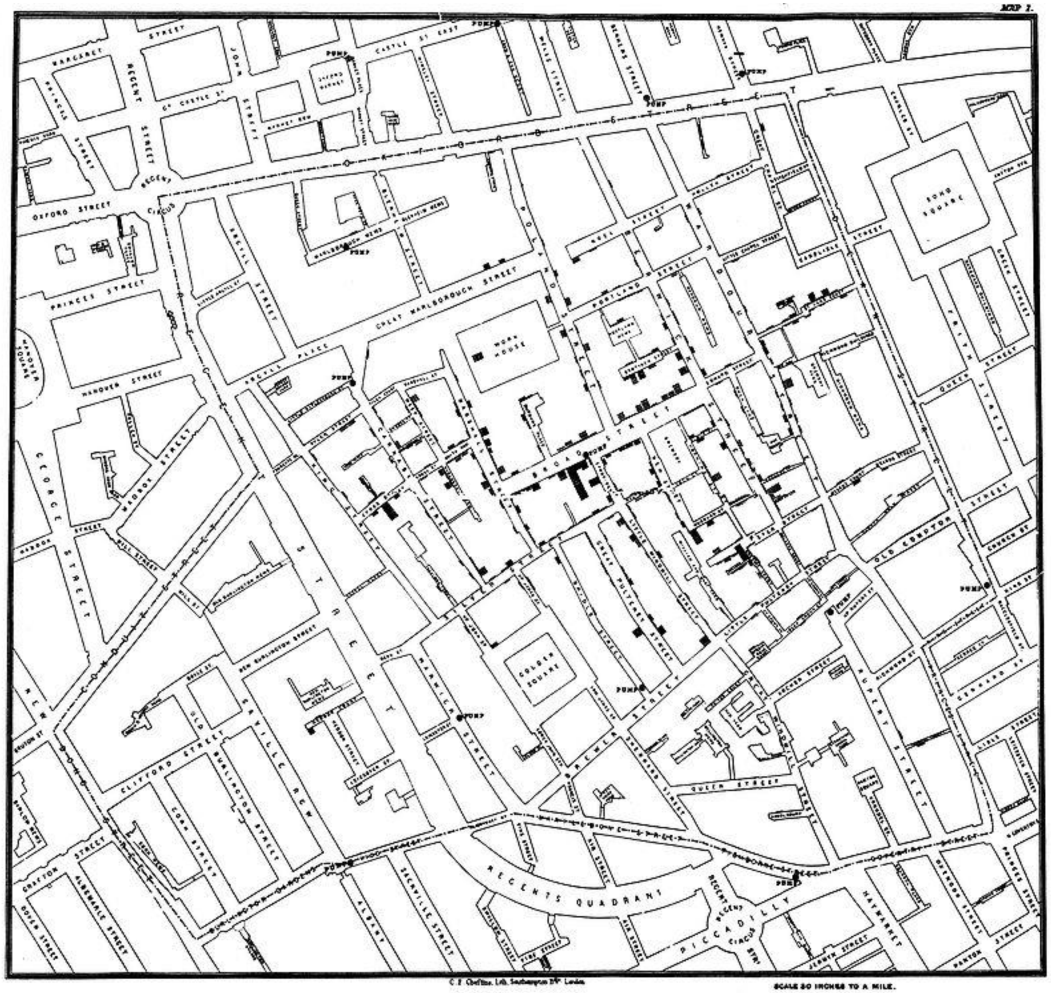
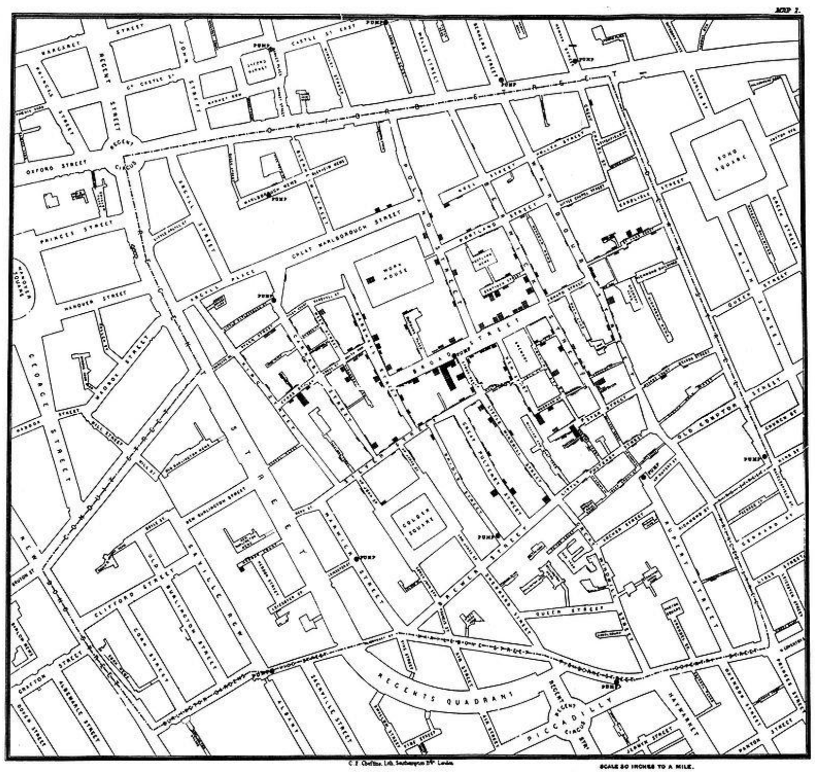
Cholera outbreak



London 1854

Cholera outbreak

- Cholera epidemic in London **1854**
- **John Snow** used a dot map to illustrate the cluster of cholera cases around the **water pump** to show the connection between the quality of the water source and cholera cases
- Snow's study was a major event in the history of public health and geography. It is regarded as the **founding event** of the science of **epidemiology**



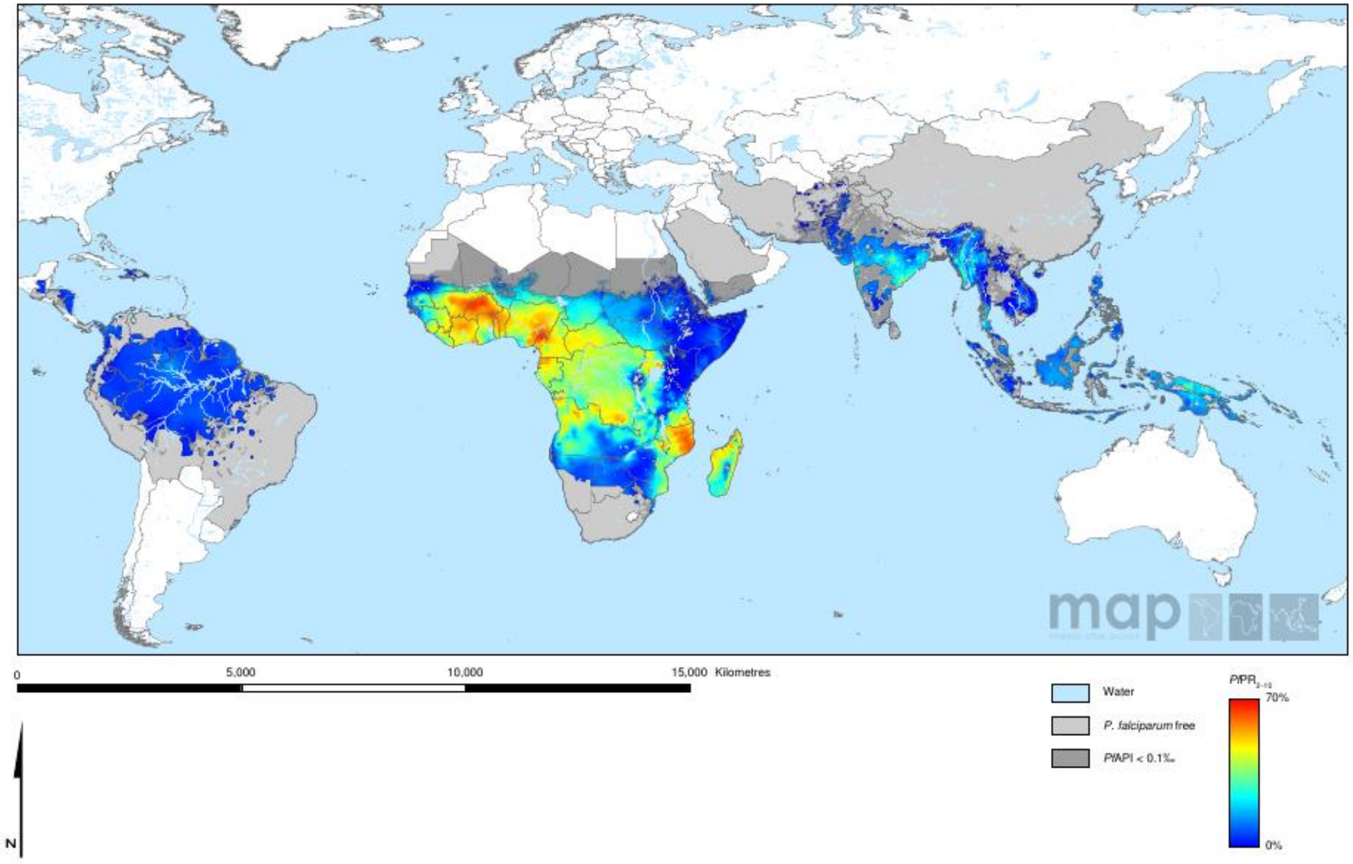
What is Health Geography?

- Health geography is the application of geographical perspectives and methods to the study of health, disease and health care

- Health geography uses the concepts and techniques of geography to investigate health-related issues

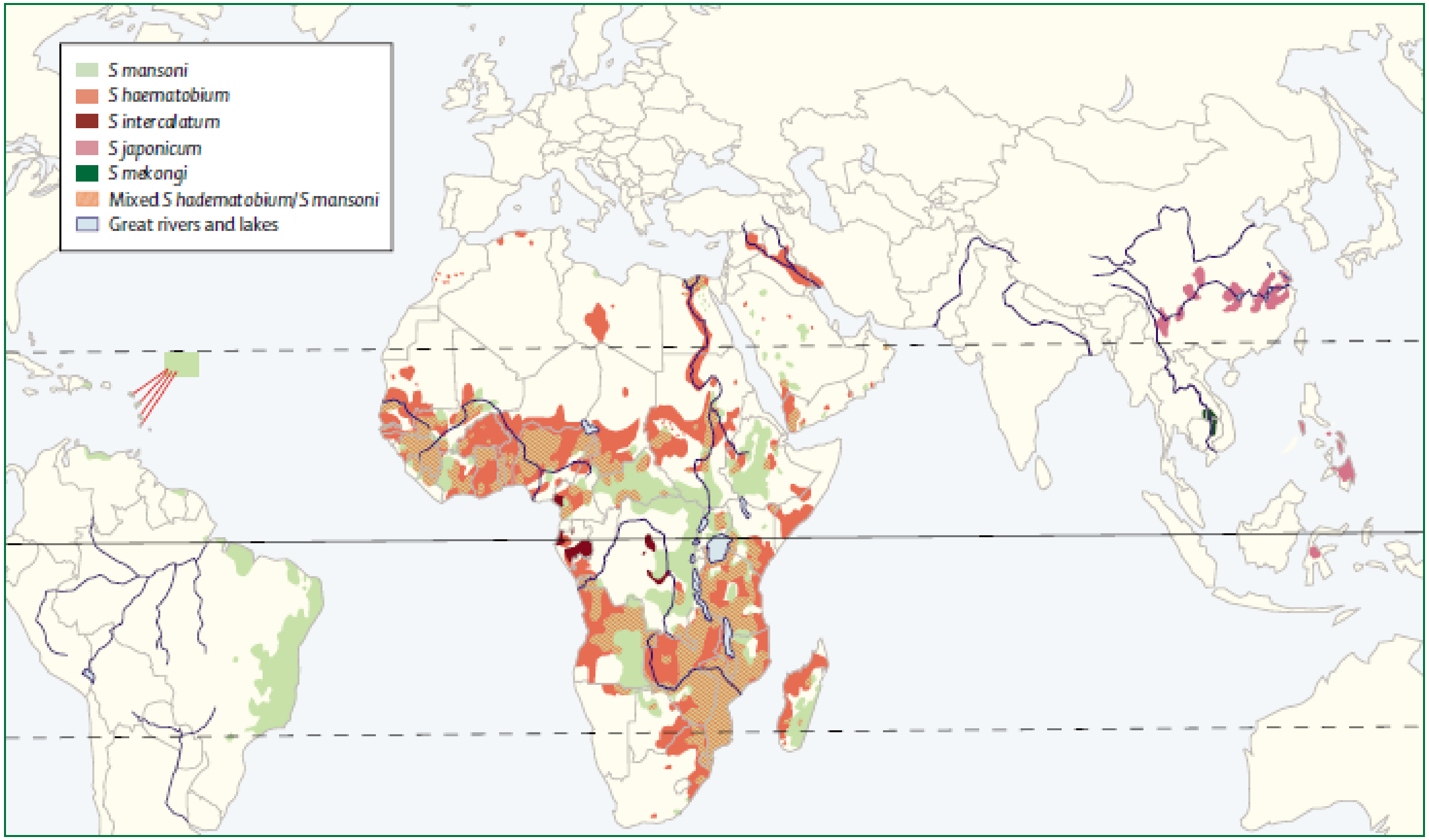
- Health geography, uses the tools and approaches of geography to tackle health-related questions focused on the importance of variations across space, with an emphasis on concepts such as location, direction, and place

Malaria

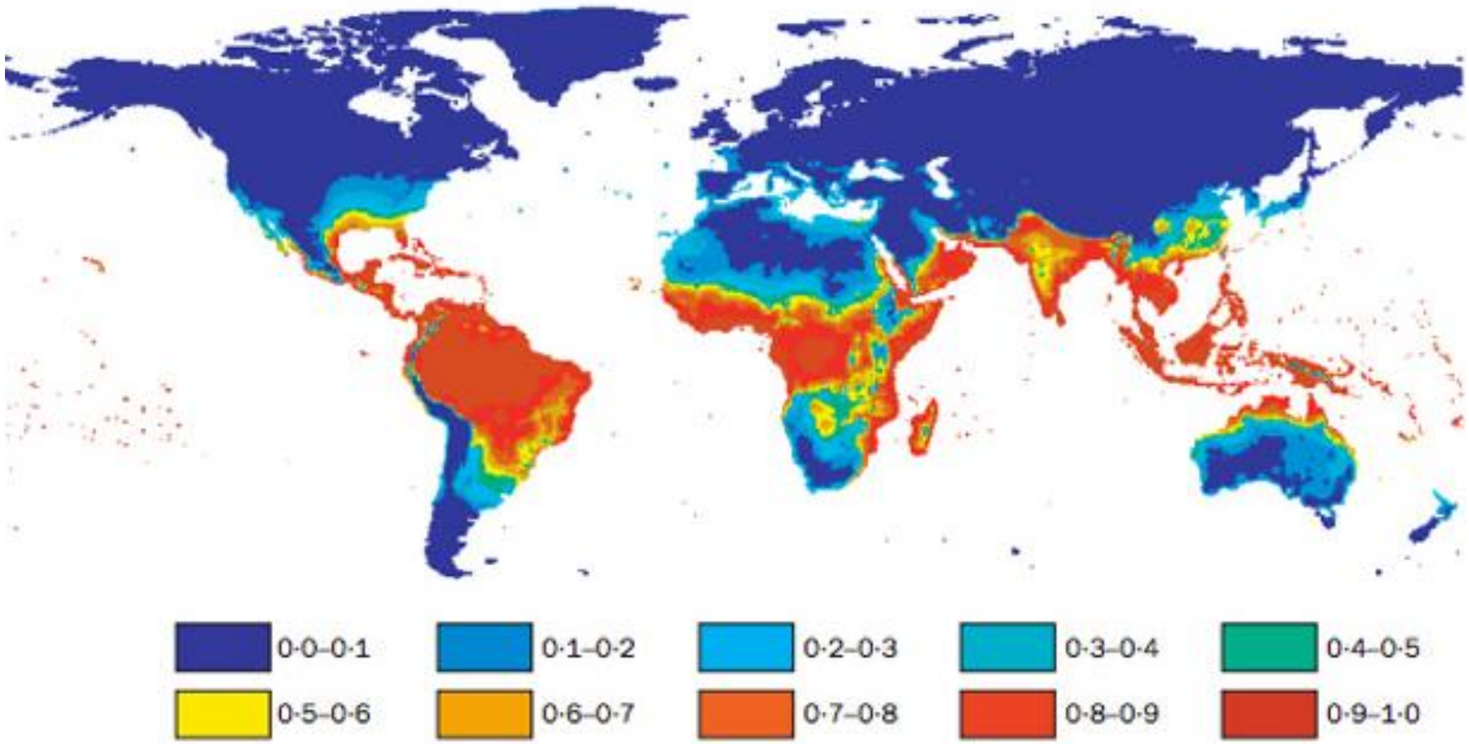


0
5,000
10,000
15,000 Kilometres
N
Water
P. falciparum free
PfAPI < 0.1‰
PfPR2-10
70%
0%

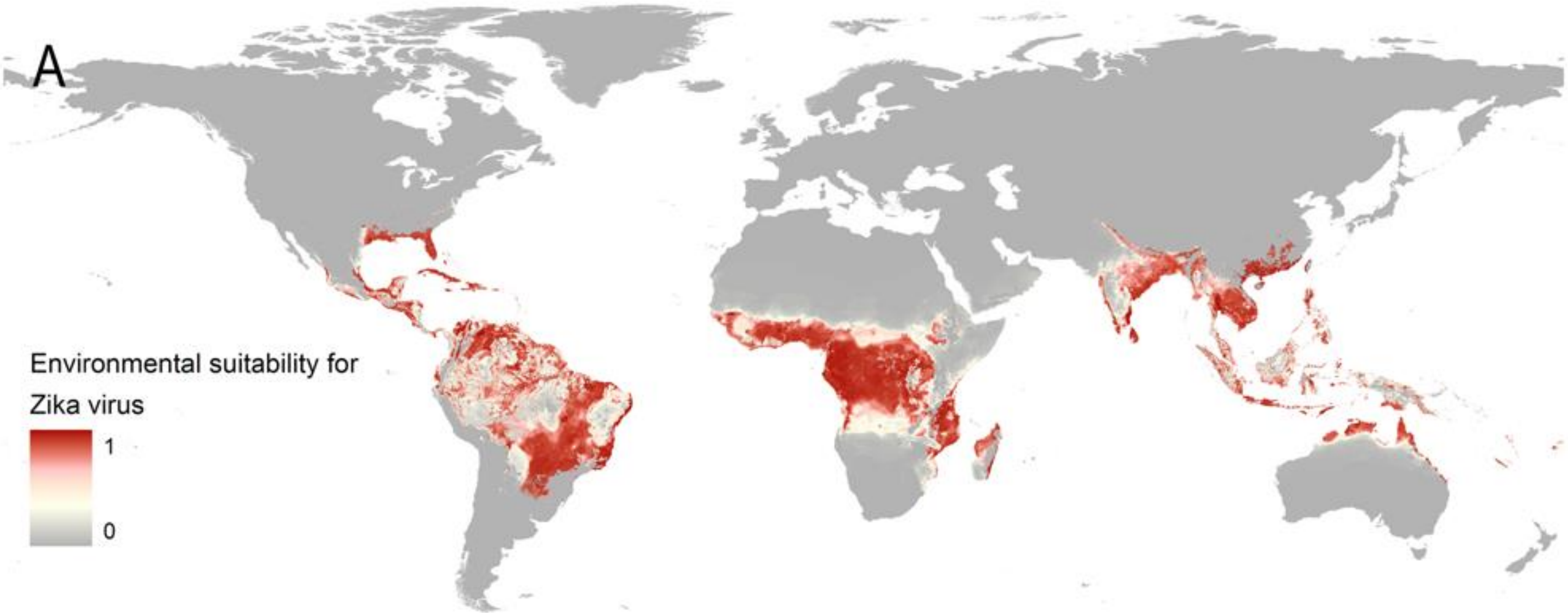
Schistosomiasis



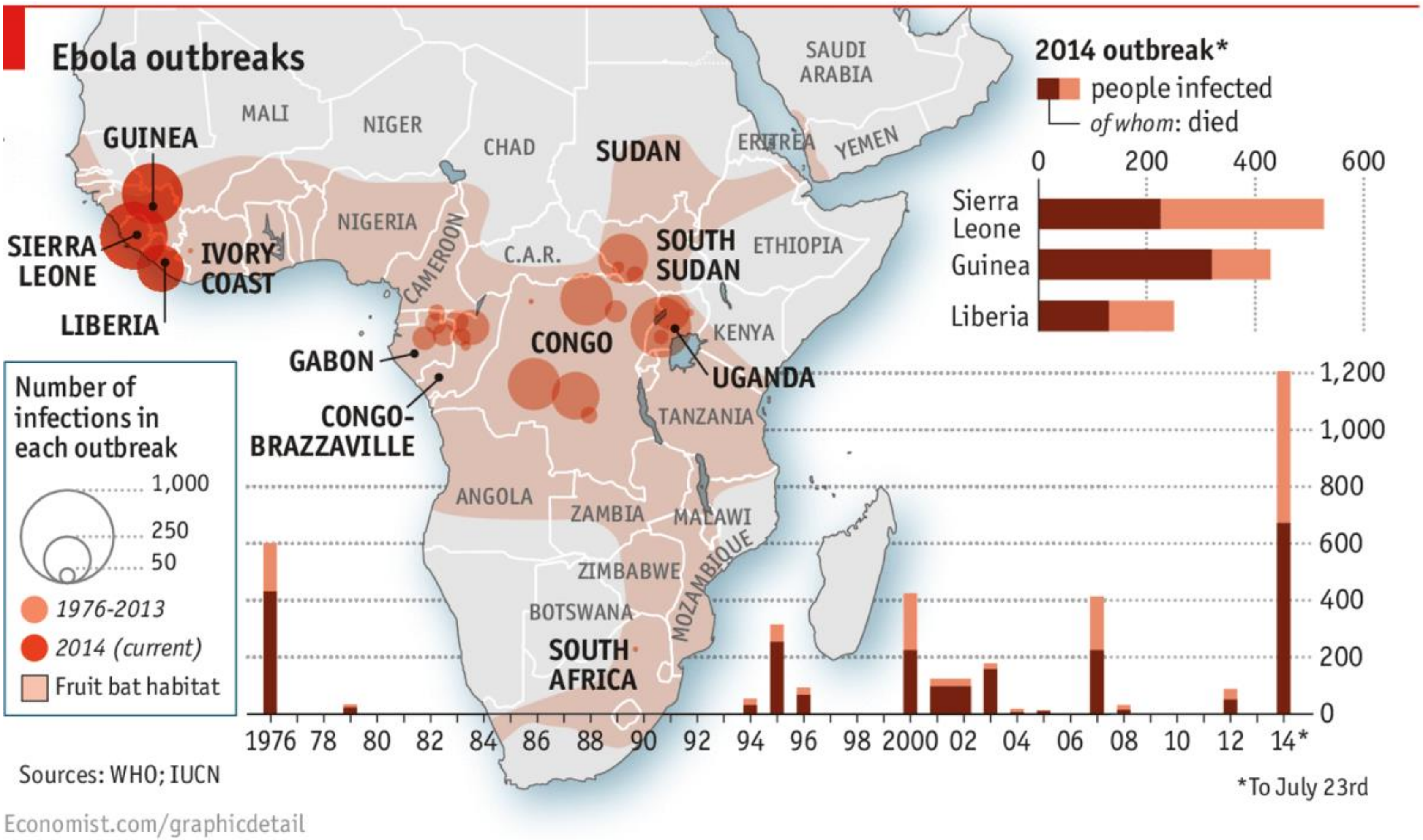
Dengue Fever



Zika virus

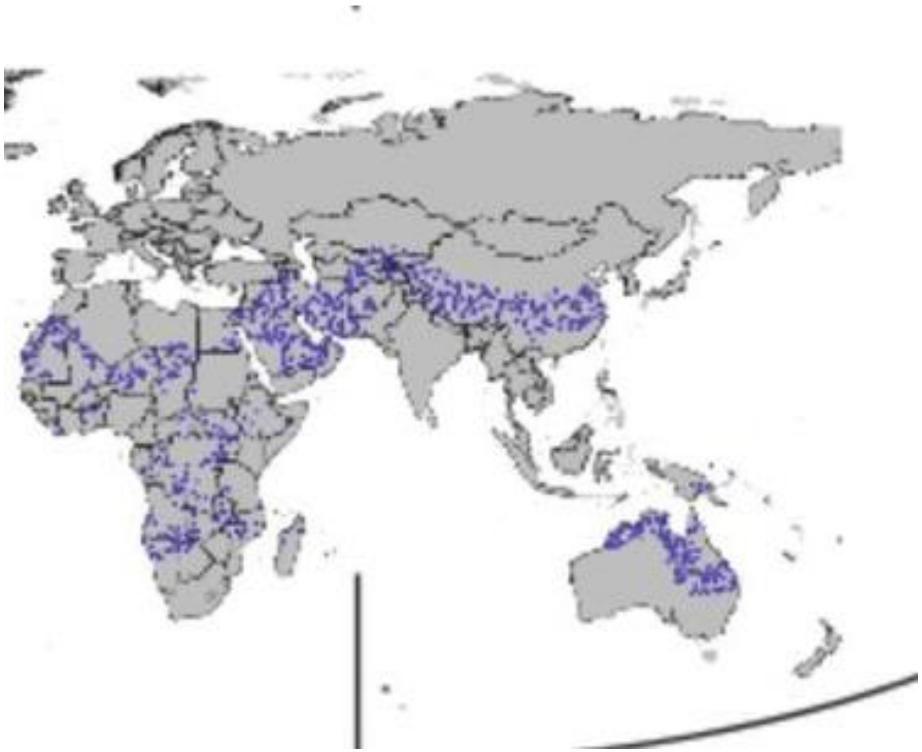


Ebola virus

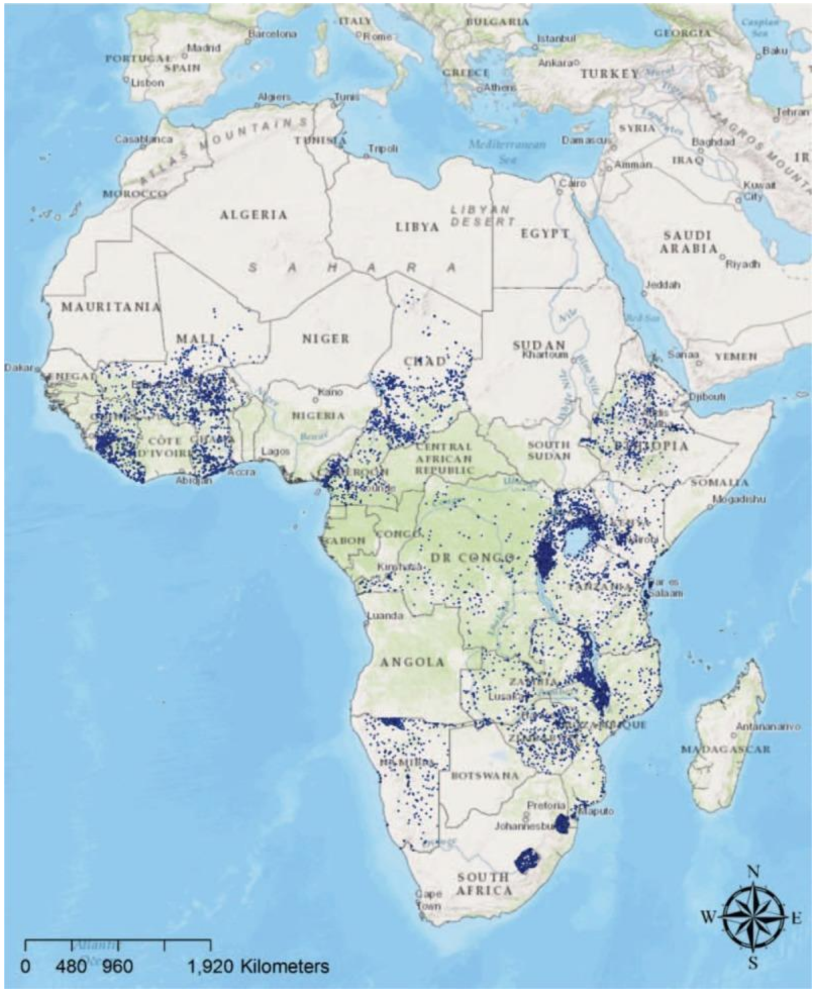

Ebola outbreaks
2014 outbreak*
people infected
of whom: died
0 200 400 600
Sierra Leone
Guinea
Liberia
MALI
NIGER
CHAD
SUDAN
SAUDI ARABIA
ERITREA
YEMEN
GUINEA
SIERRA LEONE
LIBERIA
IVORY COAST
NIGERIA
CAMEROON
C.A.R.
SOUTH SUDAN
ETHIOPIA
KENYA
UGANDA
CONGO
GABON
CONGO-BRAZZAVILLE
TANZANIA
ANGOLA
ZAMBIA
MALAWI
MOZAMBIQUE
ZIMBABWE
BOTSWANA
SOUTH AFRICA
Number of infections in each outbreak
1,000
250
50
1976-2013
2014 (current)
Fruit bat habitat
1,200
1,000
800
600
400
200
0
1976 78 80 82 84 86 88 90 92 94 96 98 2000 02 04 06 08 10 12 14*
Sources: WHO; IUCN
*To July 23rd
Economist.com/graphicdetail

Health geography and spatial epidemiology has gained popularity and relevance during the recent years, **why**?

Spatial data



Malaria sample sites



Demographic Health surveys sample sites

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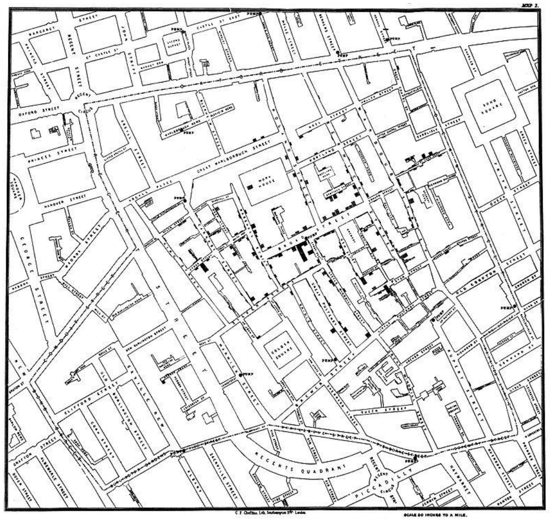
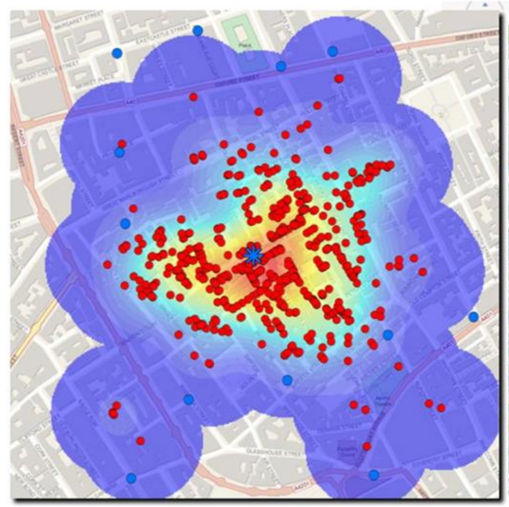
Social networks

The image is of London; red dots represent instagram uploads and blue dots are the tweets. The white dots show us which locations post to both.

Cholera outbreak



http://livinggeography.blogspot.com/2011/10/john-snows-cholera-map-redux.html



http://alastaira.wordpress.com/2011/09/08/maps-in-the-time-of-cholera/ http://donboyes.com/2011/10/14/john-snow-and-serendipity/

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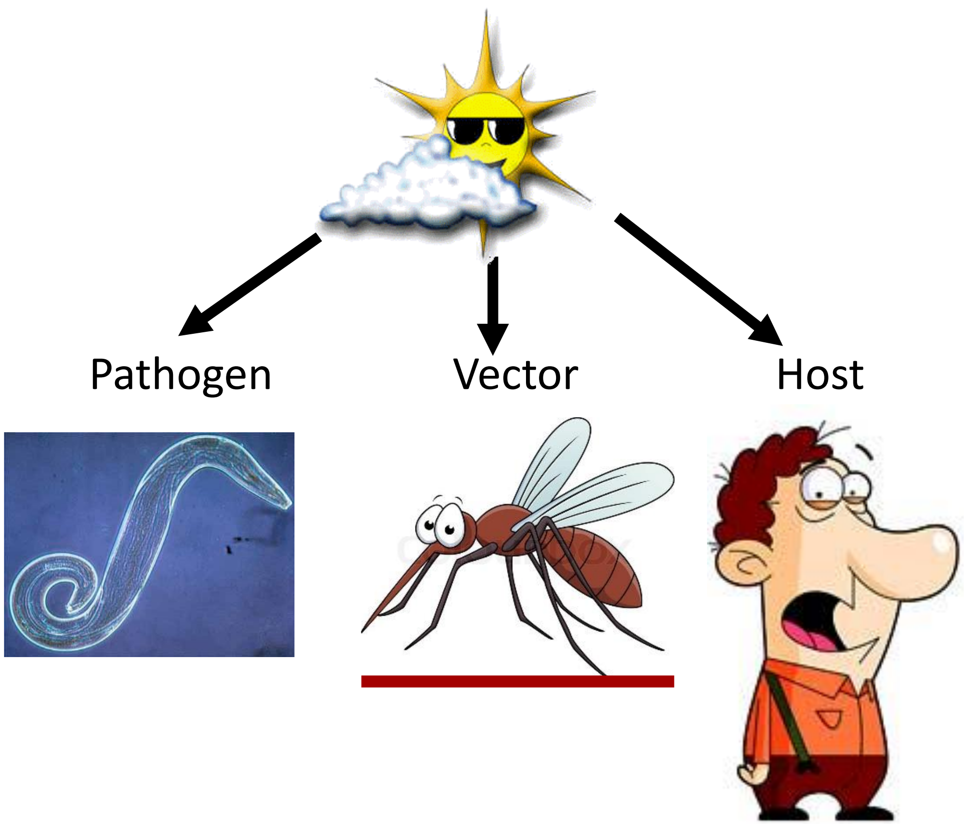
Disease mapping examples

Malaria Atlas Project

Ecological Niche Modeling: Vector-borne diseases

Vector-borne diseases



Cofactors

Environmental variables:

- Normalized Difference Vegetation Index (NDVI)

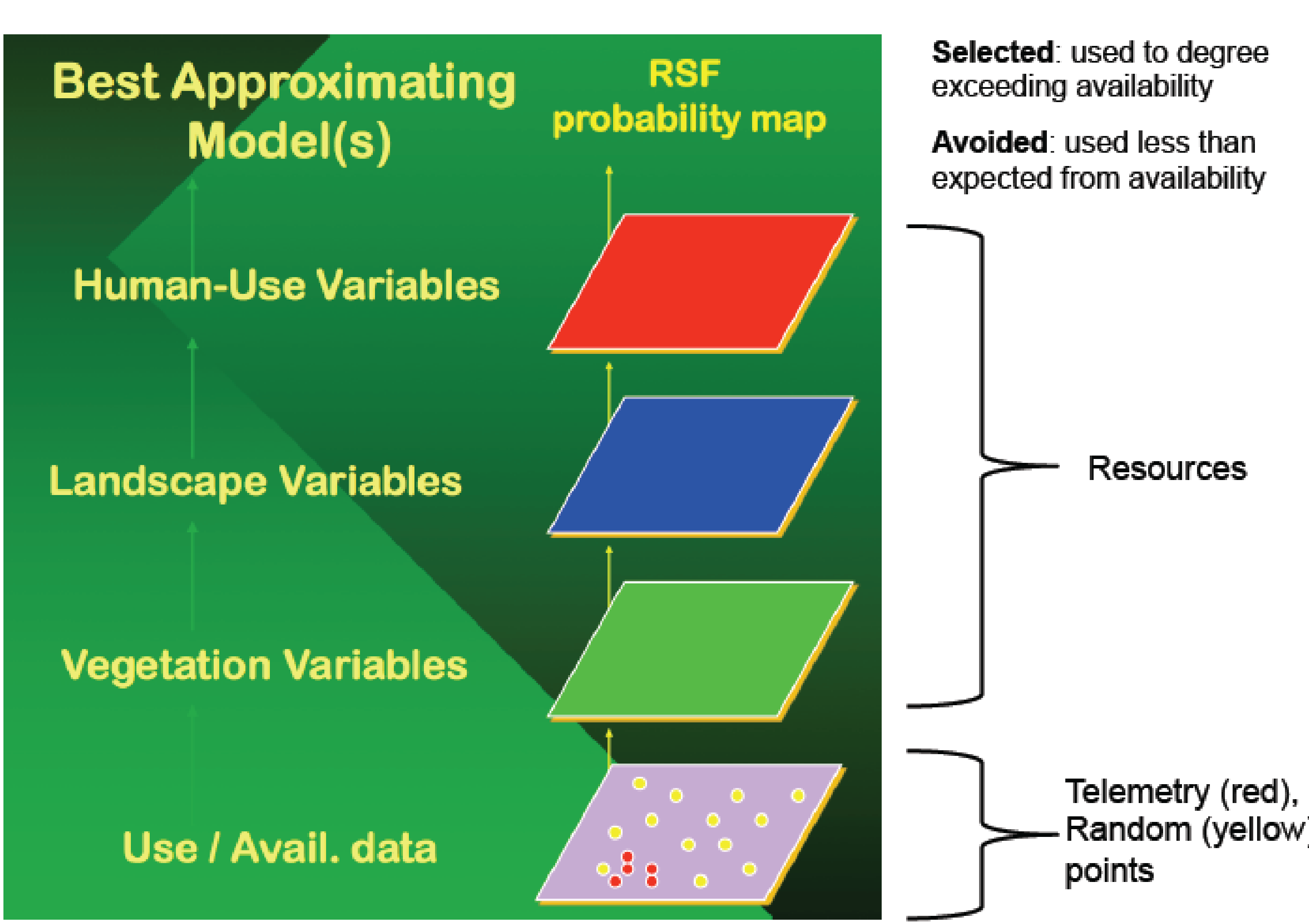
- Temperature

- Precipitation

- Evapotranspiration

- Elevation

Ecological Niche Modeling



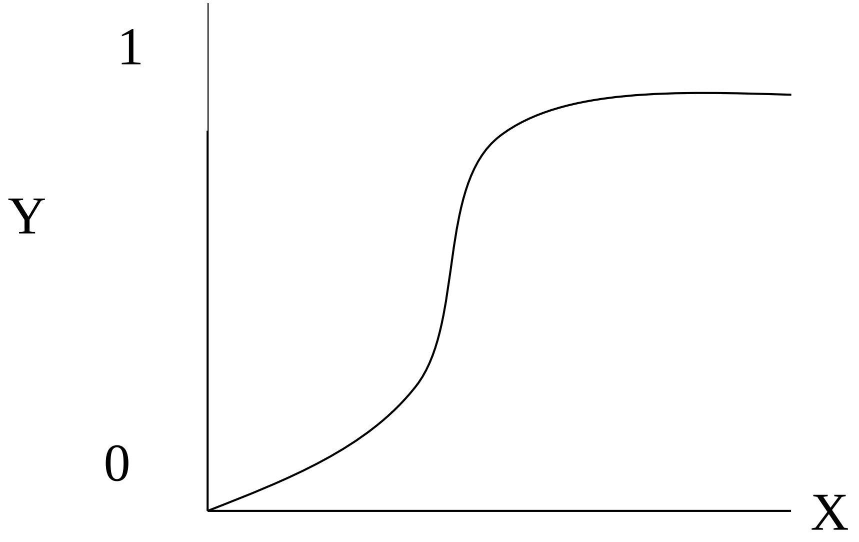
Habitat Evaluation Procedures

Logistic regression:

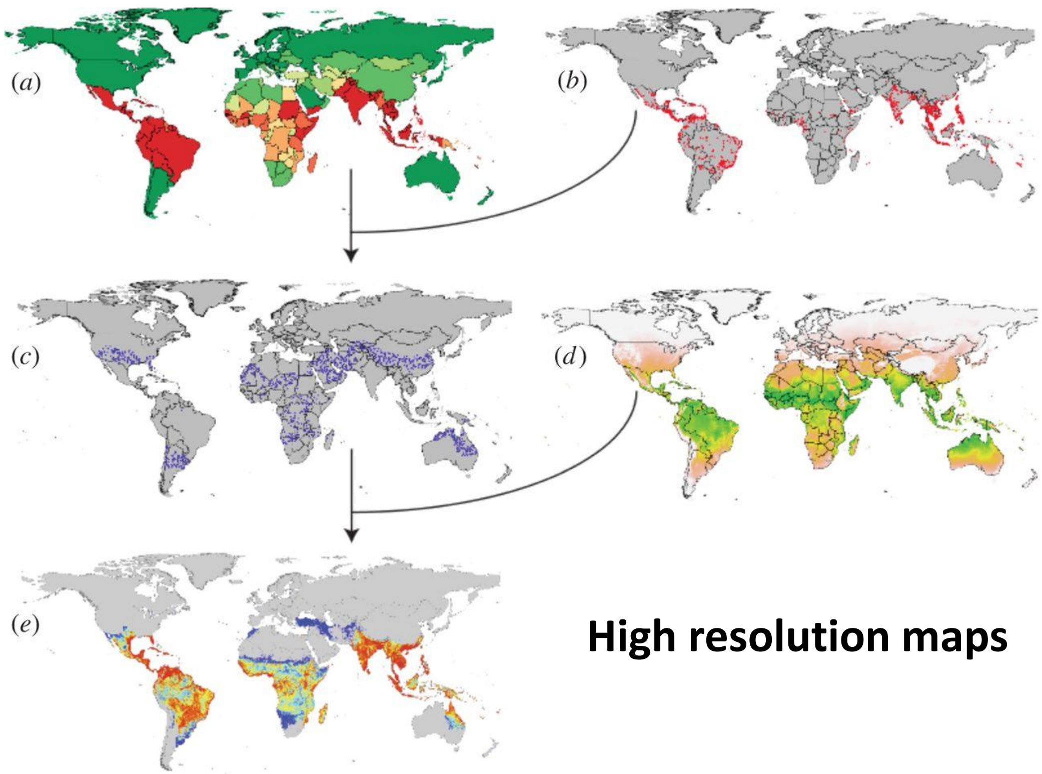
$Y = \beta 0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 = \text{logit}(p)$

$\Pr(Y = 1 \mid \text{the explanatory variables } x) = \pi$

$\pi = e^{-\text{logit}(p)} / [1 + e^{-\text{logit}(p)}]$



Ecological Niche Modeling: Vector-borne diseases



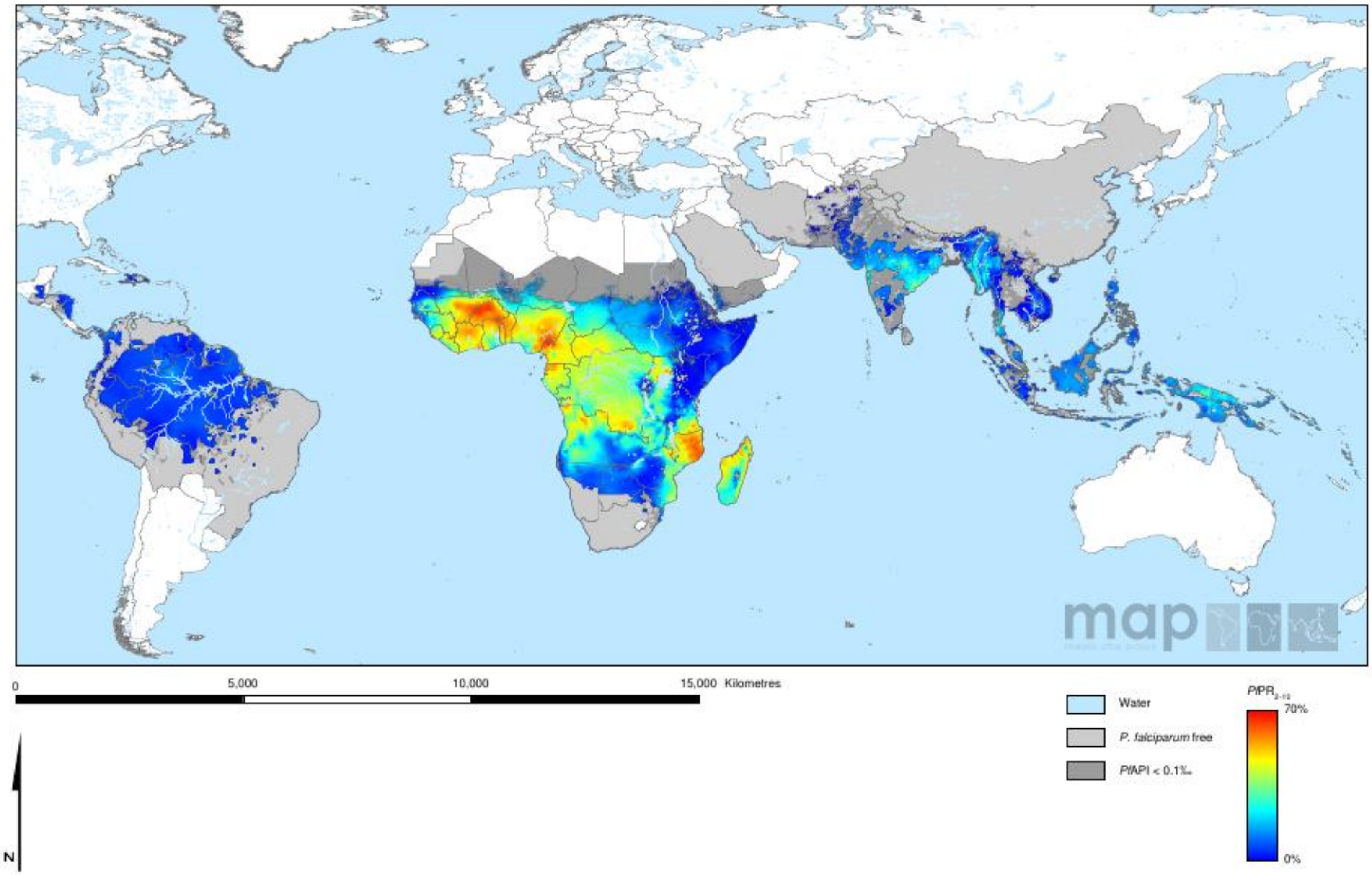
Georeferenced data points

Environmental cofactors

High resolution maps

High resolution maps of the **geographic distribution of a disease**. The use of the survey data from a **sample of locations** to predict continuous surfaces of risk, informed by **environmental and demographic covariates**

Malaria



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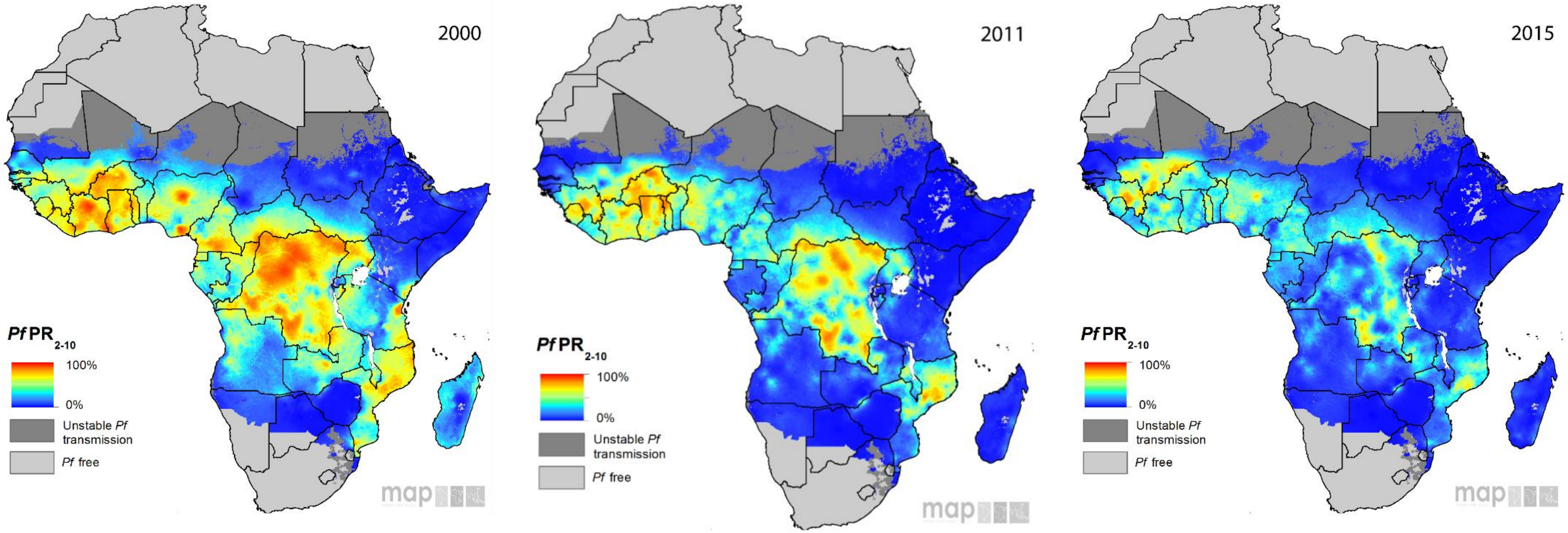
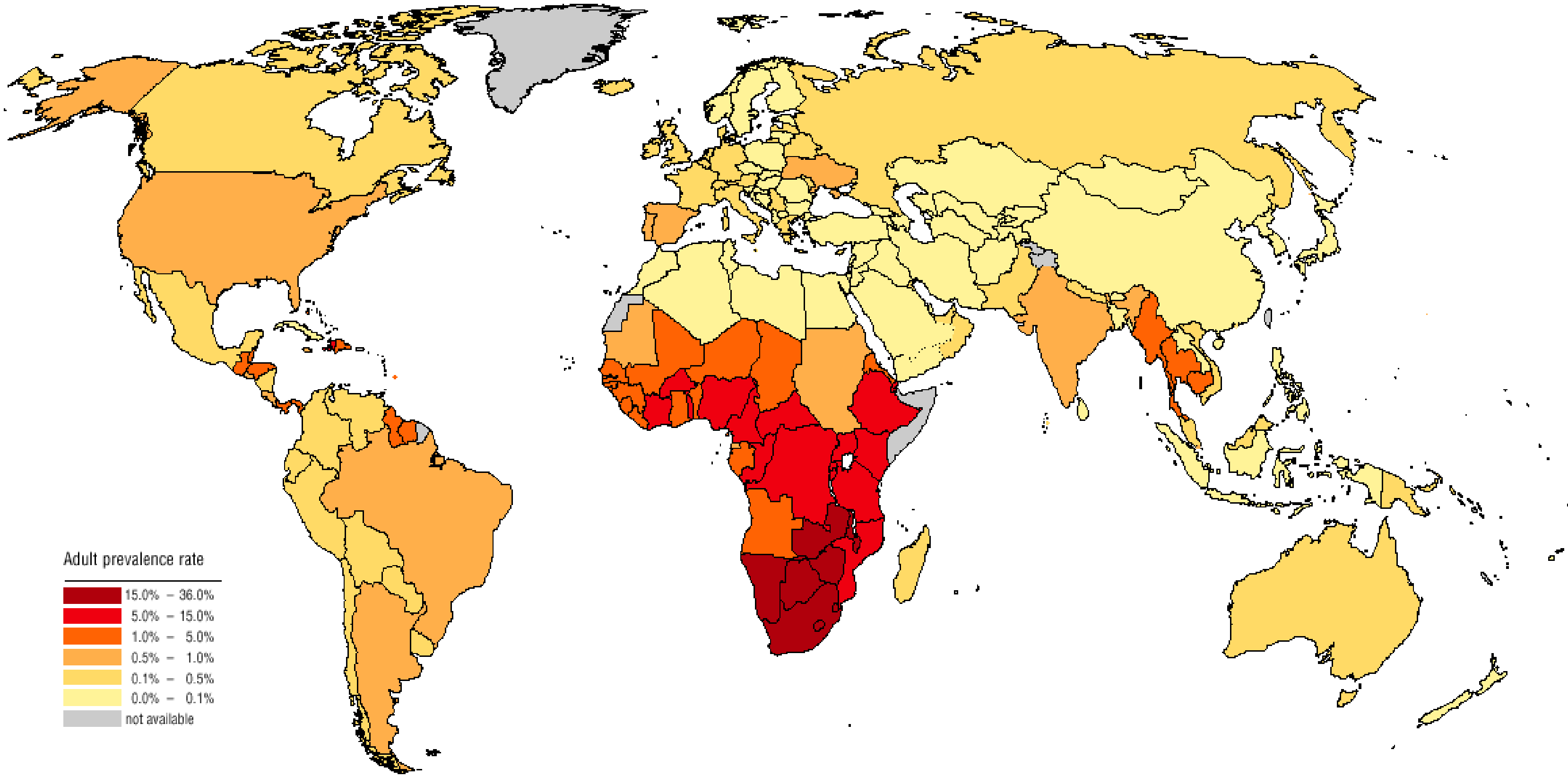
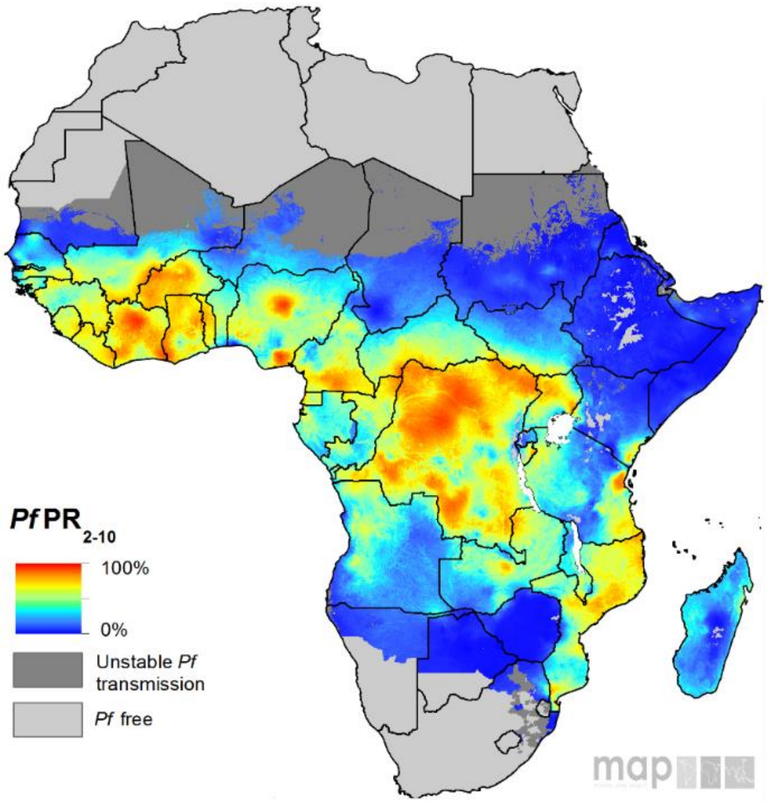
Spatio-temporal dynamics of malaria



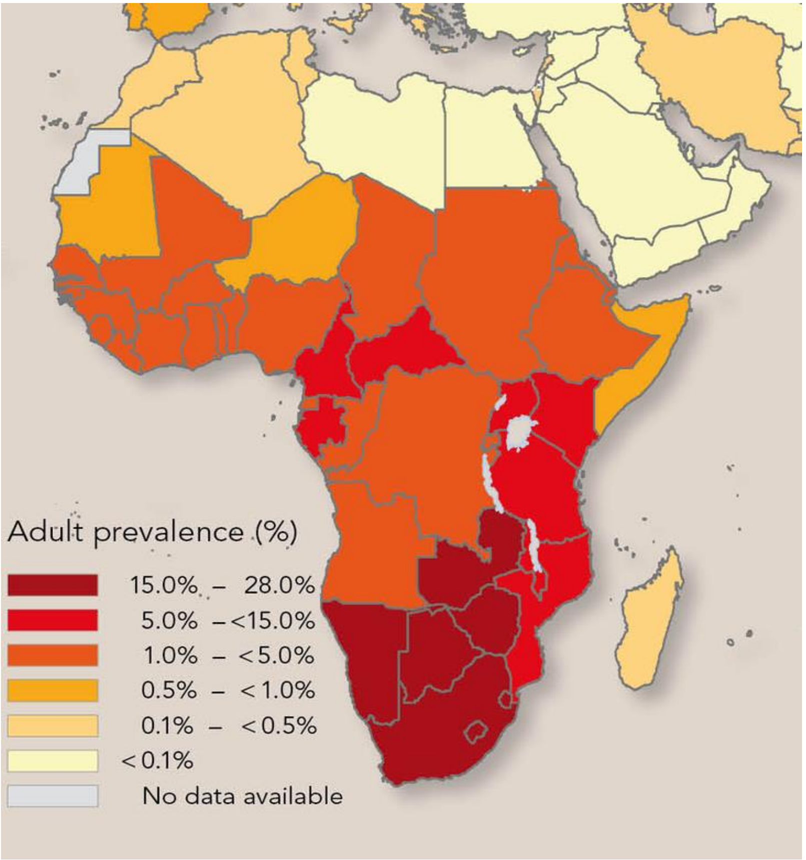
HIV



Adult prevalence rate
15.0% – 36.0%
5.0% – 15.0%
1.0% – 5.0%
0.5% – 1.0%
0.1% – 0.5%
0.0% – 0.1%
not available



Malaria



HIV

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Introduction: HIV

- The human immunodeficiency virus (HIV) is retrovirus that causes HIV infection and over time acquired immunodeficiency syndrome (AIDS)

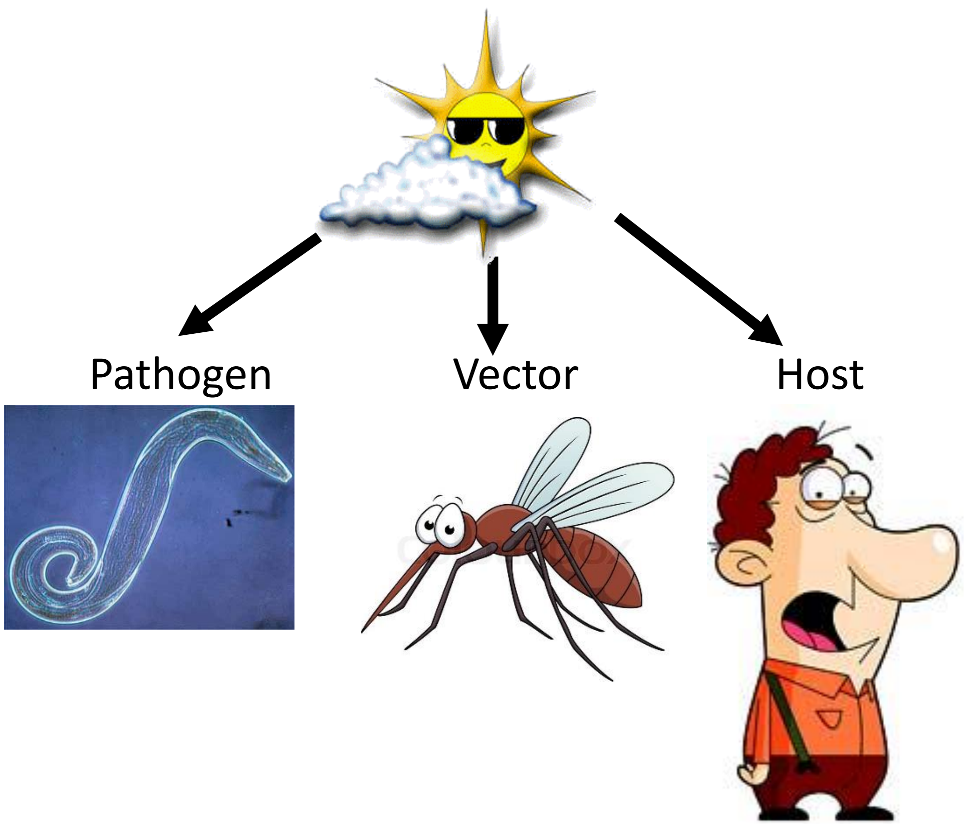
- AIDS is a condition in humans in which progressive failure of the immune system allows life-threatening opportunistic infections to thrive

- Without treatment, average survival time after infection with HIV is estimated to be 9 to 11 years

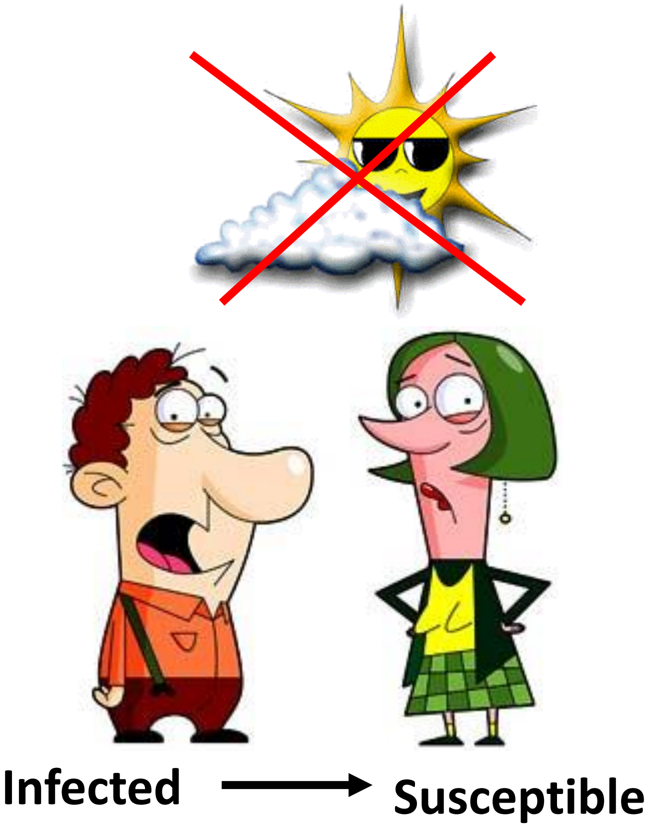
- **Infection with HIV occurs by the transfer of blood, semen, vaginal fluid, or breast milk**

Introduction: HIV

Vector-borne diseases

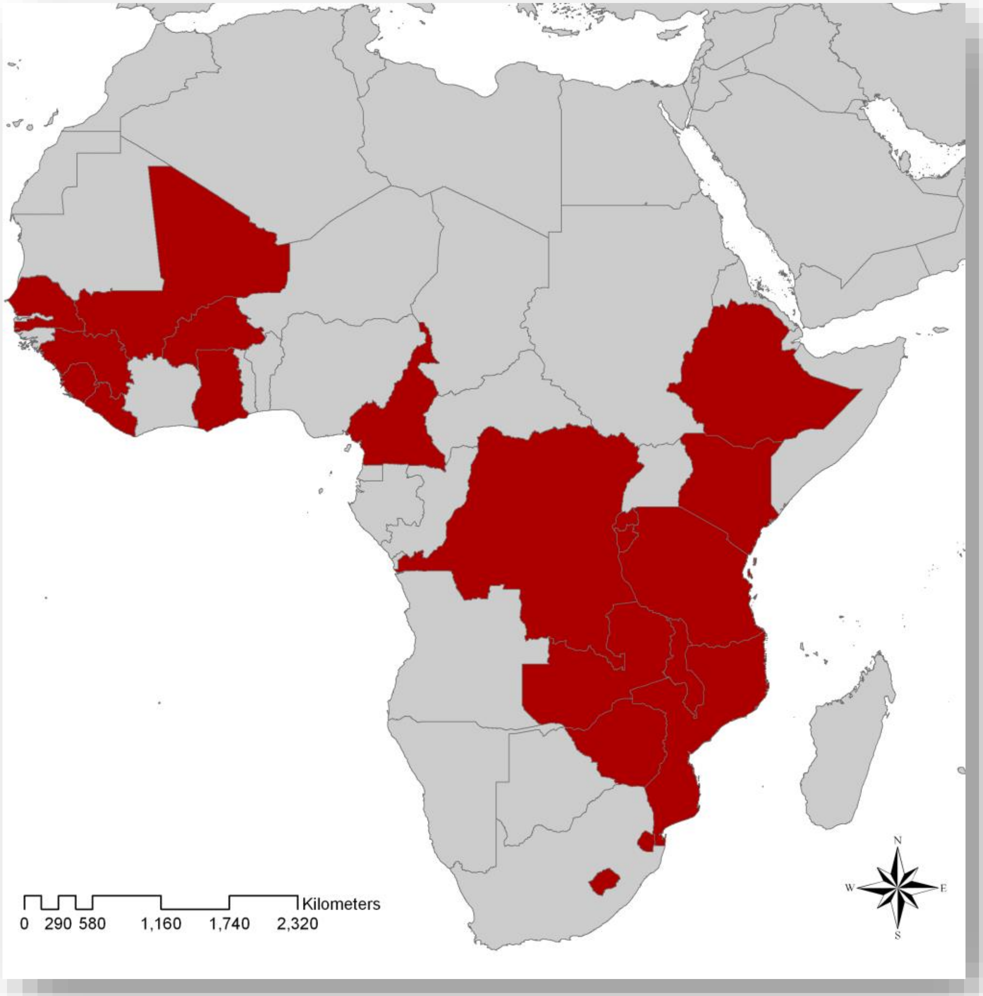


Sexually transmitted infections (STI)



Is the spatial distribution of HIV random? Clustered?

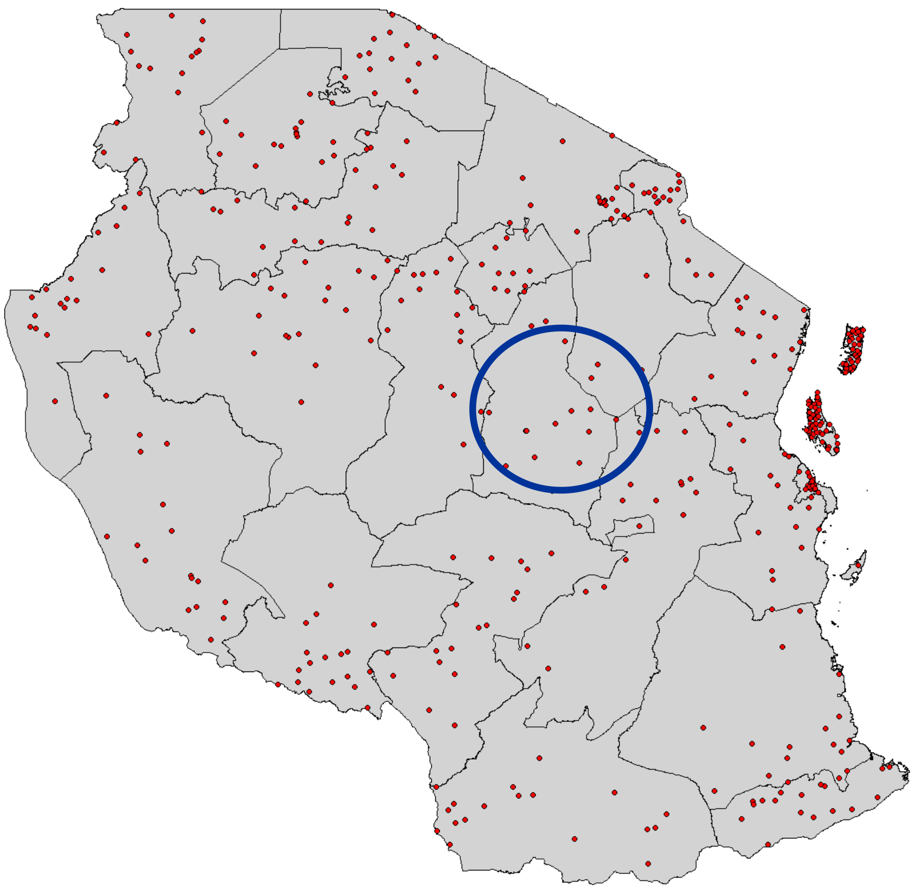
- For each country, we only considered the most recent Demographic Health Survey where HIV data were collected. As a result, a total of **20 countries in SSA were included**



Methods: Clustering analysis

- **Spatial scan statistics** is a cluster detection test able to find the location of areas with **higher or lower numbers of cases** (for instance HIV infections) than expected

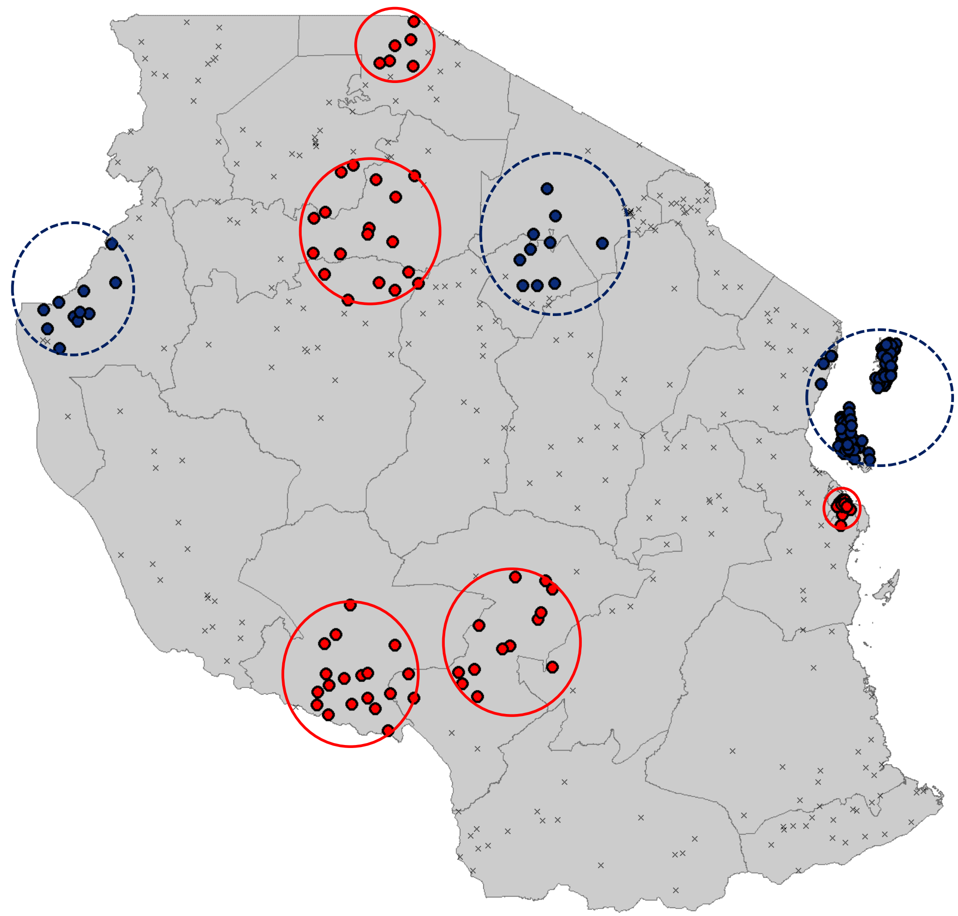
- For each potential cluster, a likelihood ratio test was computed. The numbers of observed and expected HIV infections within and outside the circular window were then compared to test the **null hypothesis of spatial randomness**



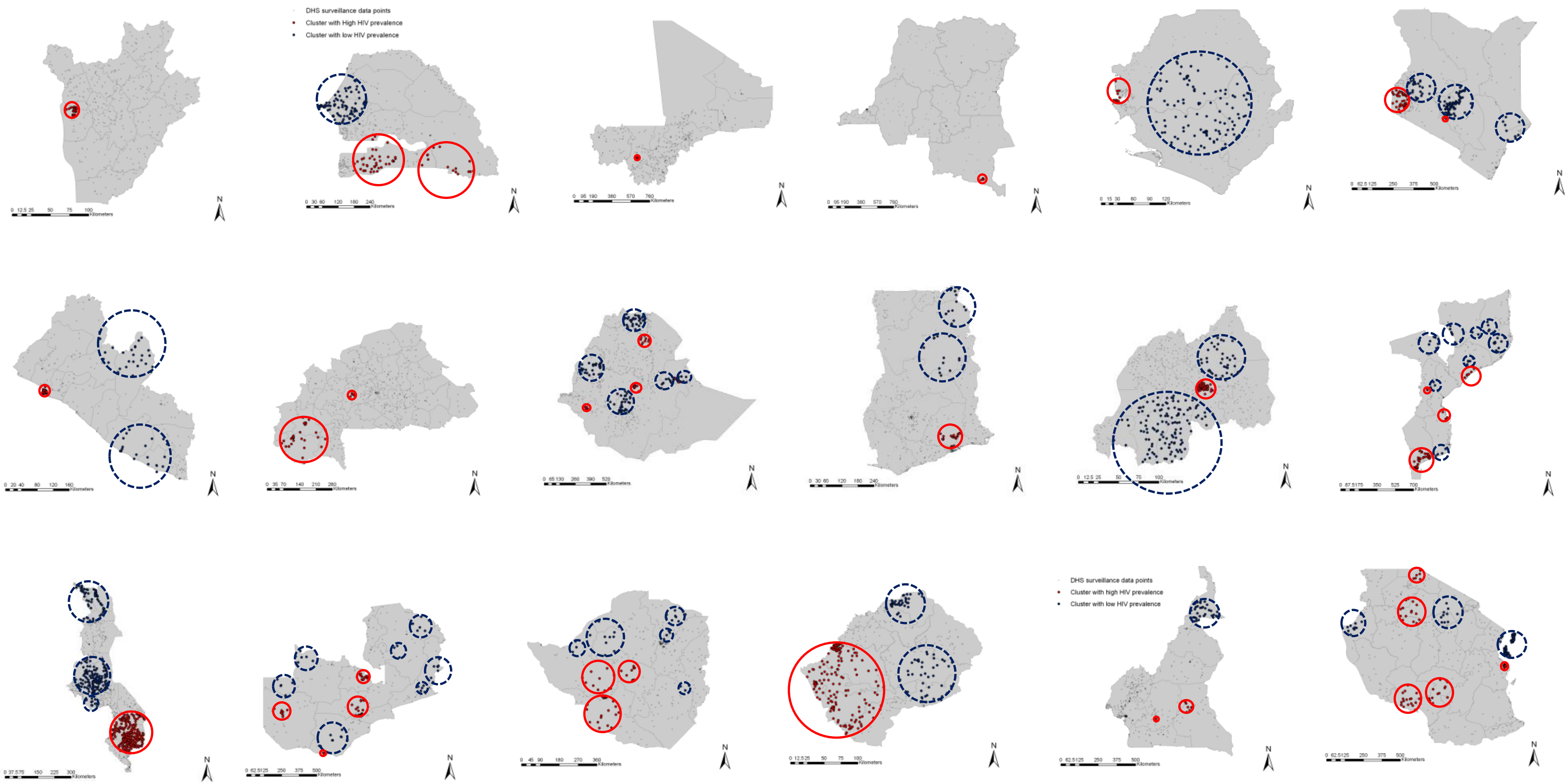
Hot and cold spots

- We identified **38** clusters with high HIV prevalence (**hot spots; red circles**), and **45** clusters with low HIV prevalence (**cold spots; blue circles**)

- The HIV seroprevalence within the clusters with high HIV seroprevalence ranged from 1.9% in a cluster in Senegal to 30.8% in a cluster in Zimbabwe, with a **median of 11.5%**



HIV clustering



Cuadros, Diego F., Susanne F. Awad, and Laith J. Abu-Raddad. "Mapping HIV clustering: a strategy for identifying populations at high risk ofHIV infection in sub-Saharan Africa." International journal of health geographics (2013)

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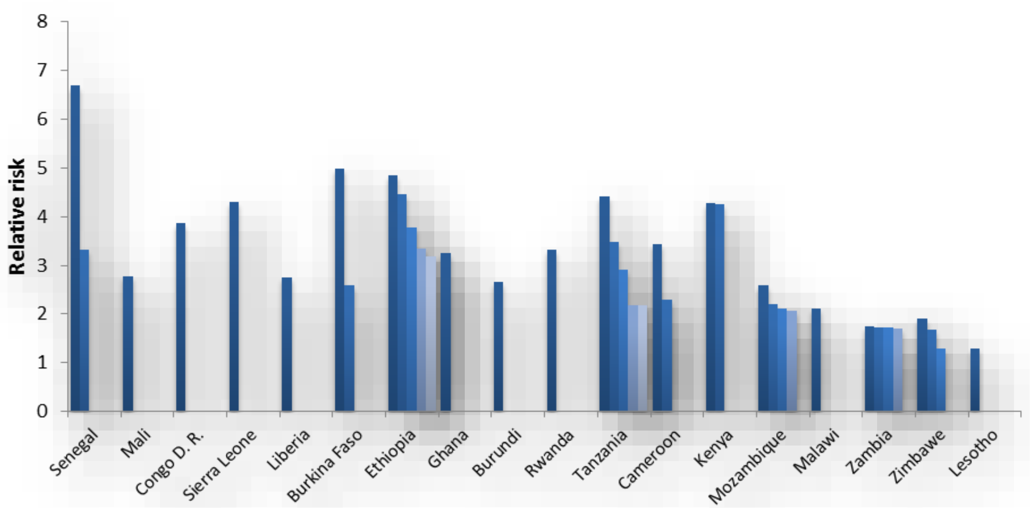
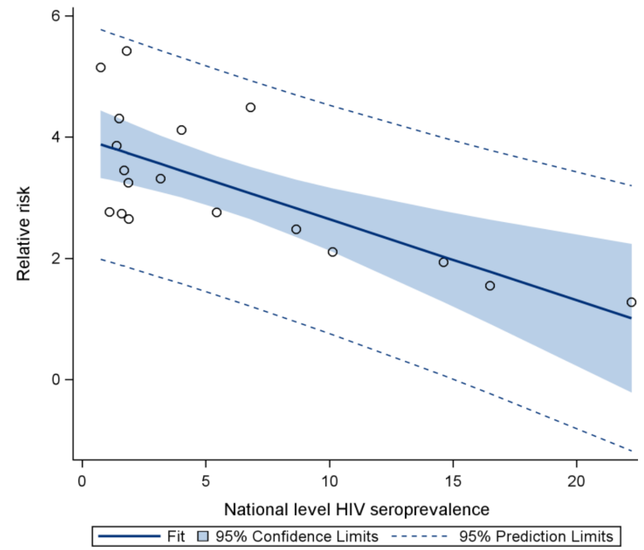
Results: HIV clustering





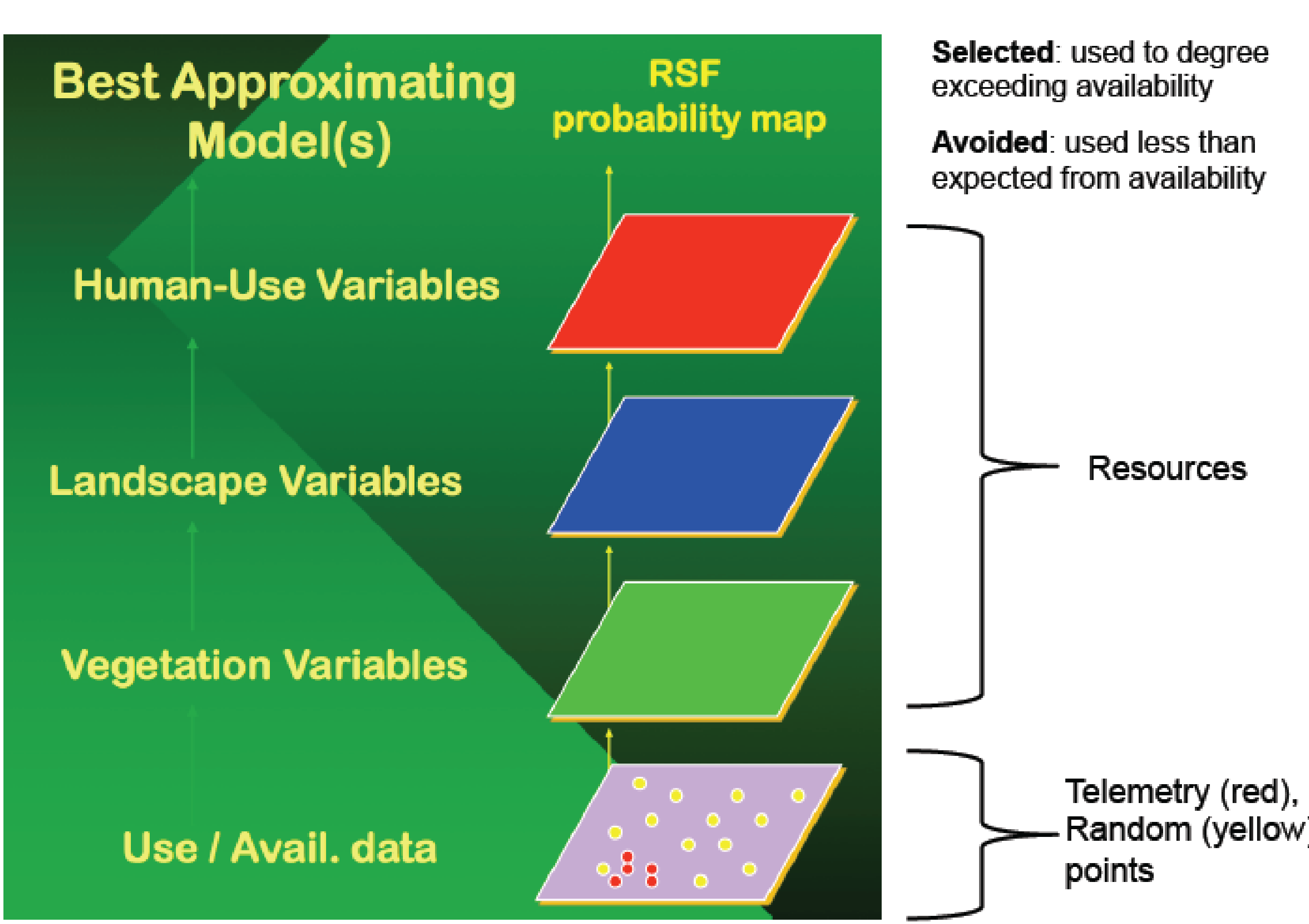
The relative risk of HIV infection for individuals within clusters with high HIV seroprevalence was **negatively associated with HIV prevalence** of the corresponding country ($p < 0.001$)

Cuadros, Diego F., Susanne F. Awad, and Laith J. Abu-Raddad. "Mapping HIV clustering: a strategy for identifying populations at high risk ofHIV infection in sub-Saharan Africa." International journal of health geographics (2013)

- The results of our analysis indicate **stark geographical variation in HIV prevalence** in most of the countries. The observed spatial variation in HIV prevalence highlights **a clustered HIV transmission across SSA** within micro-epidemics of different scales

Could environmental and socio-economic and behavioral factors be used to generate high resolution maps of HIV prevalence in SSA?

Ecological Niche Modeling



HIV factors

Four countries

Tanzania, Kenya, Malawi and Mozambique

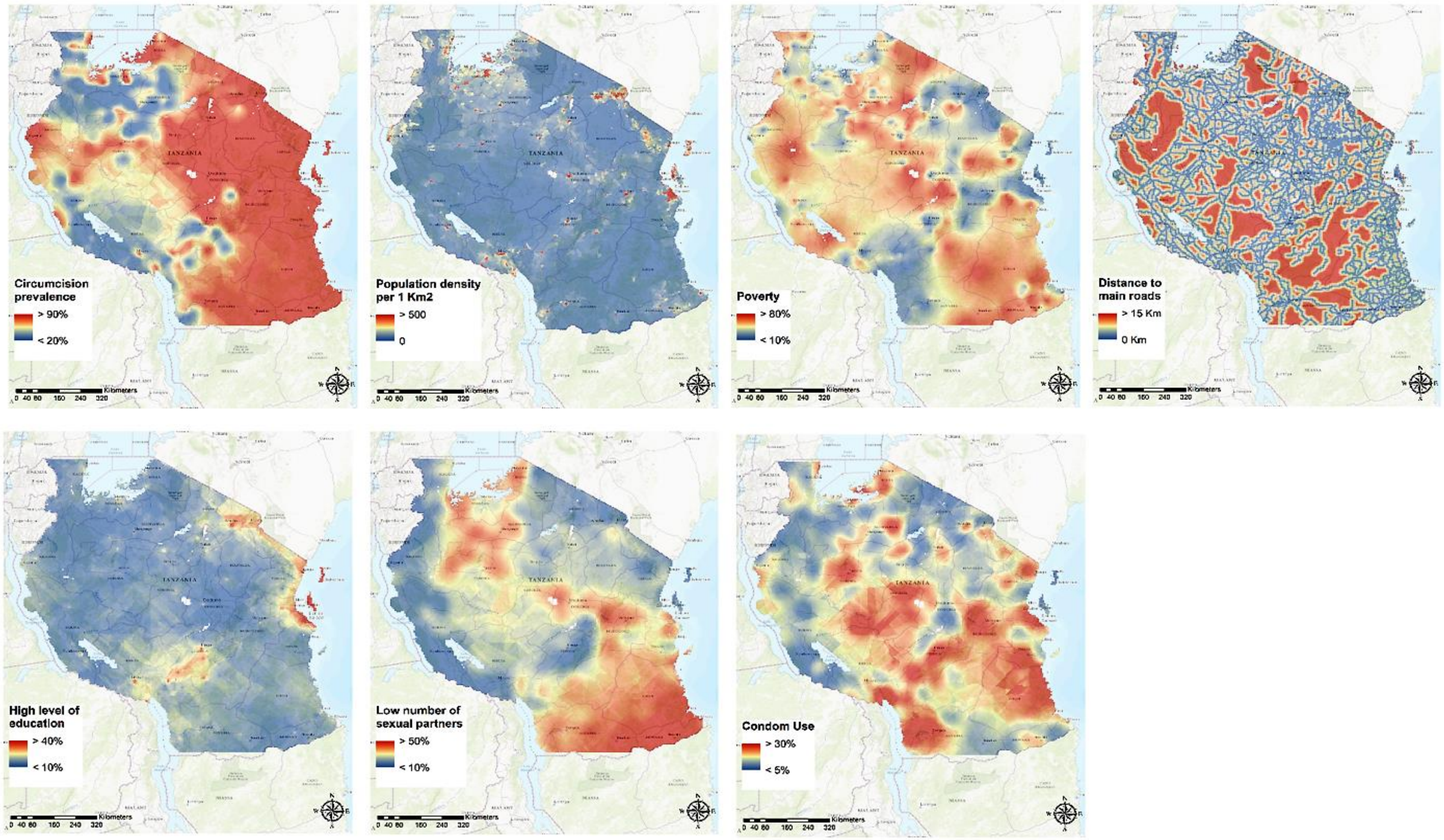
Environmental (geographical) factors:

- Normalized Difference Vegetation Index (NDVI)
- Population
- Distance to main roads

Socio-economic and behavioral factors:

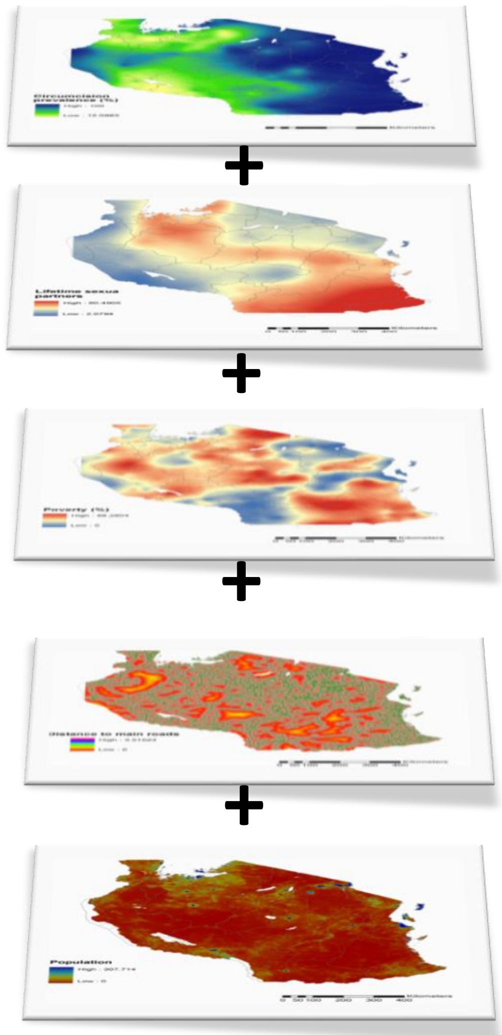
- Wealth index
- Male circumcision
- Lifetime sexual partners
- Education
- Ever been tested for HIV
- Condom use

Maps of cofactors



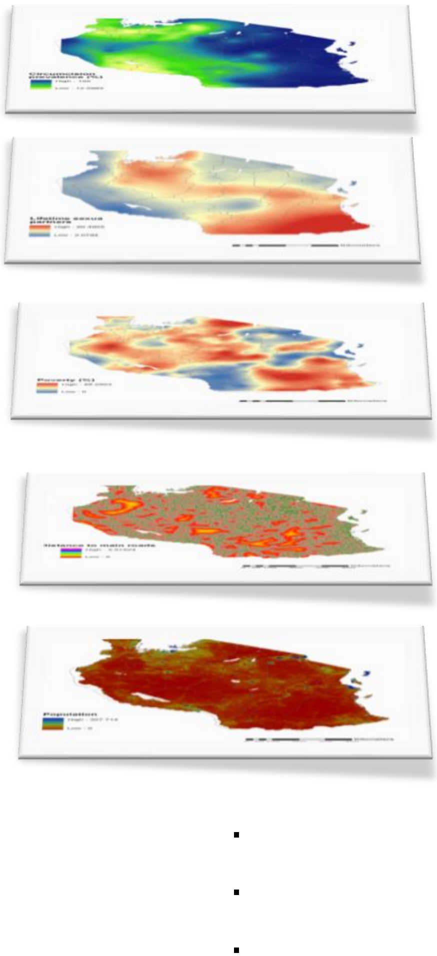
Cuadros, Diego F., et al. "Mapping the spatial variability of HIV infection in Sub-Saharan Africa: Effective information for localized HIV prevention and control." Scientific reports (2017)

Maps of cofactors



= High Resolution HIV prevalence map

High resolution map of HIV in Tanzania



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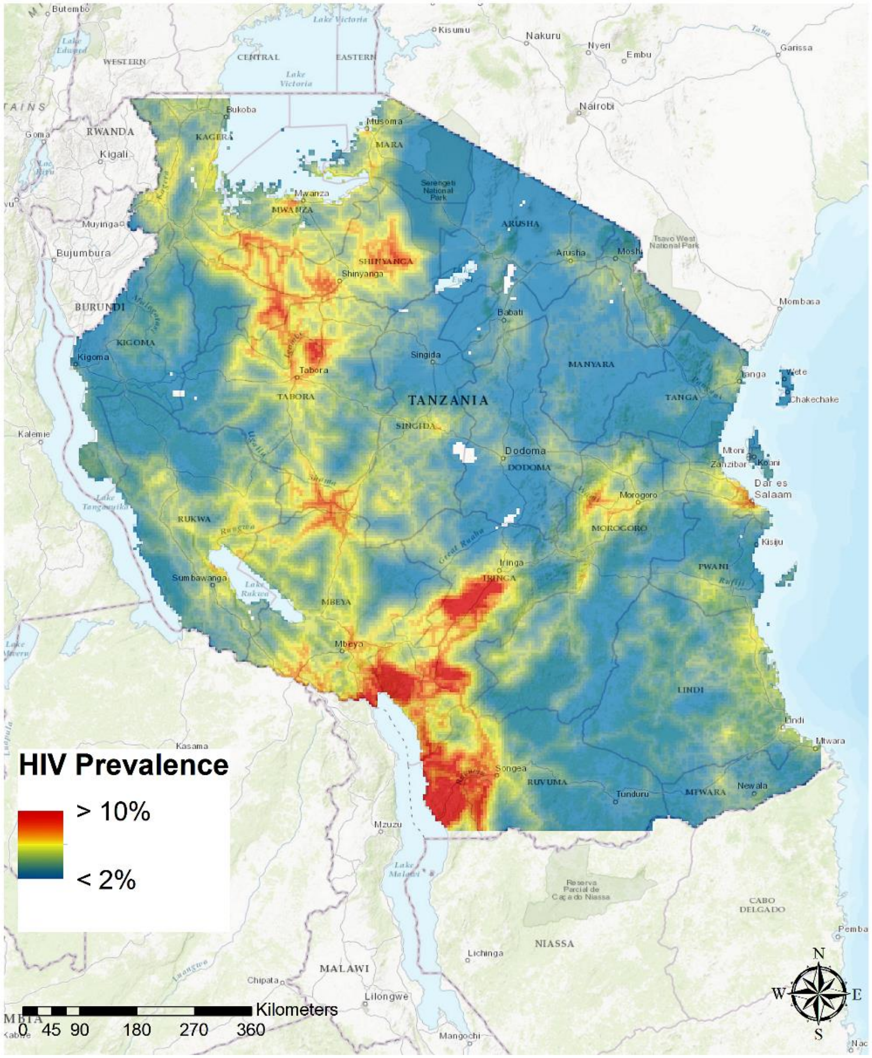
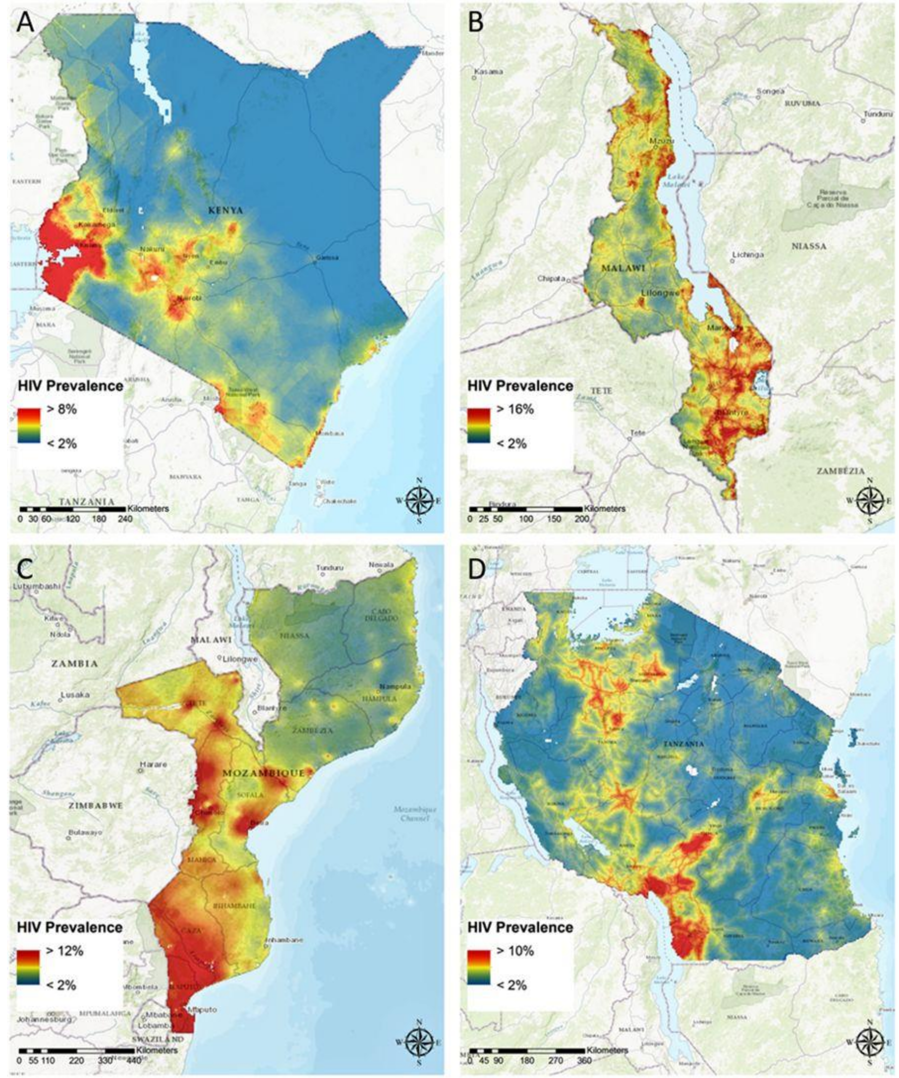


High resolution maps for HIV prevalence in East Africa



High resolution maps for HIV prevalence in (**A**) Kenya; (**B**) Malawi; (**C**) Mozambique; and (**D**) Tanzania.

Cuadros, Diego F., et al. "Mapping the spatial variability of HIV infection in Sub-Saharan Africa: Effective information for localized HIV prevention and control." Scientific reports (2017)

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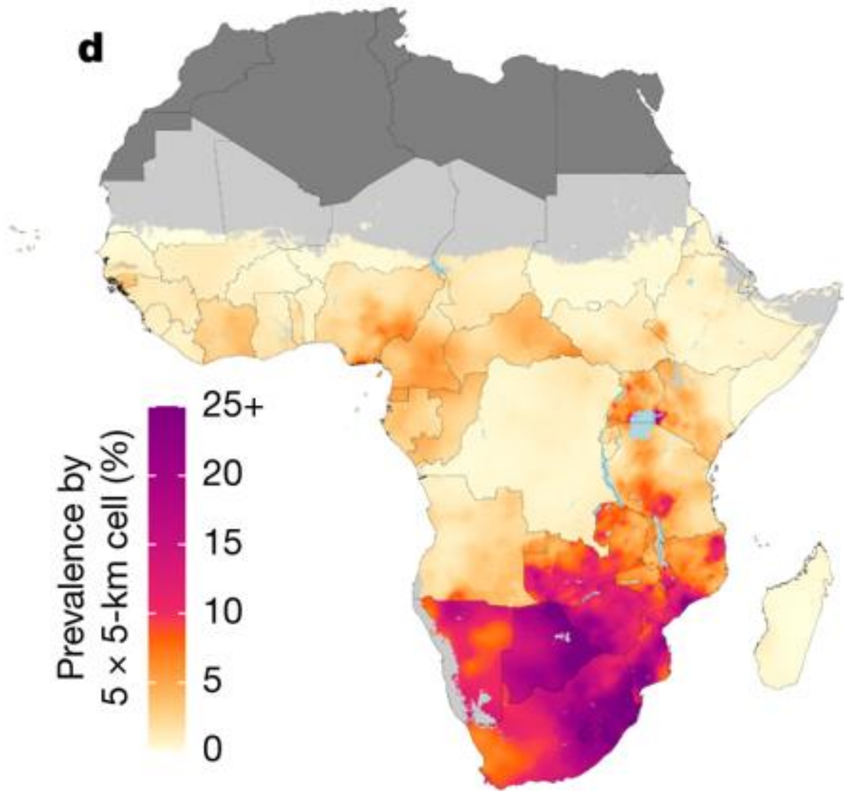
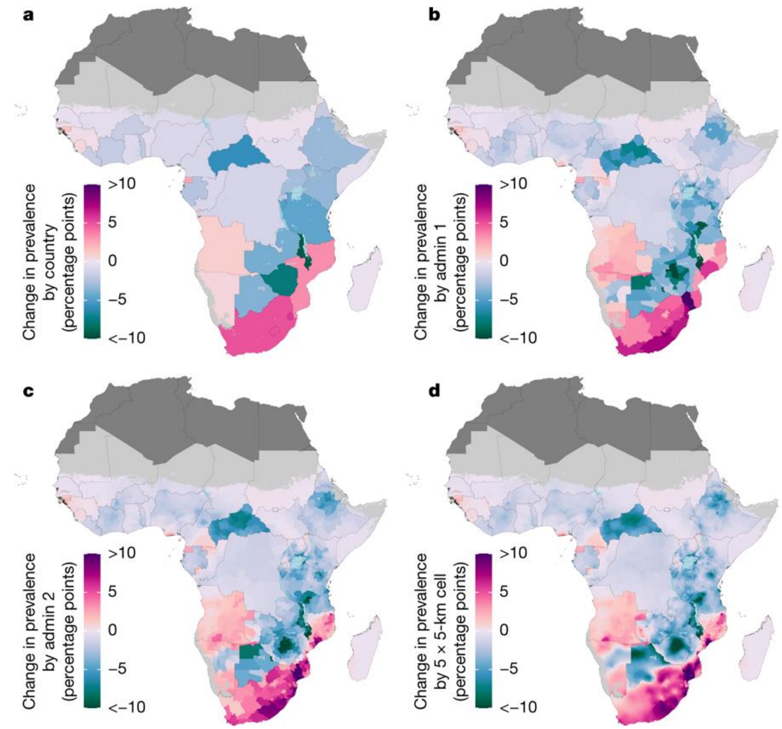
HIV prevalence distribution in Africa



Dwyer-Lindgren, Laura, et al. "Mapping HIV prevalence in sub-Saharan Africa between 2000 and 2017." Nature (2019)



Absolute change in HIV prevalence among adults aged 15–49 between 2000 and 2017 at the country level (**a**), first administrative subdivision level (**b**), second administrative subdivision level (**c**) and 5 × 5-km grid-cell level (**d**).

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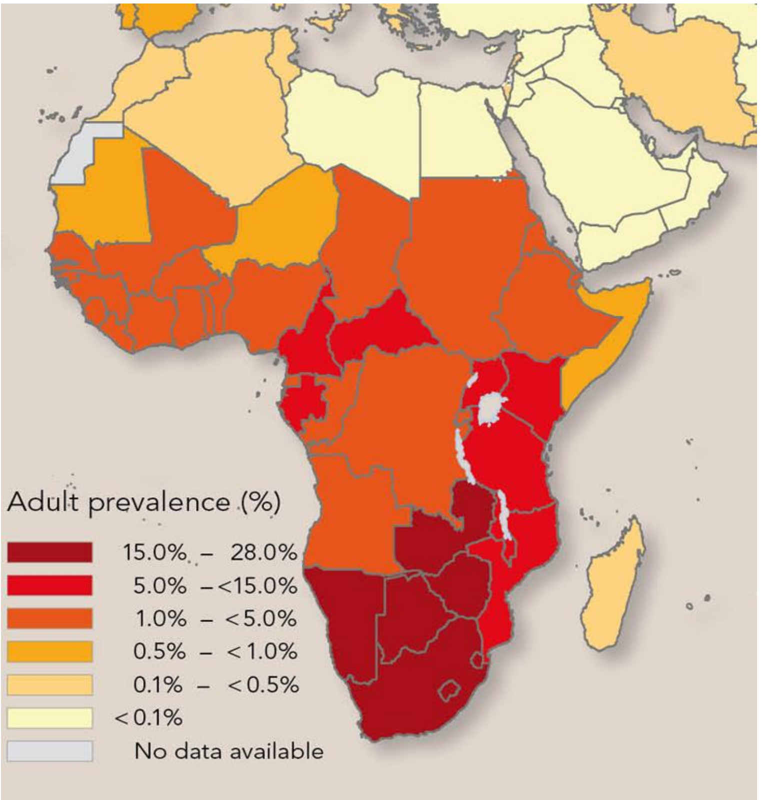
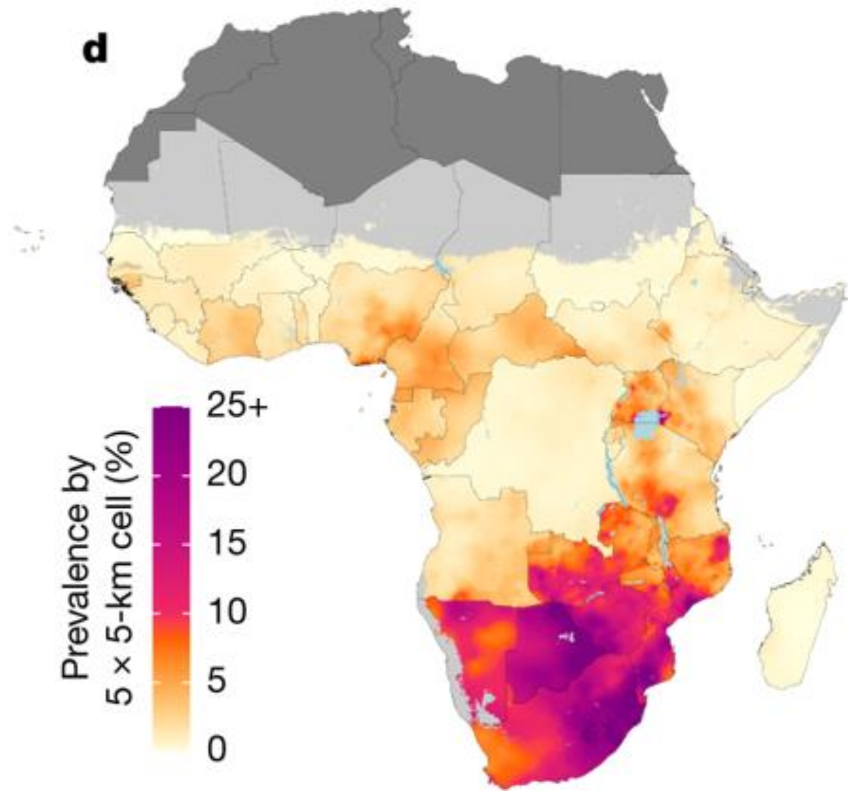
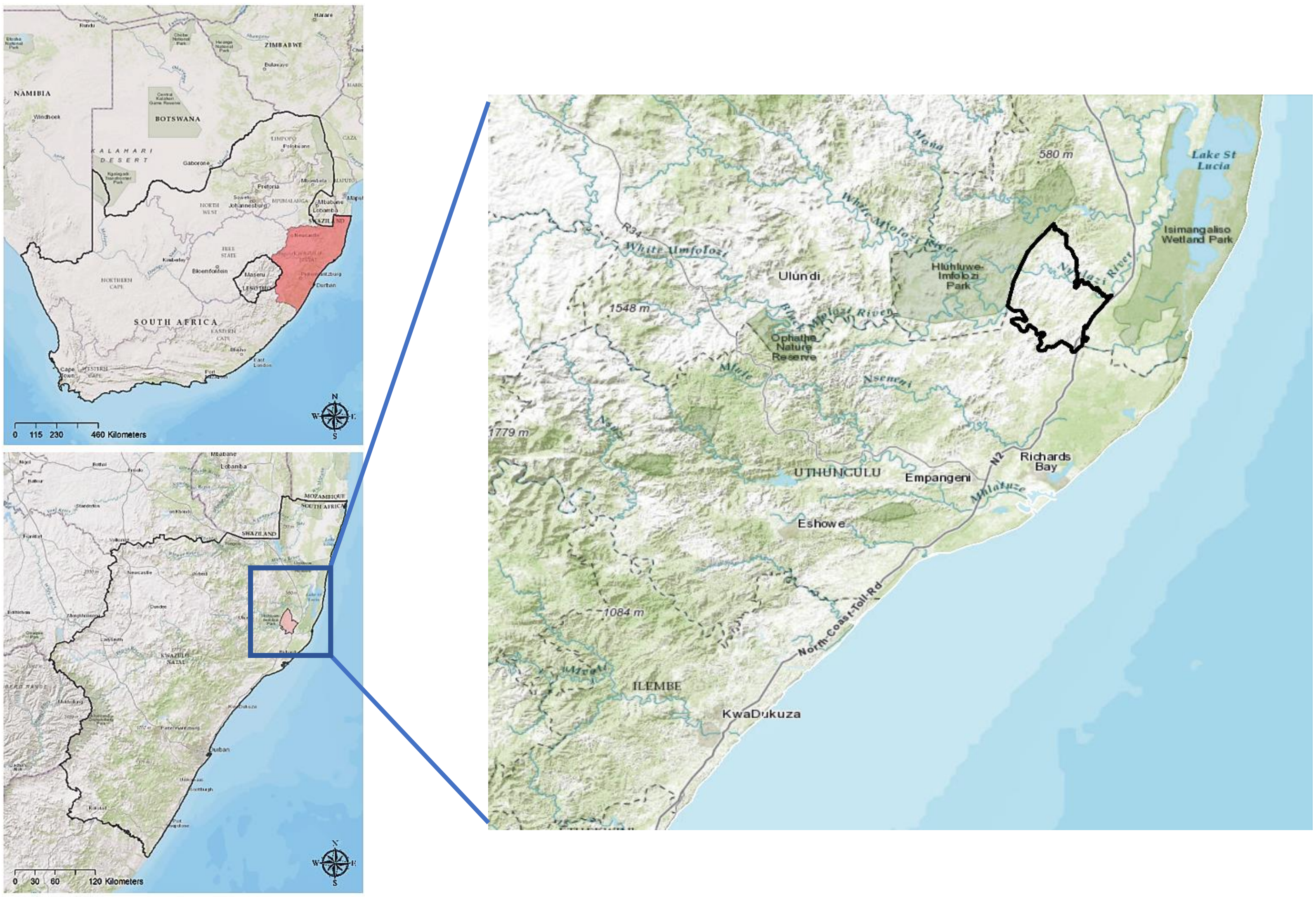
HIV prevalence distribution in Africa





Dwyer-Lindgren, Laura, et al. "Mapping HIV prevalence in sub-Saharan Africa between 2000 and 2017." Nature (2019)

AHRI Surveillance System



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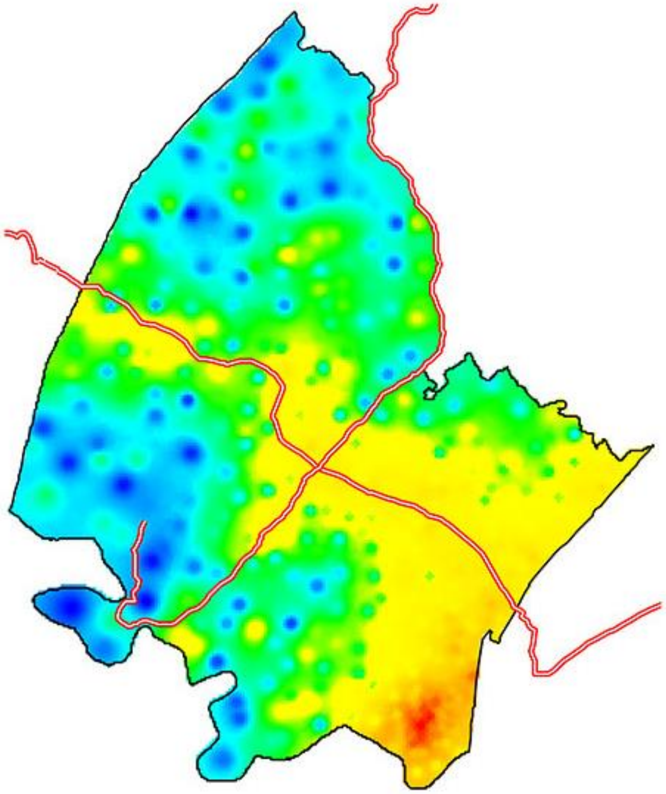
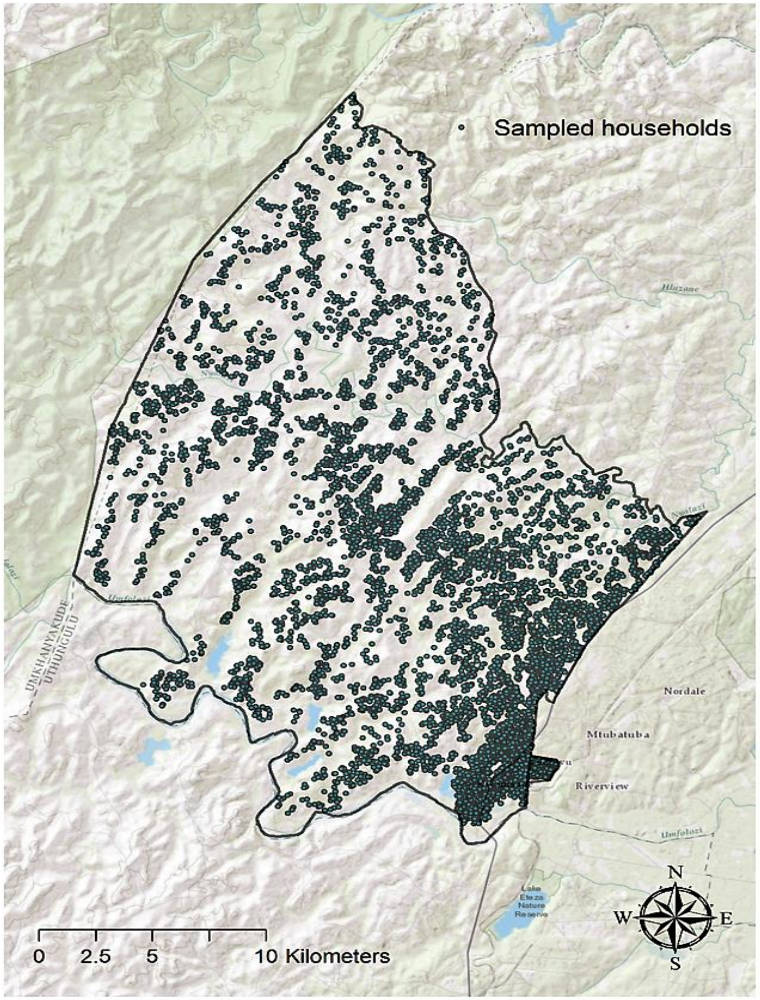
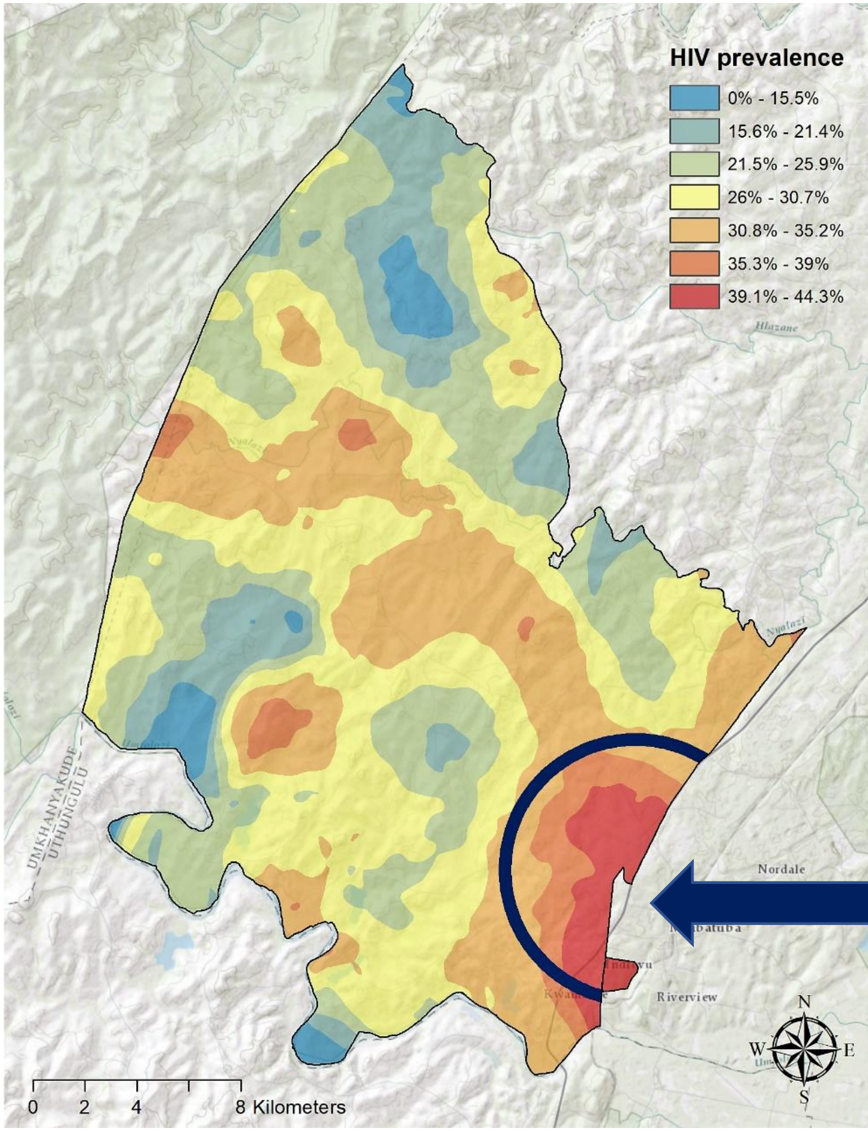
AHRI Surveillance System

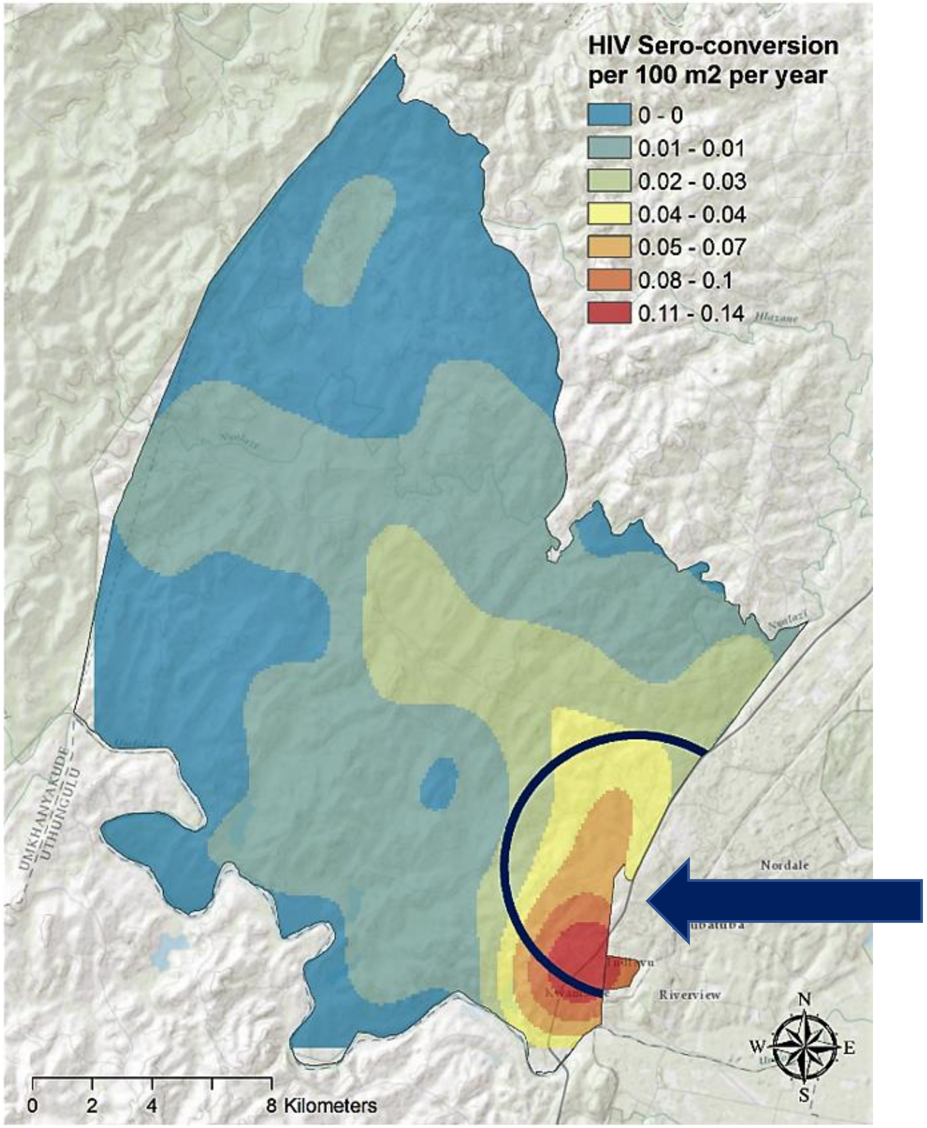




- The site has collected socio-demographic information on a population of 87,000 participants within a circumscribed geographic area (438 km^2) for over a decade



- The HIV hotspot contained 40.8% of the total HIV-positive individuals, and individuals located within the geographical cluster had 46% higher risk of HIV infection compared to individuals located outside the cluster



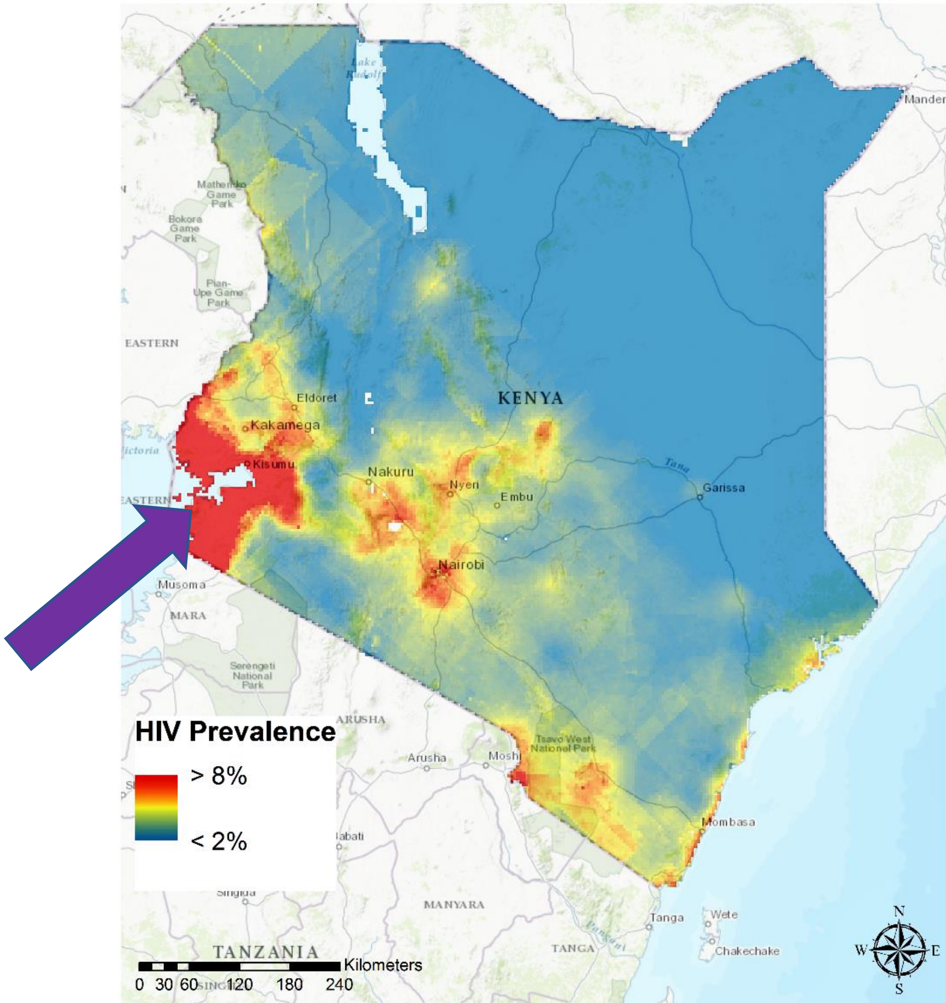
- Estimated HIV seroconversions per year were highly concentrated within the HIV hotspot with and an average of 0.04 seroconversions per year per 100 m2, compared to 0.01 seroconversions per year per 100 m2 in the area outside of the HIV hot-spot

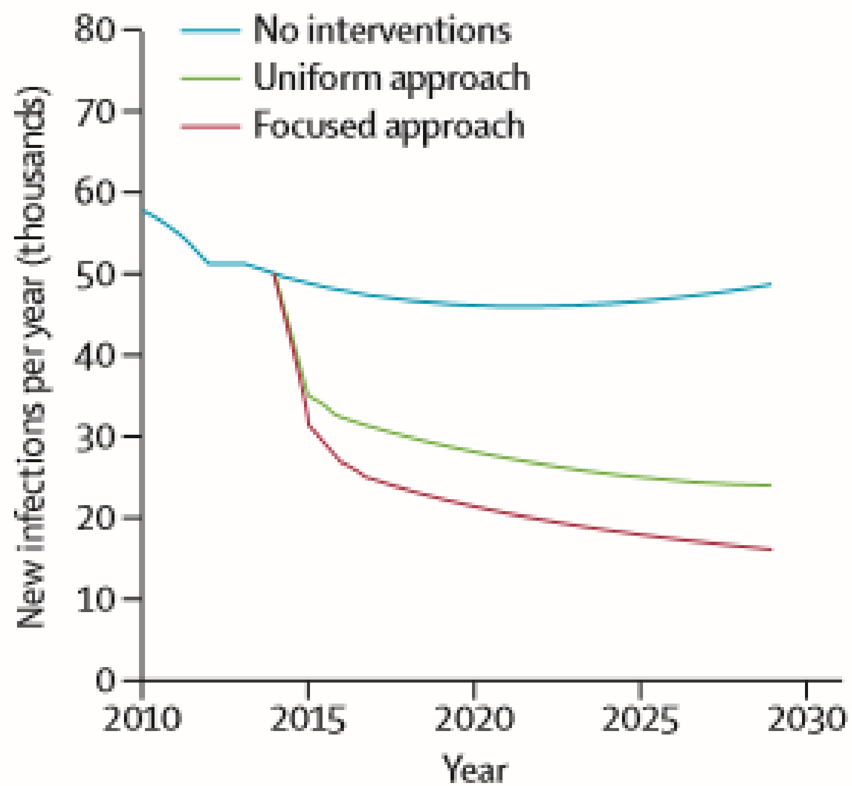
Why mapping diseases?

- Maps of disease distribution and intensity allow an immediate visualization of the extent and magnitude of the public health problem

- The identification of the settings where both the burden of disease and the drivers of the disease are concentrated could play an important role for **optimization of resource allocation based on geographically targeted interventions**

Resource allocation

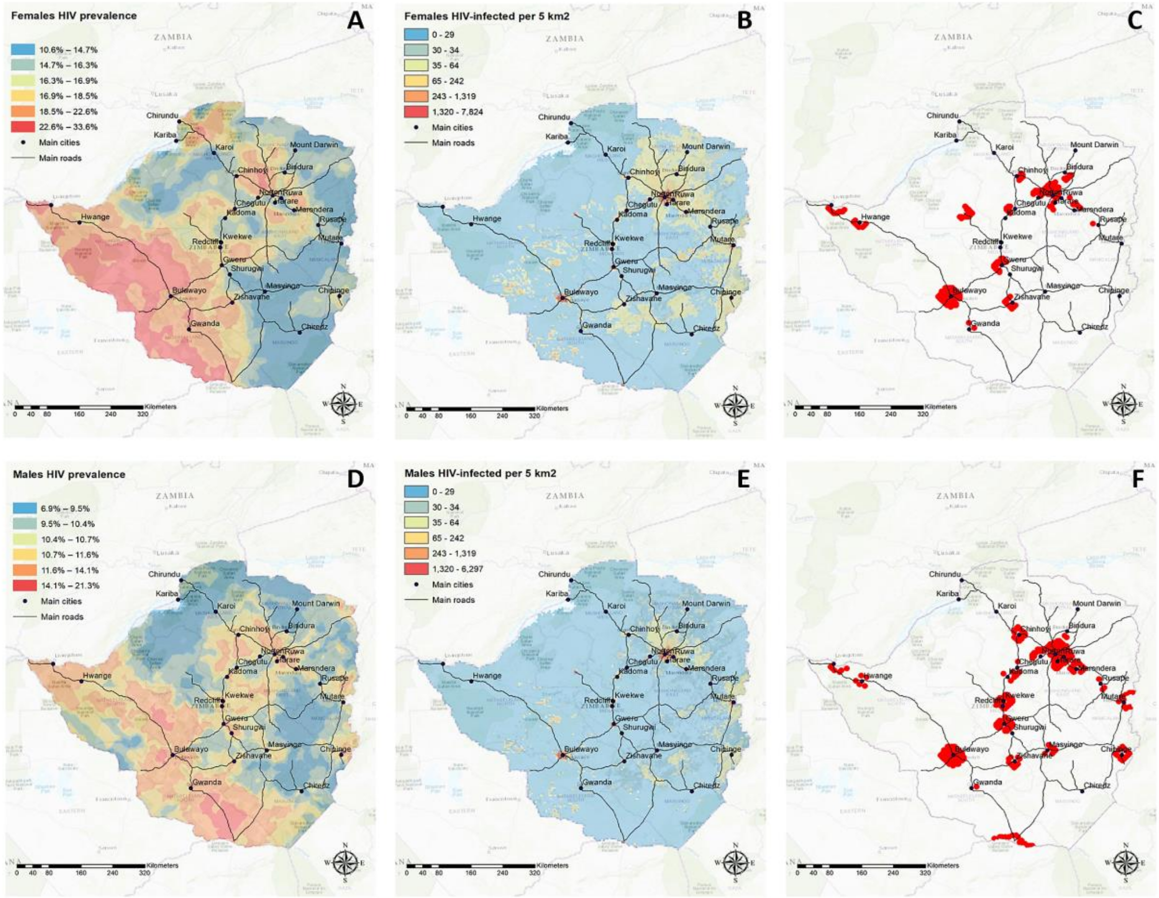




Difference in health gains between the uniform and focused approaches
Anderson et al. *Lancet HIV* 2014

HIV prevention and care in Zimbabwe

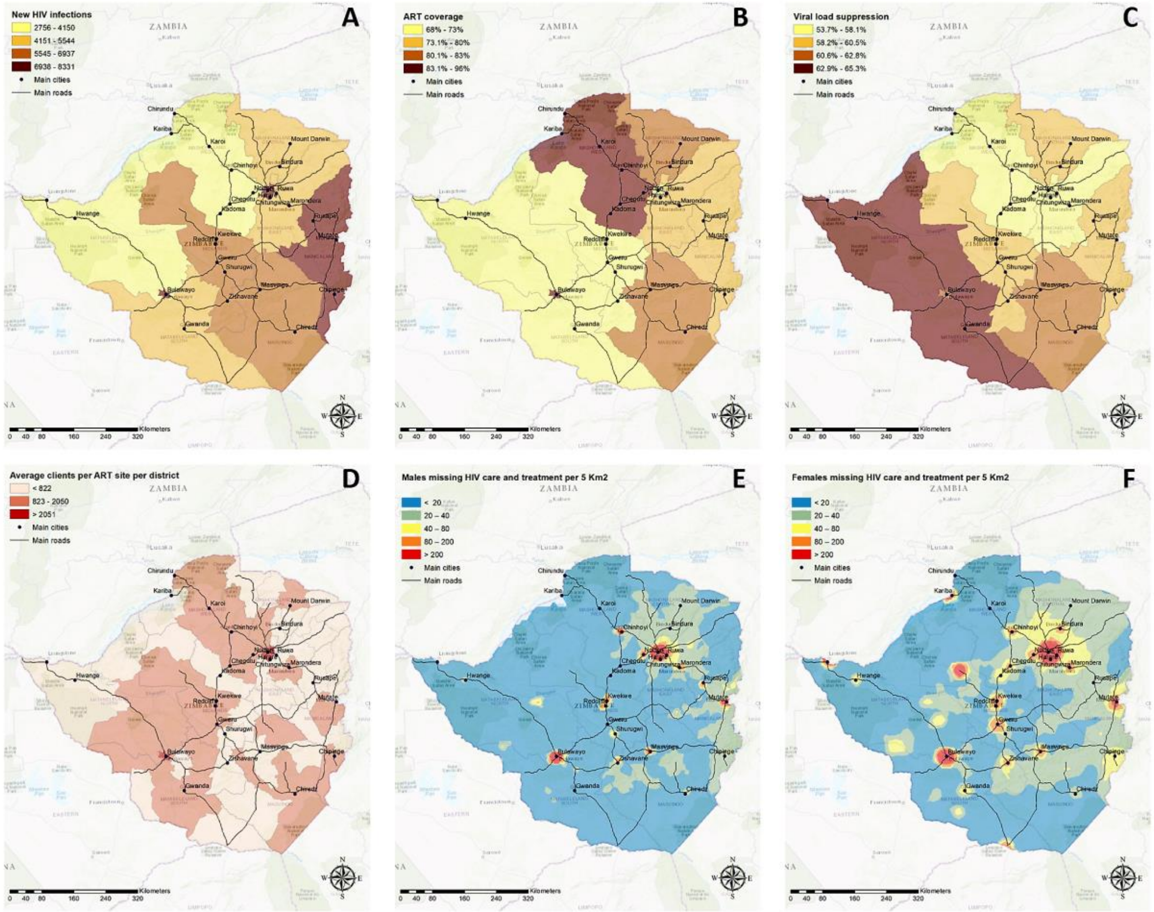
High resolution maps of HIV prevalence in Zimbabwe for (A) Females and (D) Males; geographic dispersion of HIV-infected (B) females and (E) males in Zimbabwe. High HIV burden areas are illustrated in red for (C) females and (F) males.



Cuadros, Diego F., et al. "Towards UNAIDS Fast-Track goals: targeting priority geographic areas for HIV prevention and care in Zimbabwe." Aids (2019)

HIV prevention and care in Zimbabwe

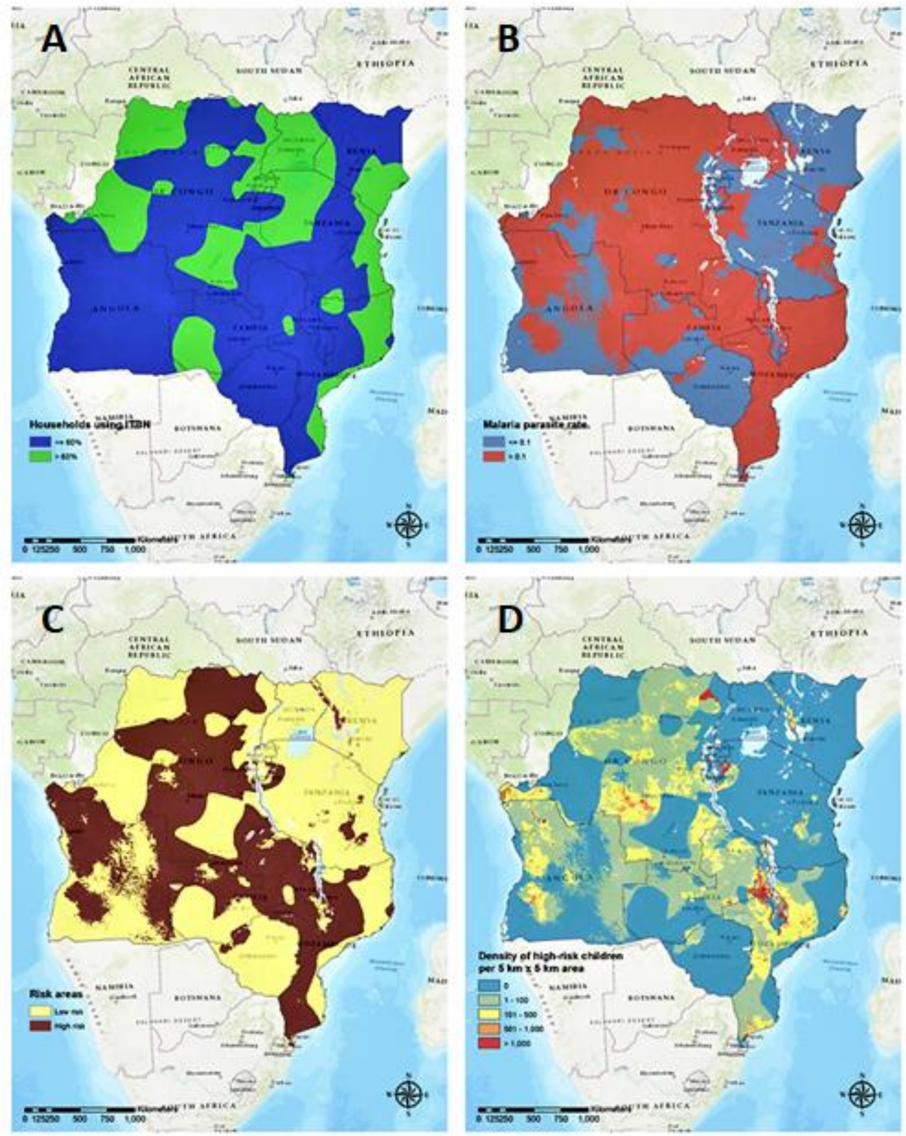
Province-level maps of (A) incidence of HIV infection in 2015, B) ART coverage, and (C) viral load suppression of those on ART. Map in (D) presents estimates of the average number of clients per ART site per district. Geographical dispersion of males (E) and females (F) lacking HIV treatment and care.



Cuadros, Diego F., et al. "Towards UNAIDS Fast-Track goals: targeting priority geographic areas for HIV prevention and care in Zimbabwe." Aids 33.2 (2019)

Use of mosquito bed nets in Central and East Africa

- Average of ownership of mosquito bed nets **68%**
- Average use of mosquito bed nets **46%**



Interpolated surface map of lower (<60%) and higher levels for use of mosquito net (**A**), areas with lower (Parasite Rate, PR<0.1) and higher endemic malaria (**B**). the combination of both A and B to identify high-risk areas (low mosquito net use and high malaria, **C**), and the estimated number of children at risk (**D**).

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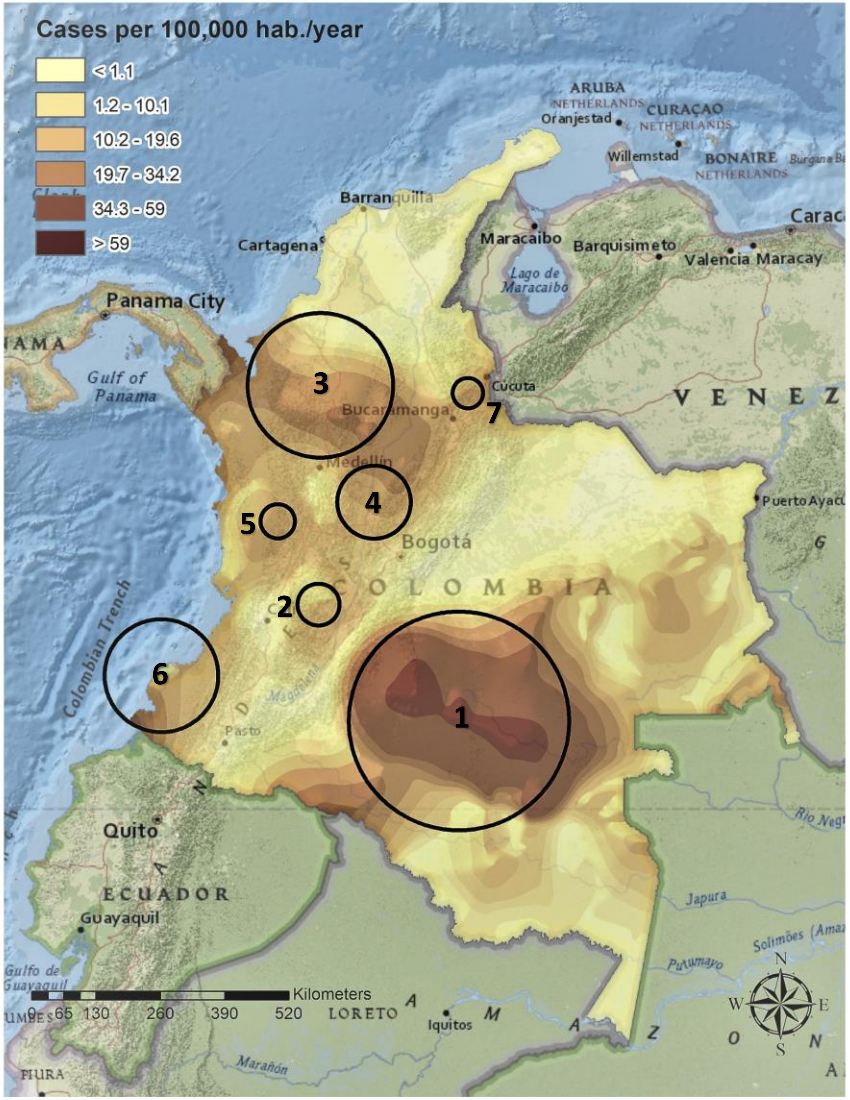
Cutaneous Leishmaniasis in Colombia

Human activities such as **deforestation linked to agriculture, livestock production and mining activities** were identified as key drivers of the spatial distribution of the cutaneous leishmaniasis epidemic in Colombia.



Hernández, Andrés M., et al. "Spatial epidemiology of cutaneous leishmaniasis in Colombia: socioeconomic and demographic factors associated with a growing epidemic." Transactions of The Royal Society of Tropical Medicine and Hygiene (2019).

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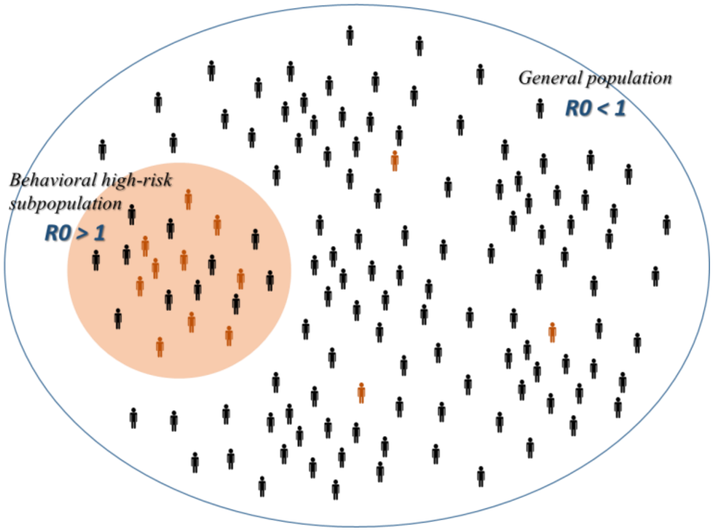
- **Other uses: identification of vulnerable populations at high risk of infection**

Spatial risk of HIV infection: Spatial structure of the transmission network

Concentrated epidemic



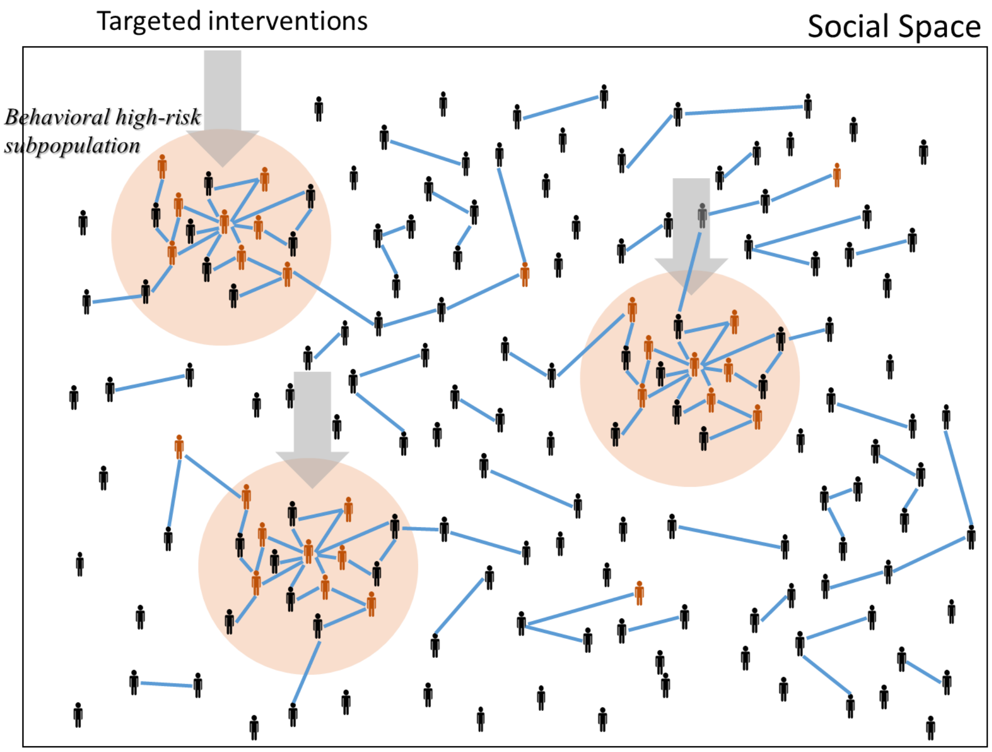
Social space

The study of sexually transmitted infections such as HIV has focused on **social space**

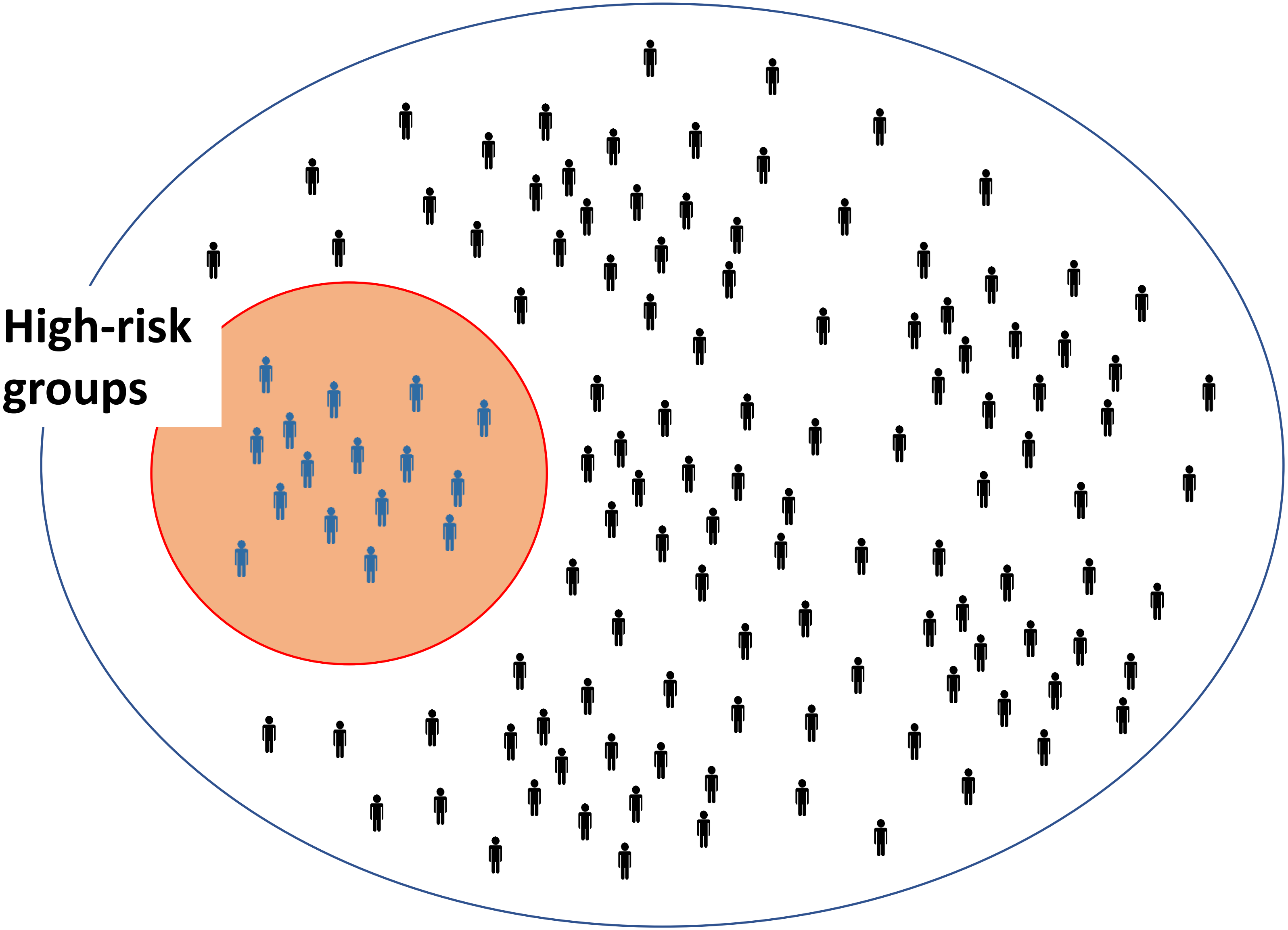
Sexual networks: groups of persons Connected to one another sexually

Characteristics:
-Number of partners (links)
-Serial monogamy
-Concurrent relationships

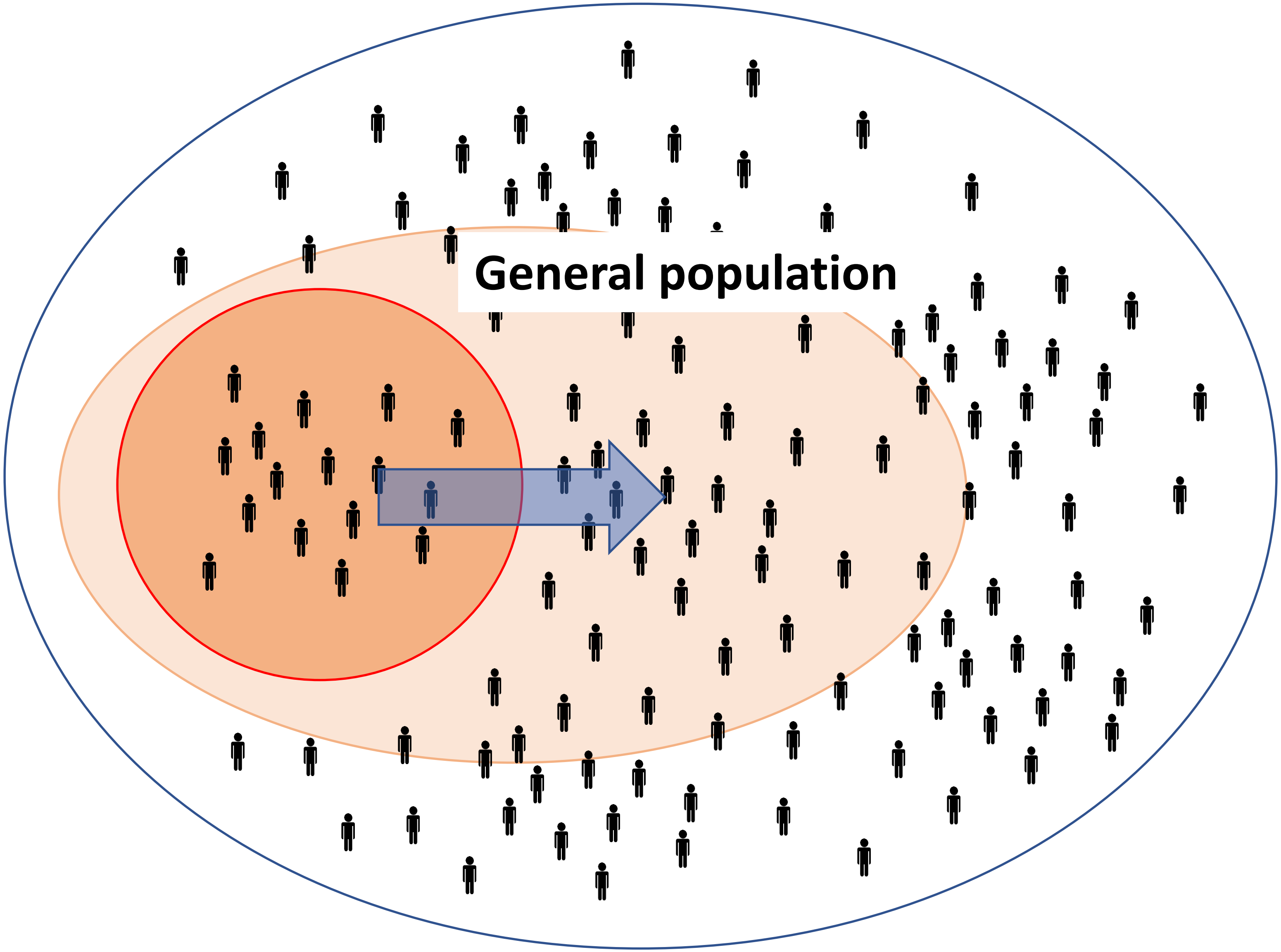
Core groups: members that have high levels of risk behavior and can fuel sustained transmission.



Concentrated epidemic



Generalized epidemic



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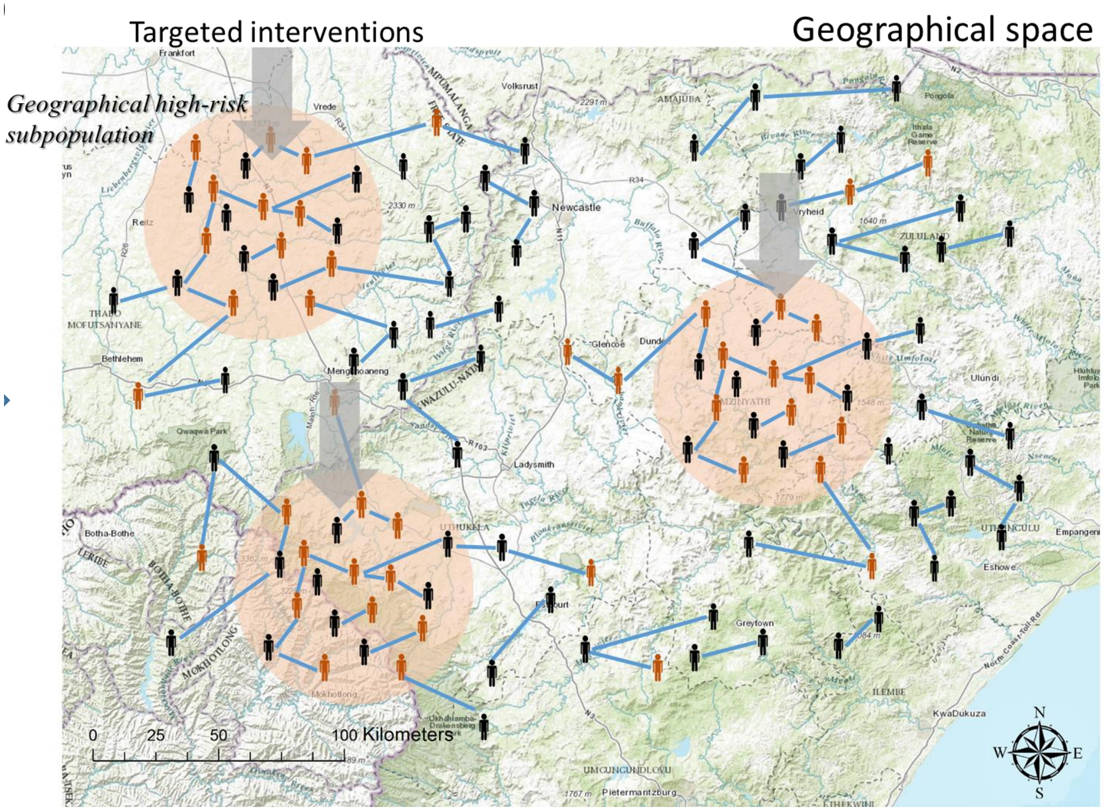
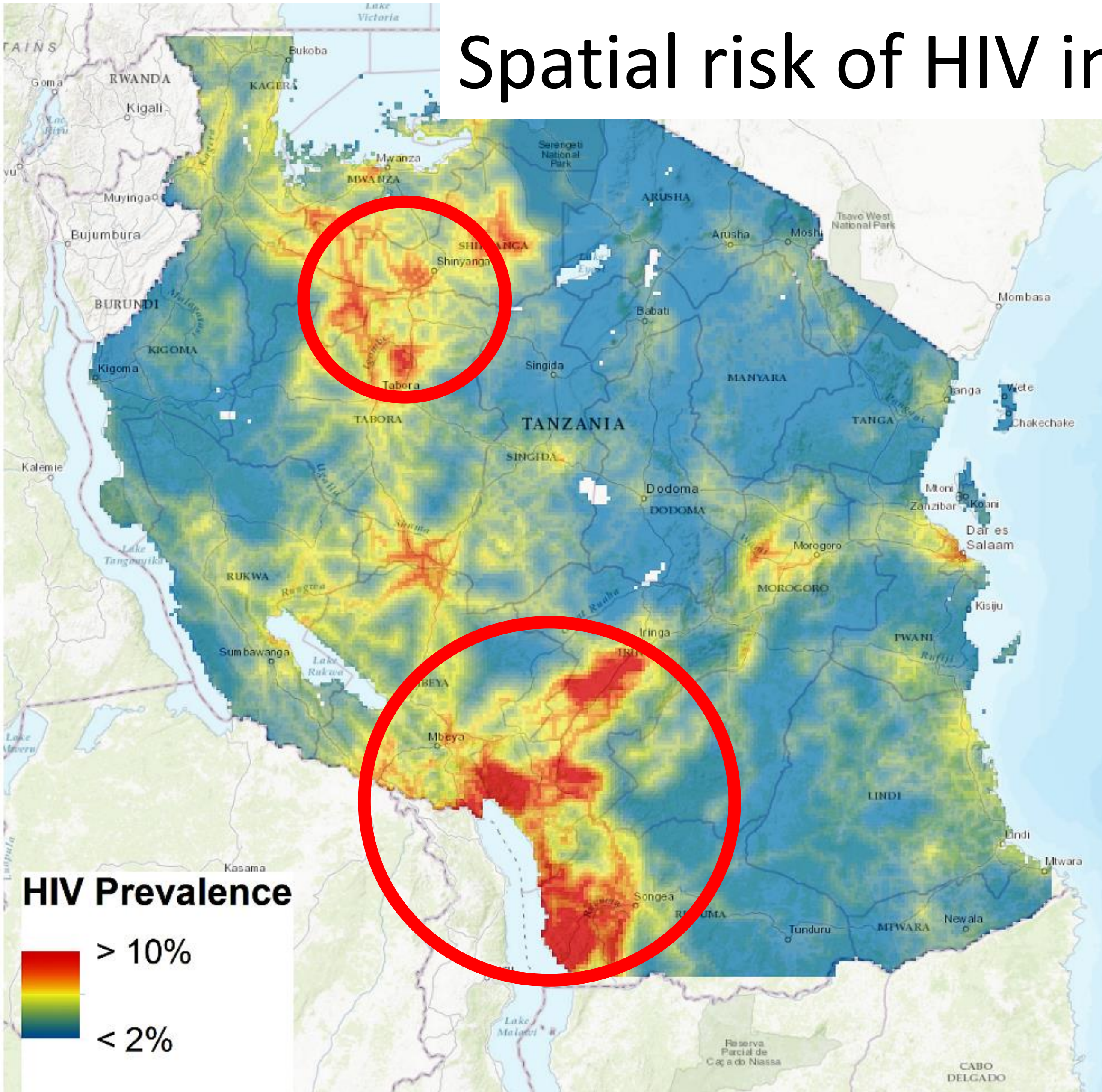
Geographical space

- HIV ‘hot-spots’ can behave as the highly connected nodes of in the transmission network



Spatial risk of HIV infection



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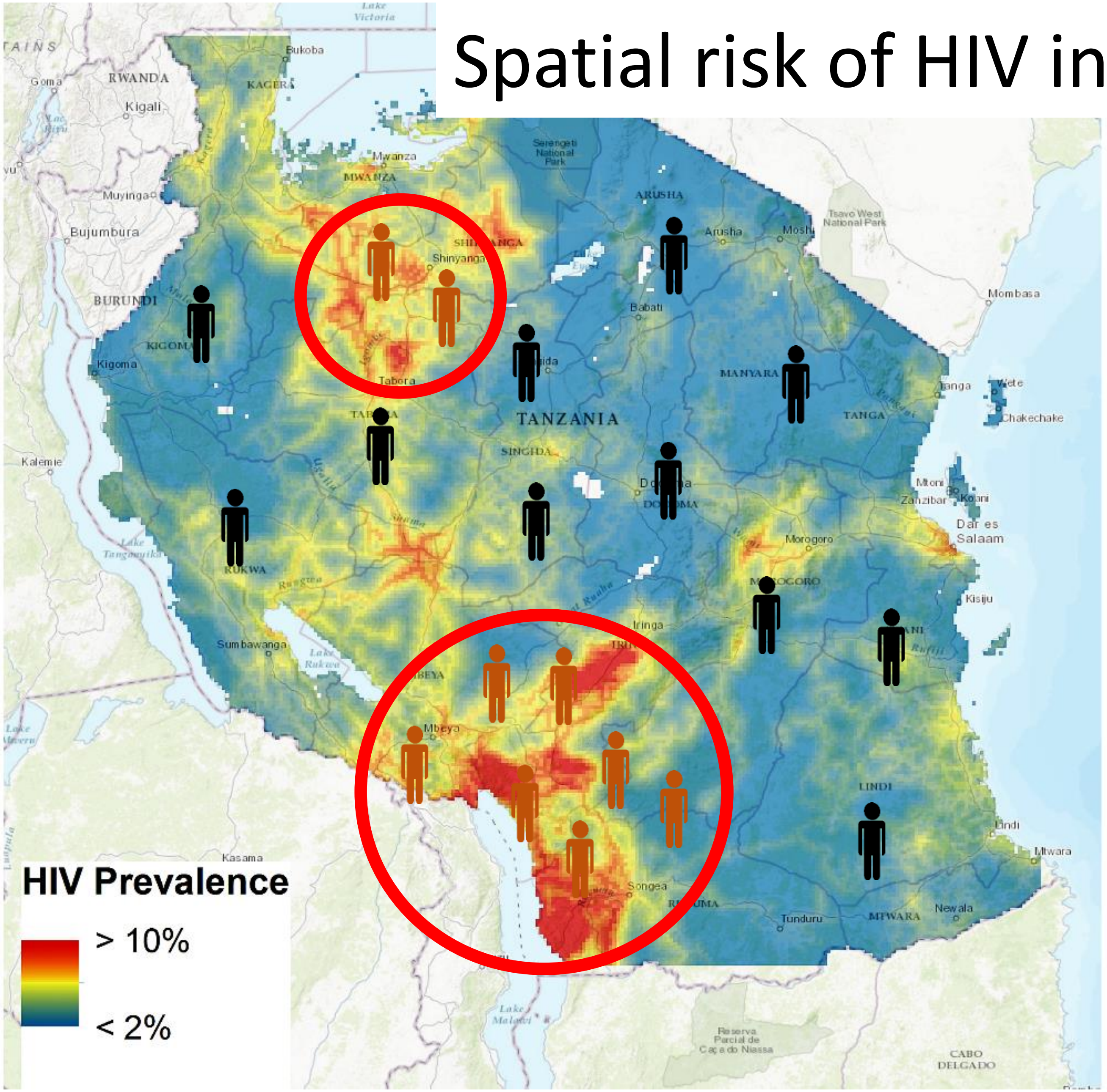
Spatial risk of HIV infection



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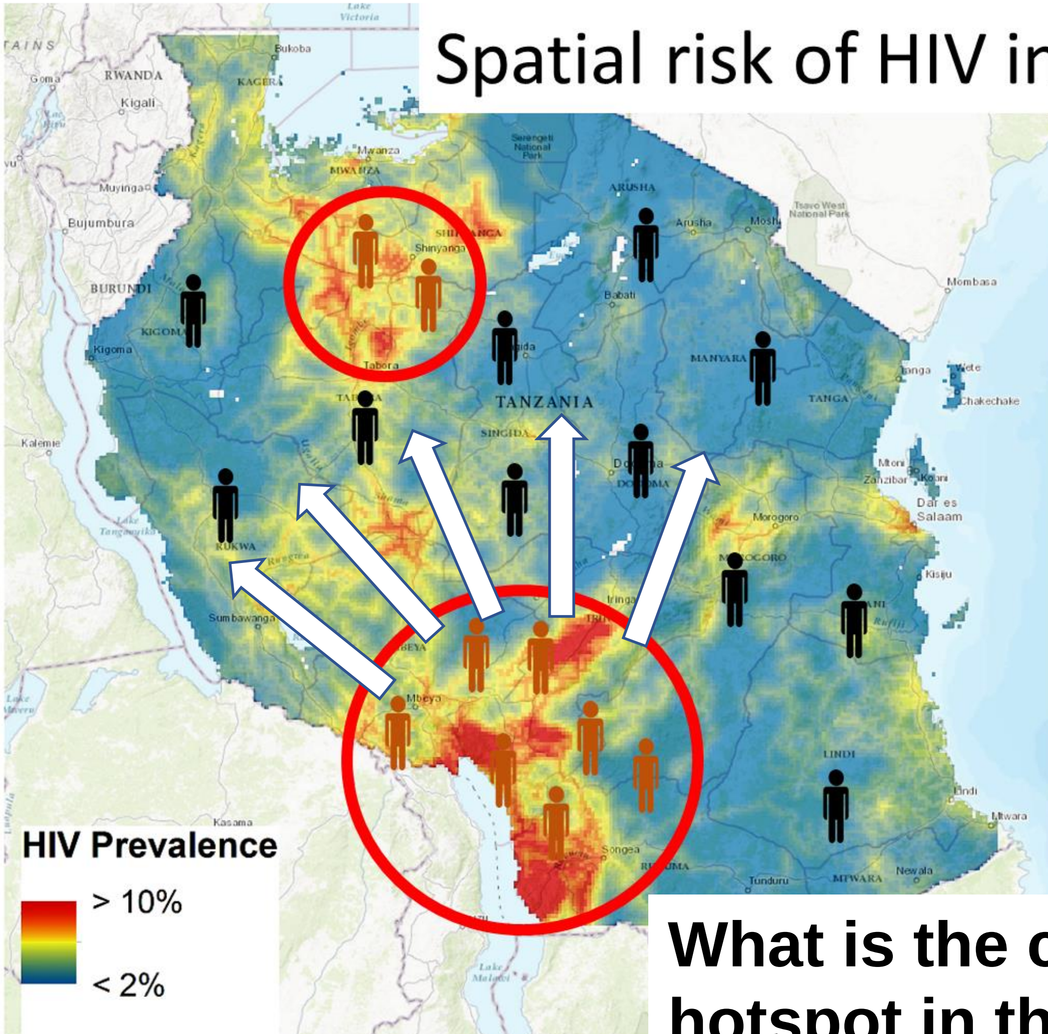
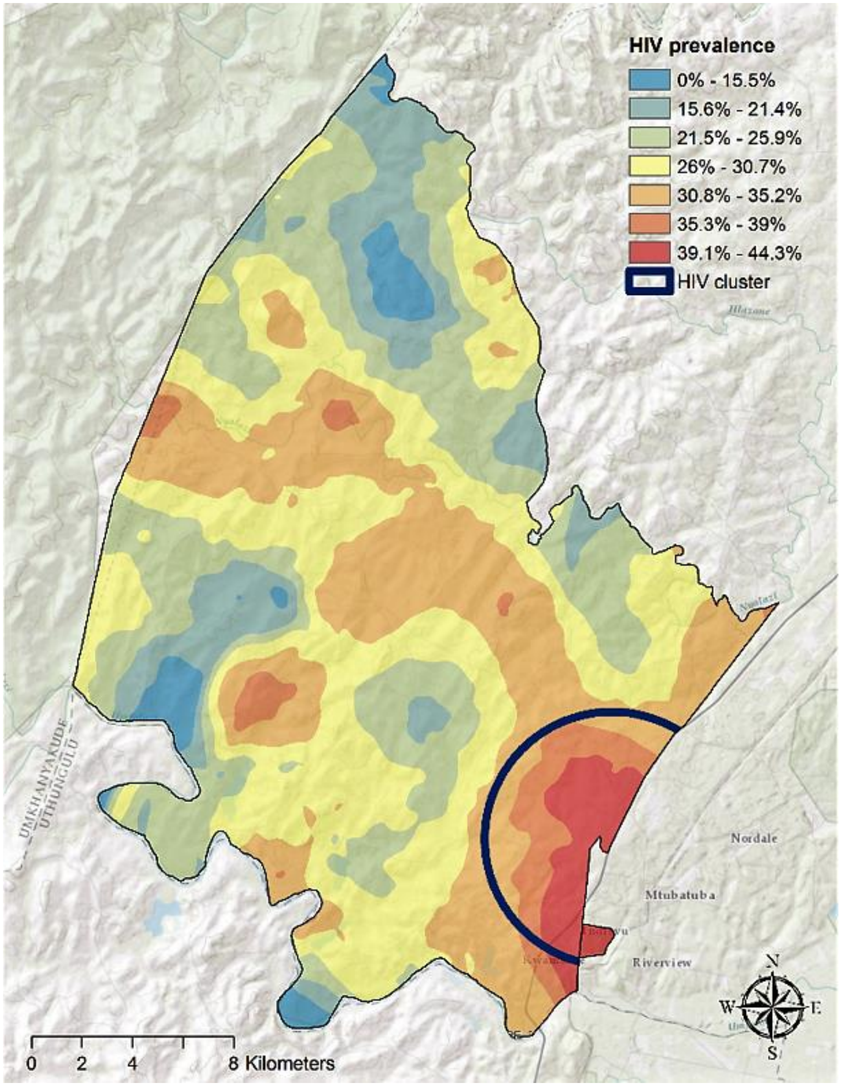
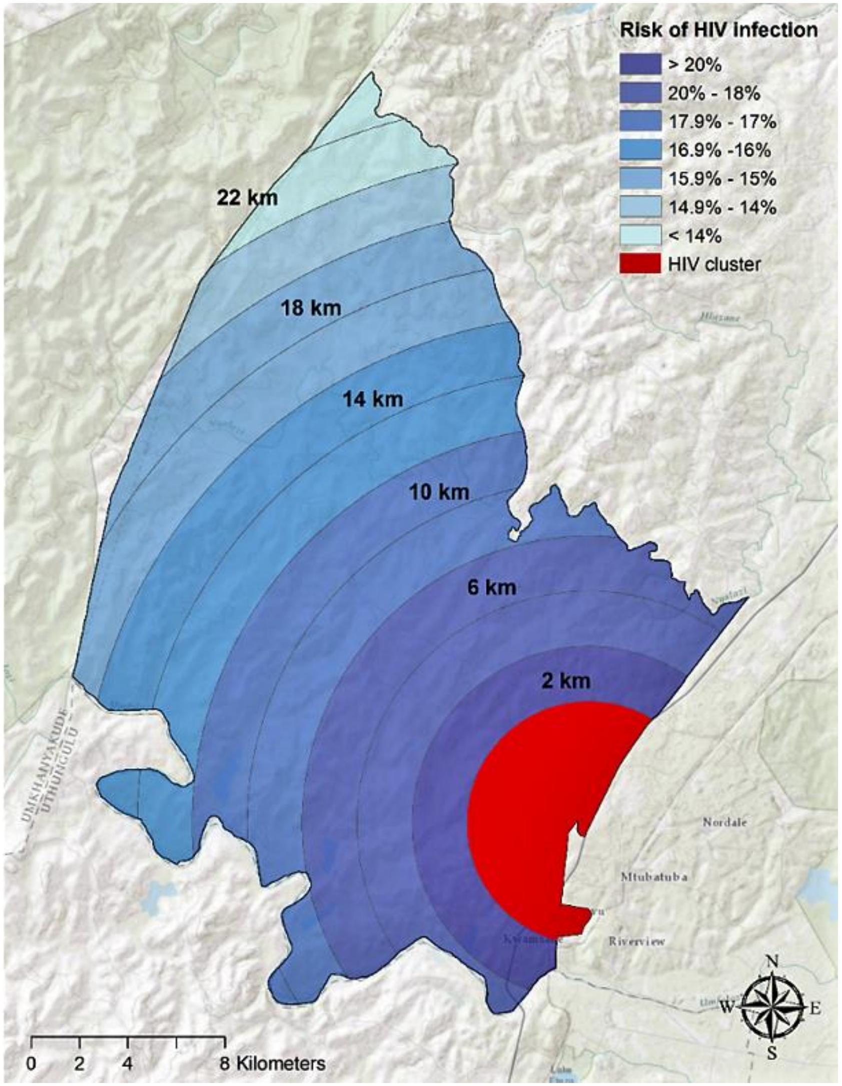
Spatial risk of HIV infection



- The spatial connectivity of the transmission network of an entire community has never been studied before, and the contribution of geographical clusters of HIV infections, or ‘hot-spots’ on the spread of the infection in the entire population is virtually unknown

What is the contribution of the HIV hotspot in the transmission network?





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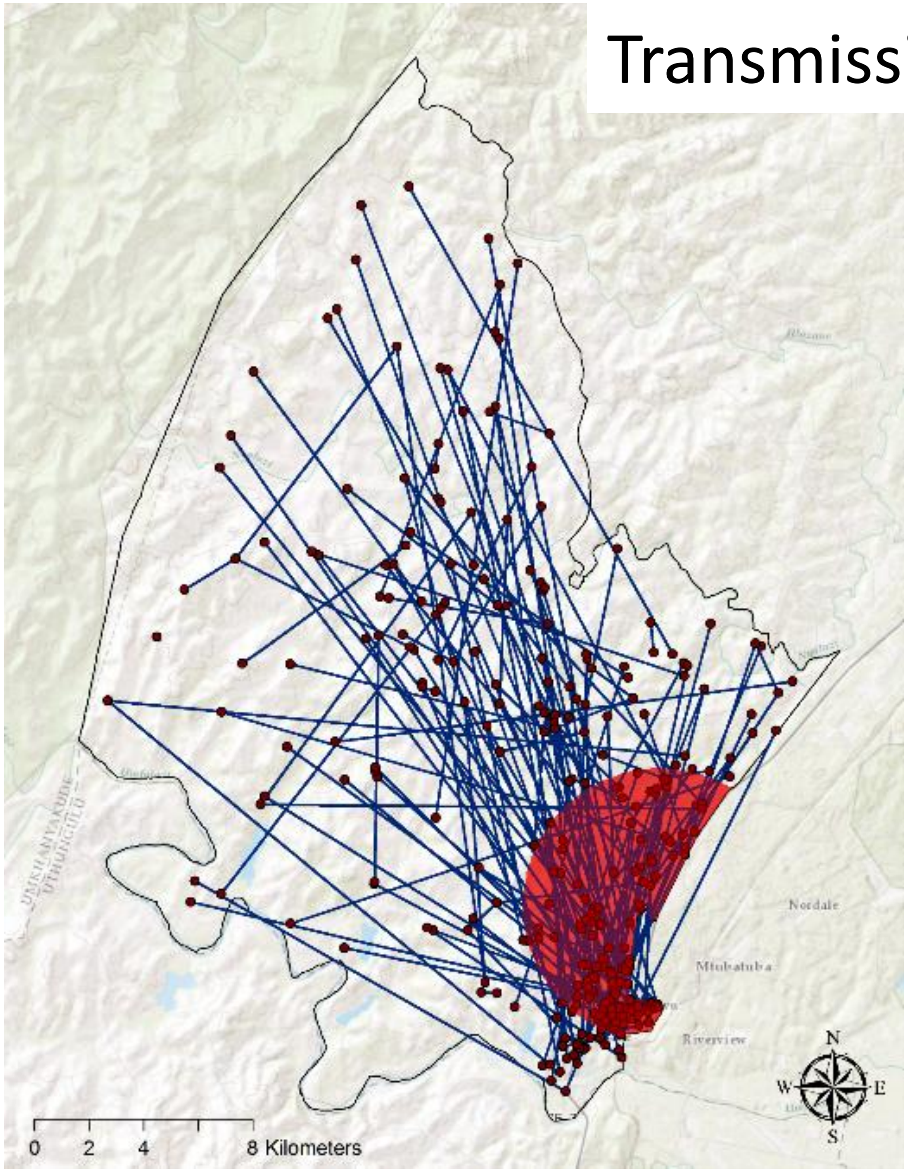
Transmission links



- We geo-located and genetically sequenced 1,222 HIV-positive individuals, from whom phylogenetic transmission clusters were identified
- We constructed the spatially explicit transmission network with 350 transmission links identified

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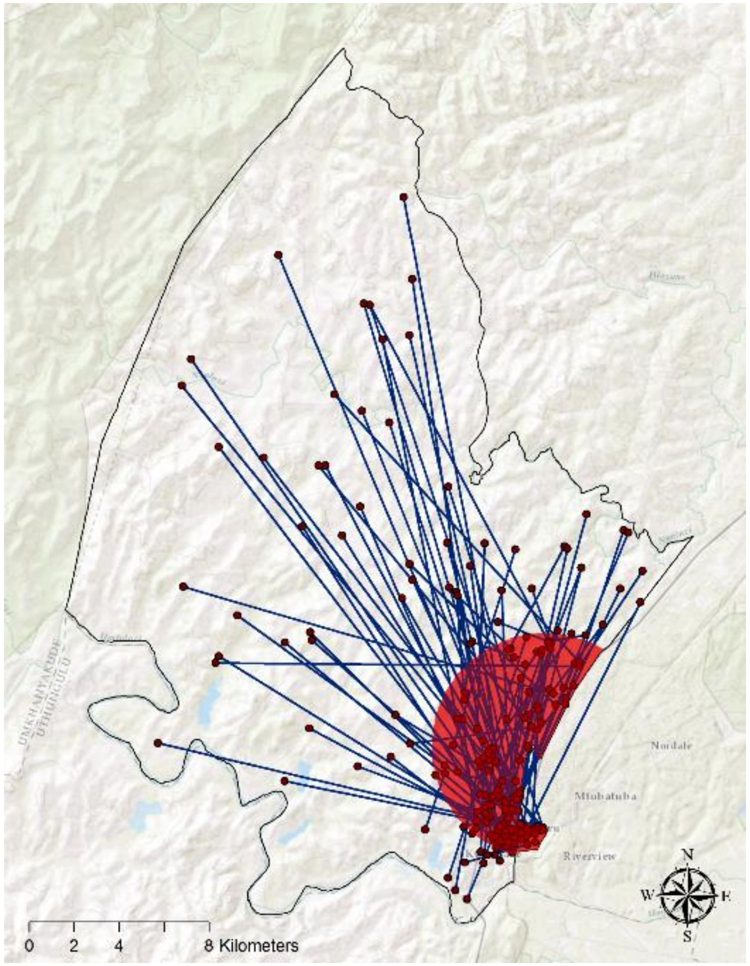

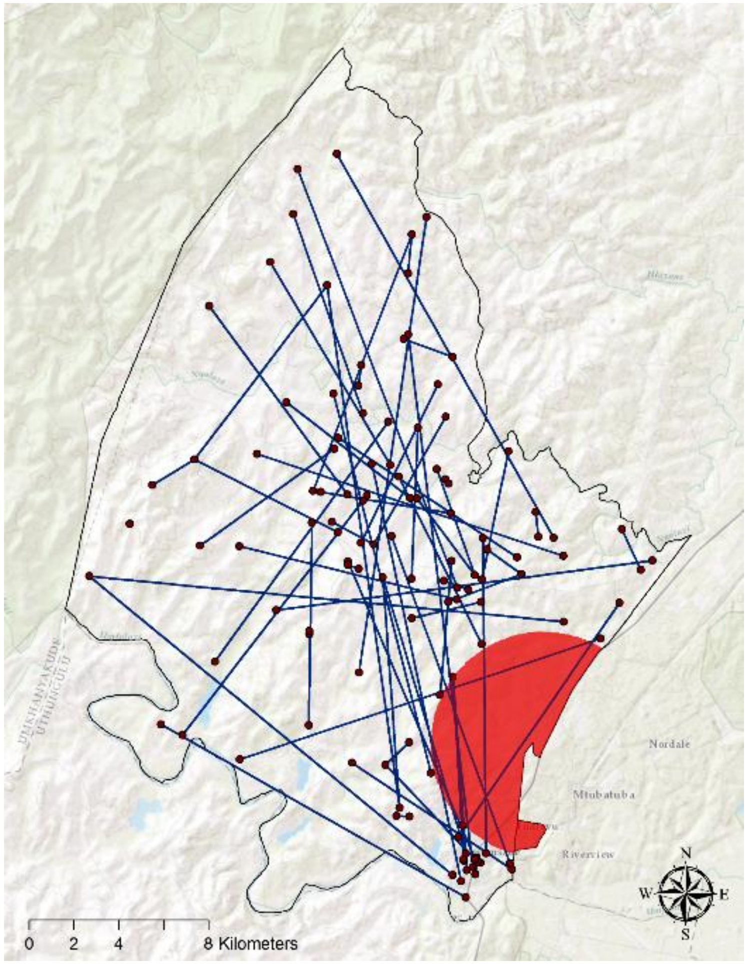

- 72% of the links included at least one individual located within the HIV hot-spot
- 28% of the links included individuals located outside the HIV hot-spot

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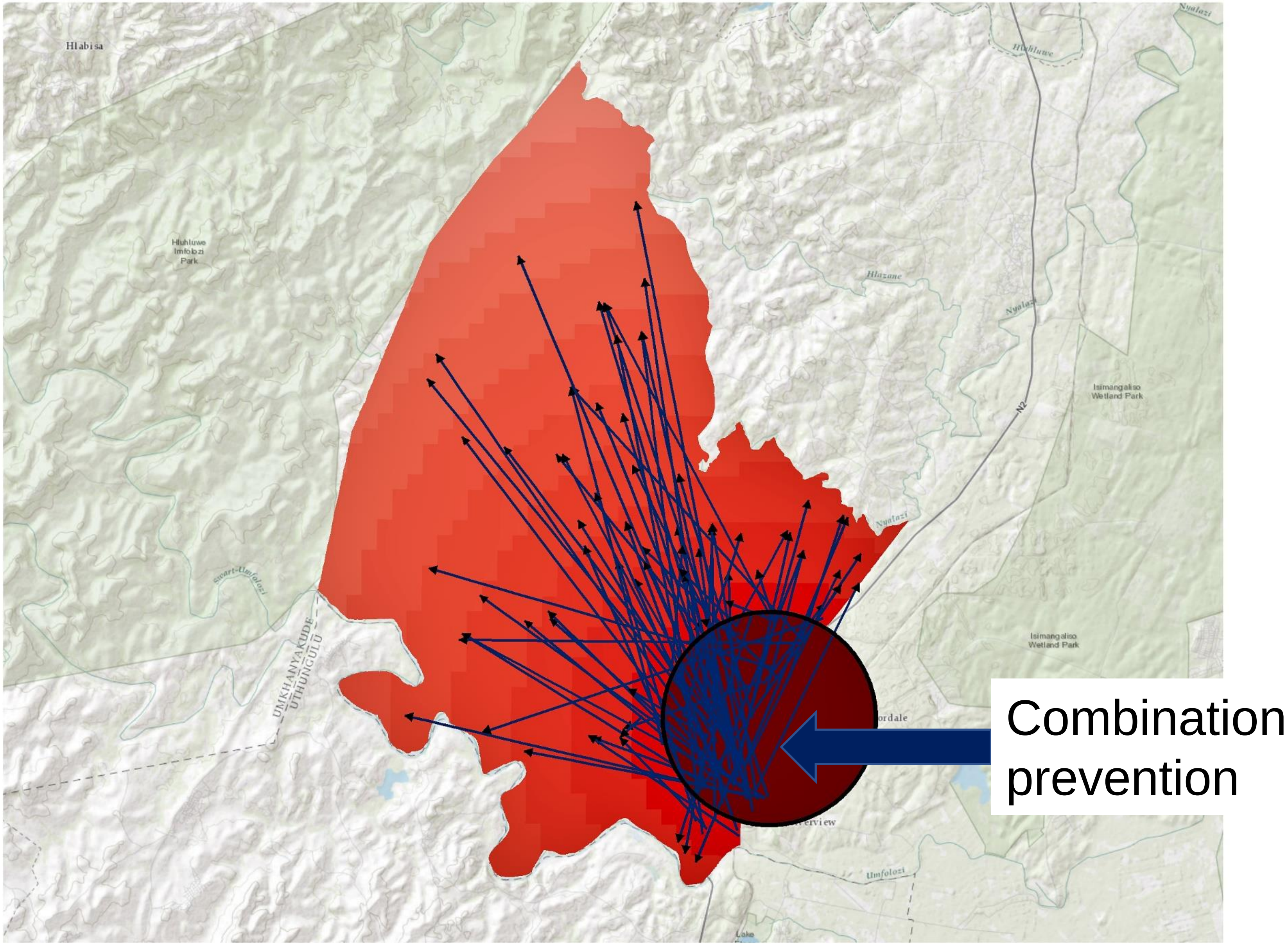
- We found that more than 70% of the HIV transmission links identified were directly connected to an HIV hot-spot, illustrating the **high connectivity between the hot-spots and the general community**

- The HIV hotspots might play a key role in the HIV transmission network and could substantially contribute to the dispersion of the infection

- We hypothesize that HIV hot-spots behave as core groups in the transmission network, and **interventions targeting these hot-spots could not only reduce the levels of new infections in these geographical core groups, but also disrupt the transmission of the infection in the entire community**



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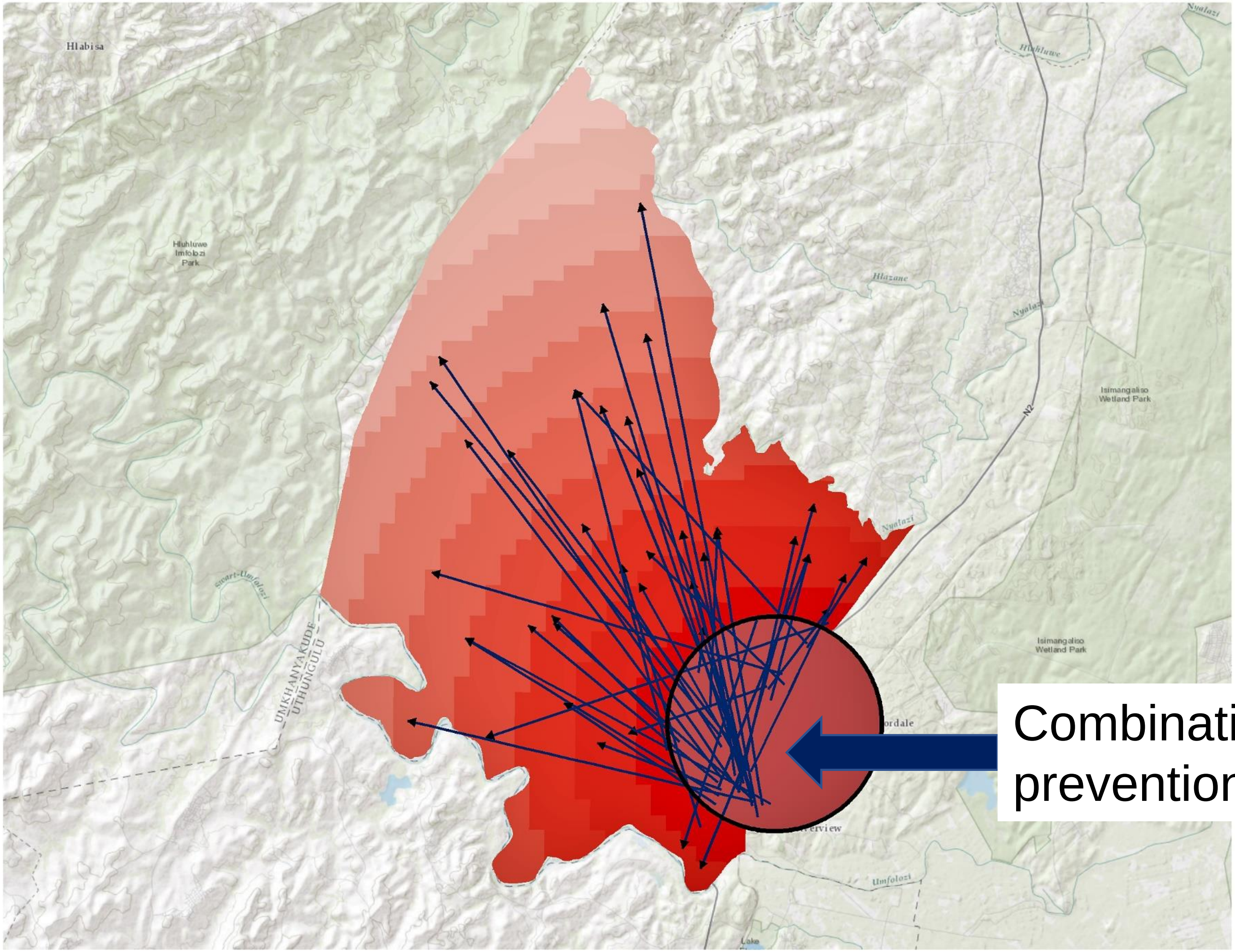

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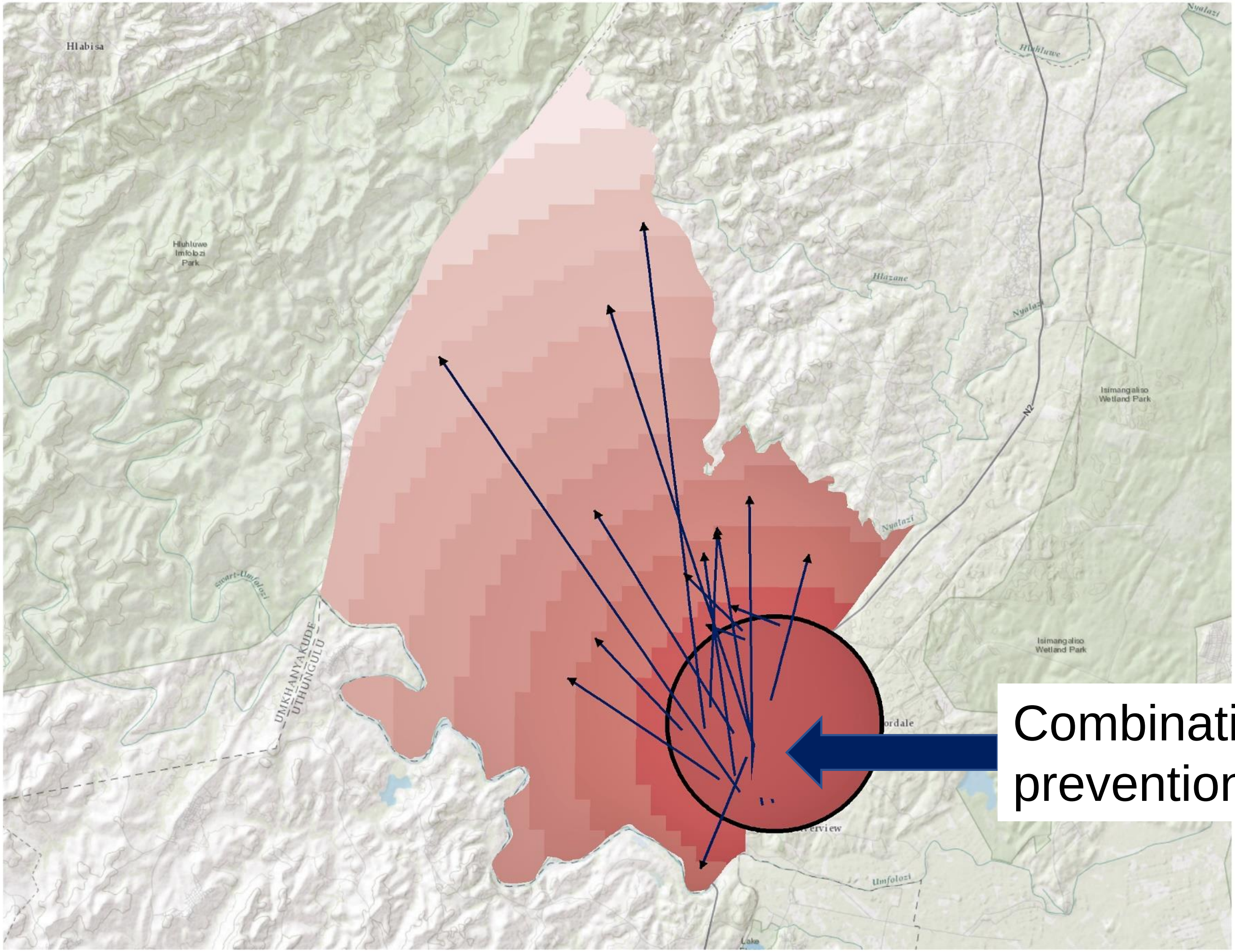
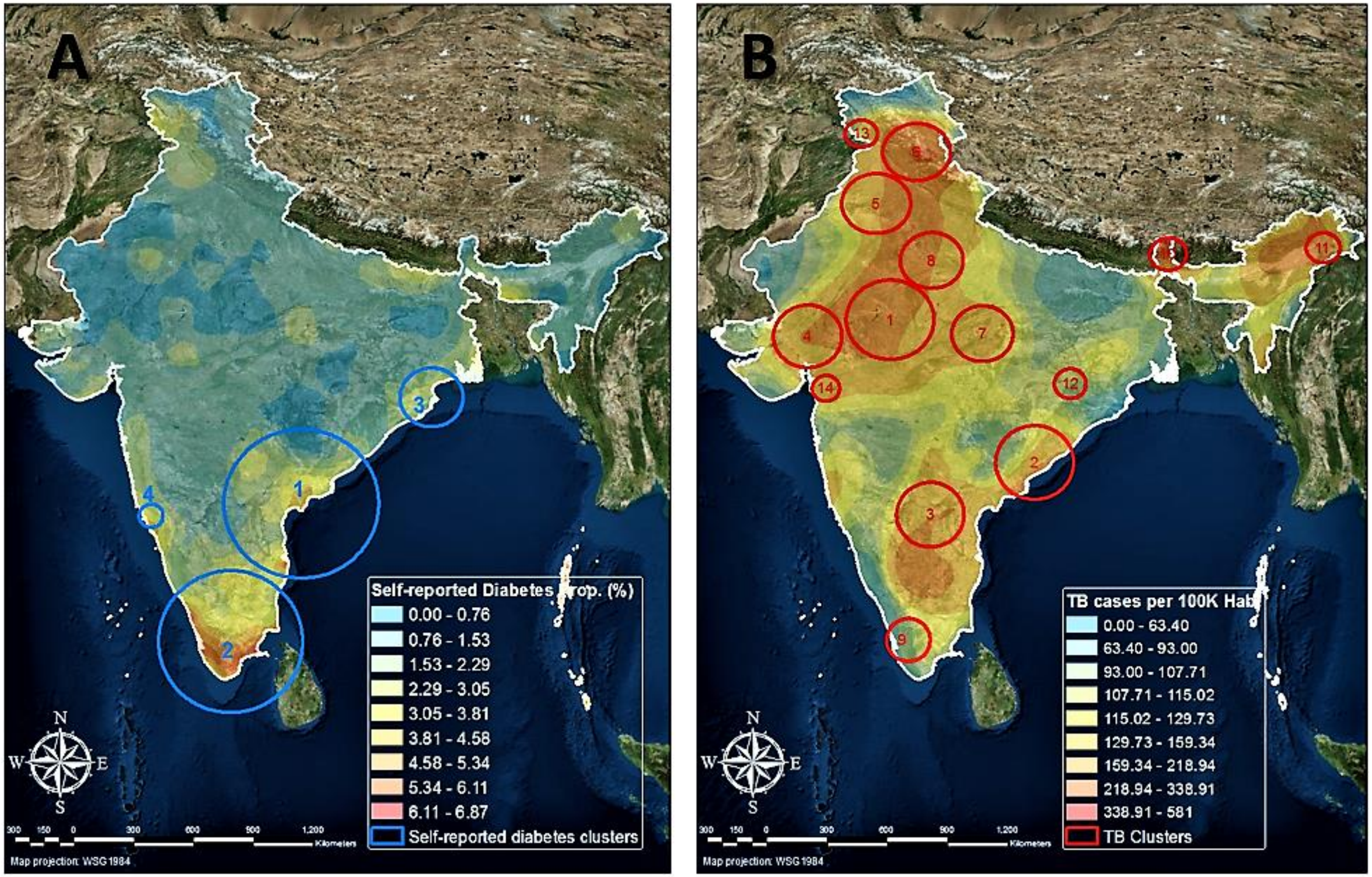


Combination prevention

- **Other uses: disease interactions**

Spatial analysis and disease mapping are powerful tools for revealing the interactions among diseases and the geographical locations where several diseases collide, thereby exposing the structure of the disease community in these areas

Diabetes and tuberculosis in India

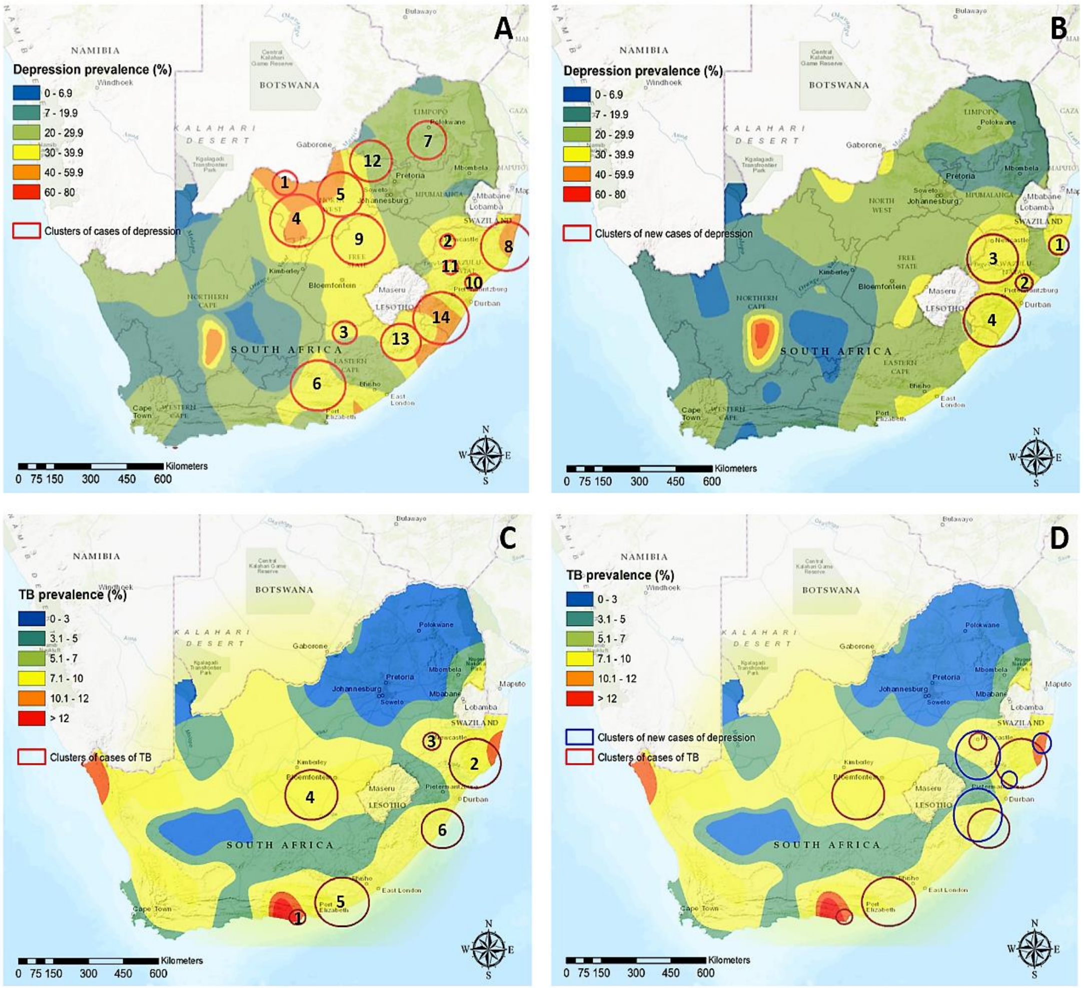


Clusters and interpolated surface prevalence levels (%) for self-reported diabetes in India (A). Clusters and interpolated surface exposure level (cases per 100 000 inhabitants) for reported cases of tuberculosis (TB) India (B)

Depression and tuberculosis in South Africa

- **Individuals who reported being infected with TB had significantly higher odds of belonging to a hotspot of new cases of depression**

- In A) Continuous surface map of prevalence of existing cases of depression and the location of spatio-temporal clusters of existing cases of depression; B) continuous surface map of prevalence of new cases of depression and the location of spatial clusters of new cases of depression; C) Continuous surface map of prevalence of tuberculosis (TB) and the location of spatio-temporal clusters of existing TB cases. D) Geographical overlap between clusters of new cases of depression (blue circles), and clusters of TB (red circles)



Cuadros, Diego F., et al. "Spatial structure of depression in South Africa: A longitudinal panel survey of a nationally representative sample of households." Scientific Reports (2019)

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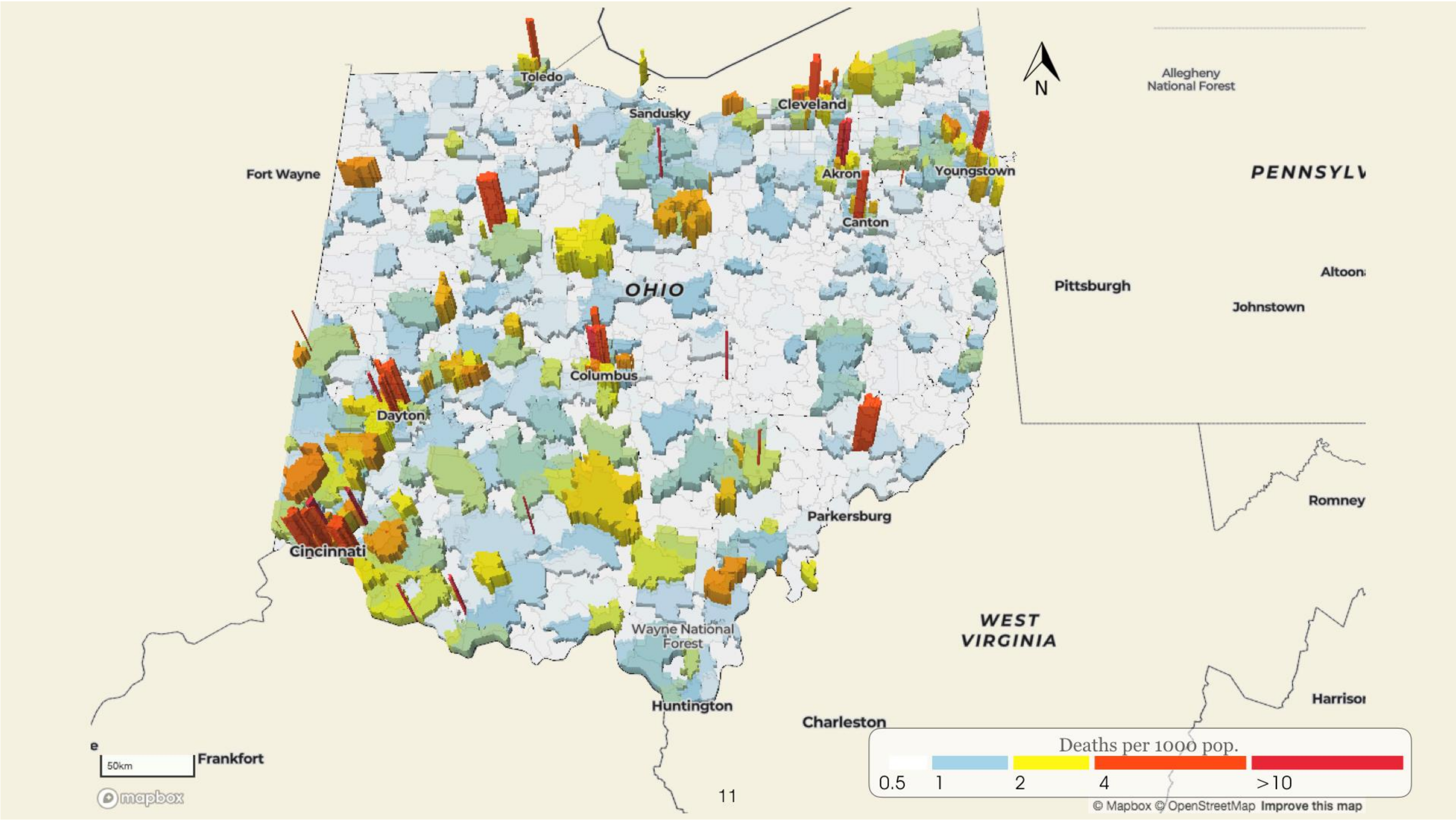
Opioid overdose epidemic in the US



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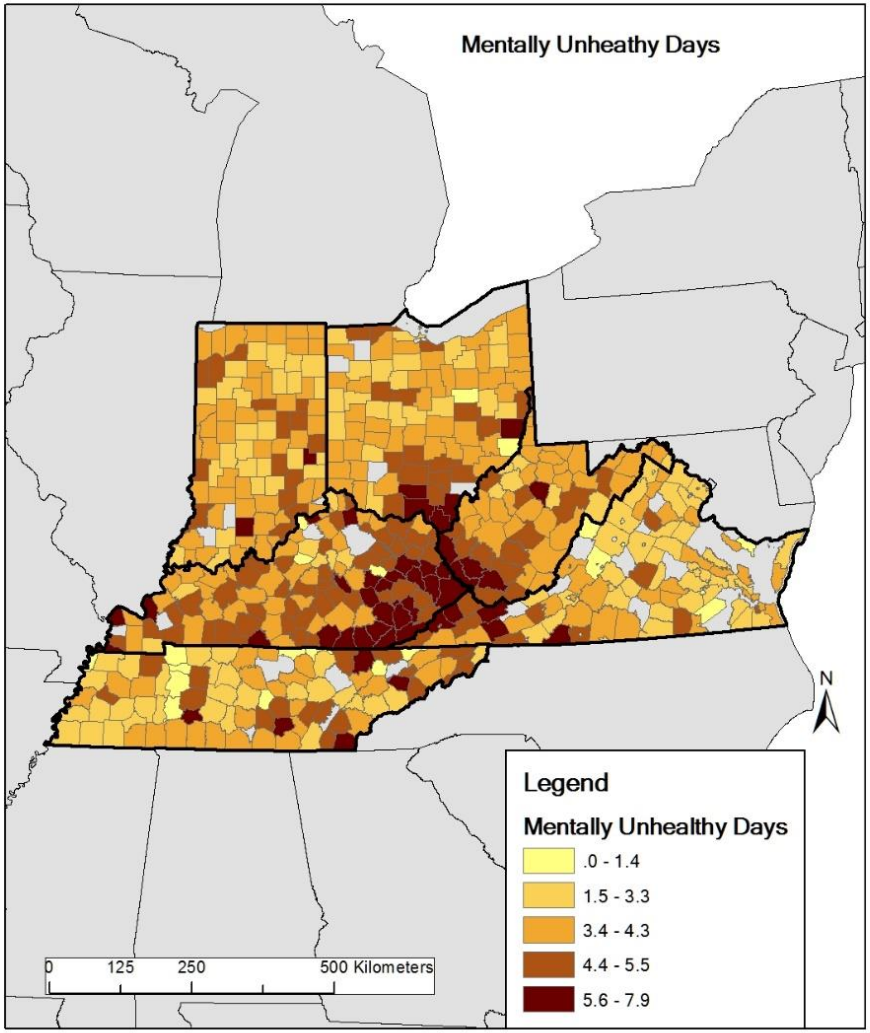
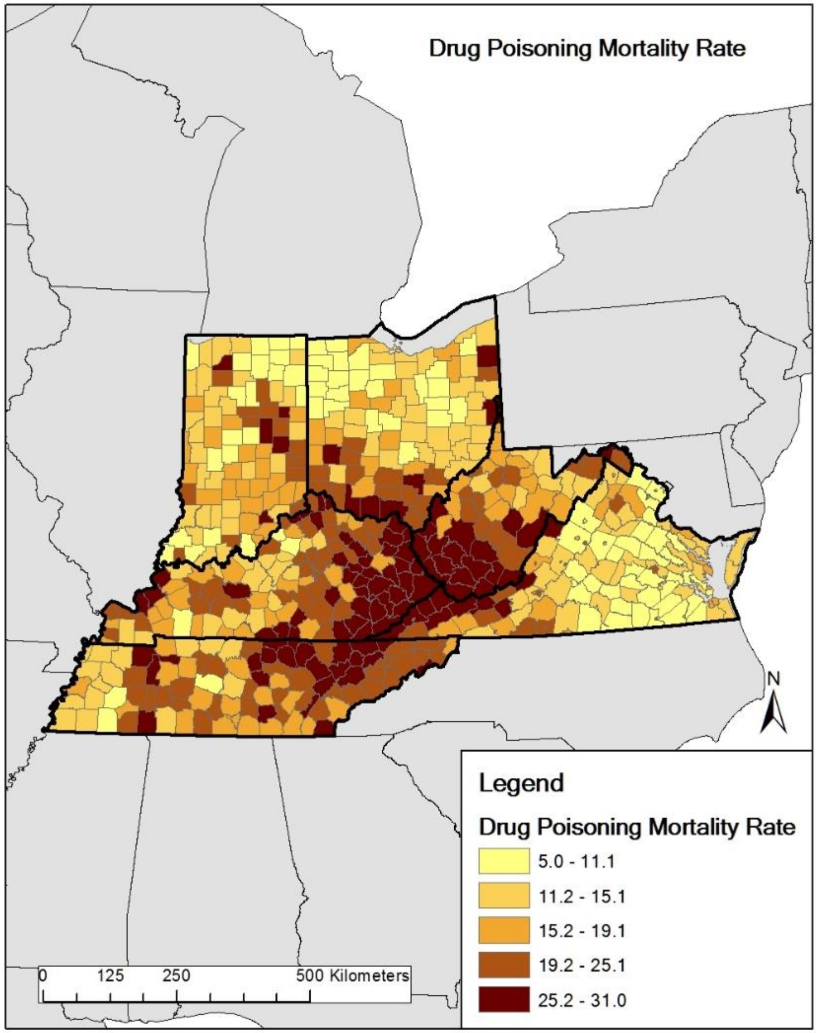
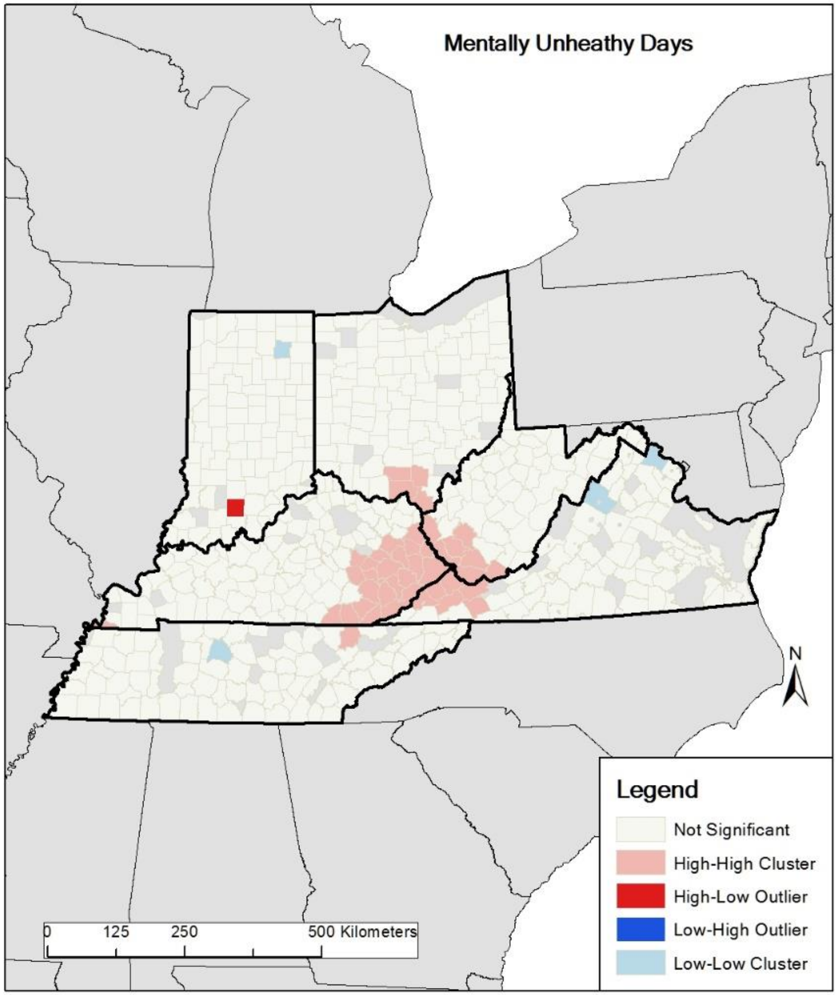
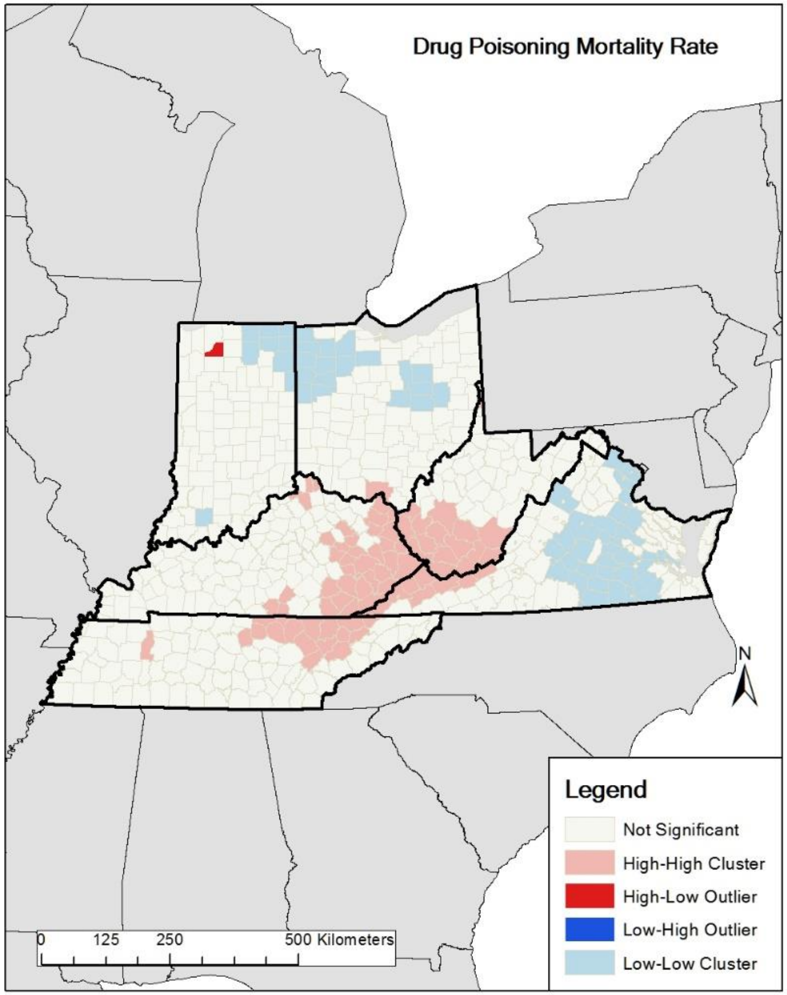
Social determinants of addiction





Social determinants of addiction





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Some other uses

- Maps can show disparity in health care delivery
- Help patients find quality health care
- Help authorities assess risk

Maps: Great Communicators!

- Graphic representations of data frequently more powerful than numeric or textual representations

- Maps seem authoritative to policy makers and stake holders

Acknowledgements

Frank Tanser

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Andrew Tomita

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Thank you!