

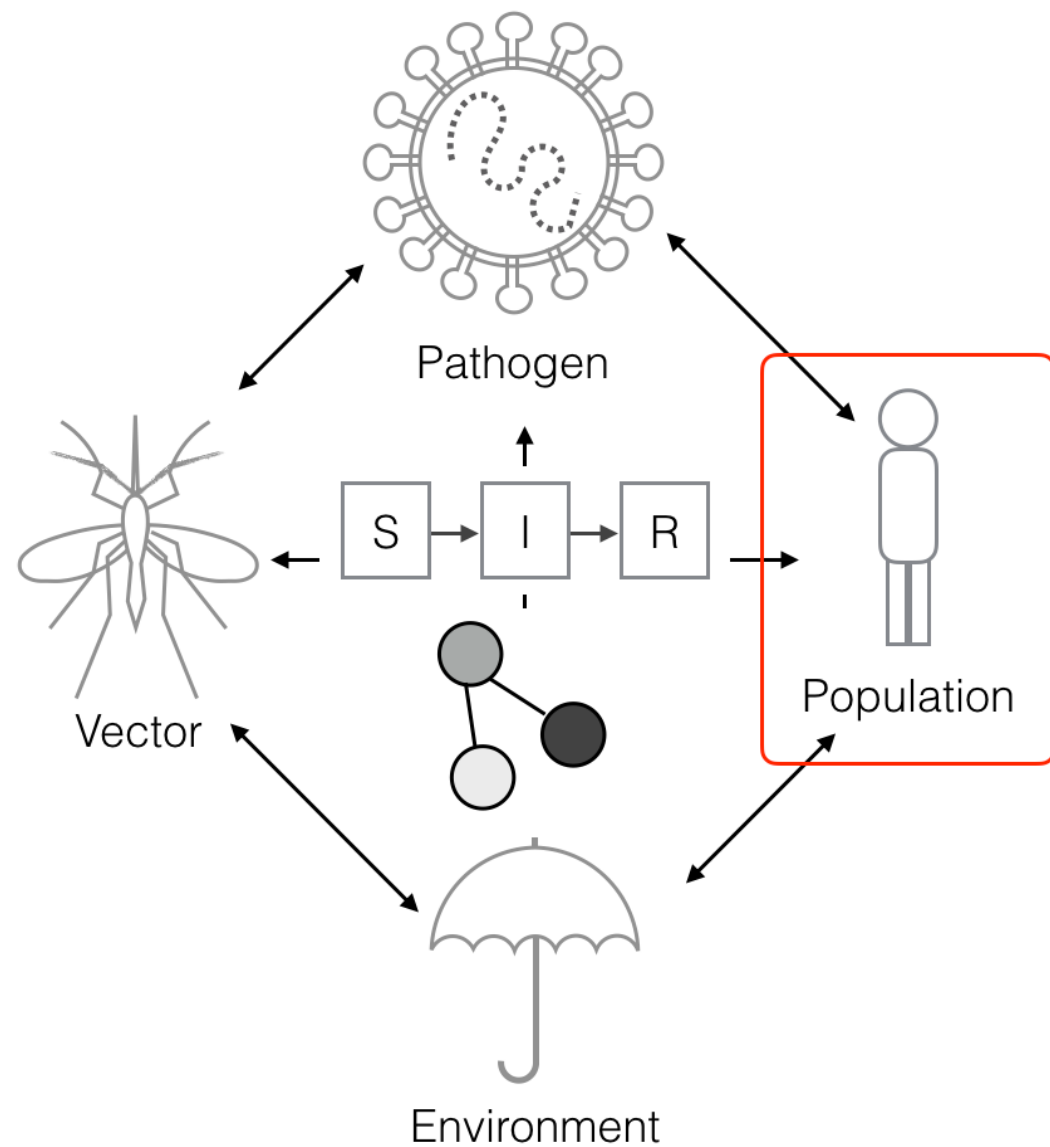


Rice planting in Antananarivo, Madagascar

Mobility and Malaria in Madagascar

Amy Wesolowski

Department of Ecology and Evolutionary Biology



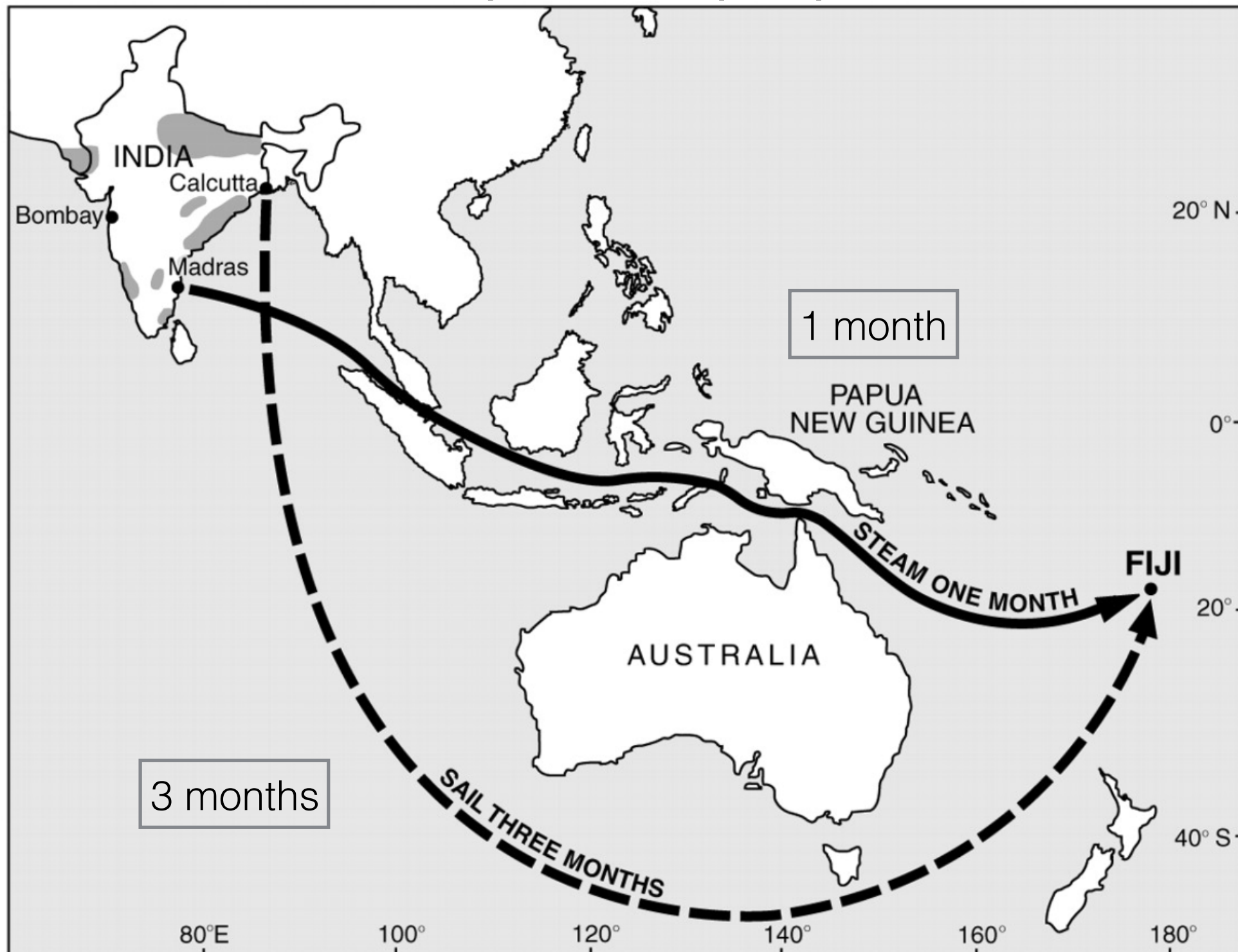
Introduction

Quantifying human mobility patterns

Modeling sources and sinks of malaria parasites in Madagascar

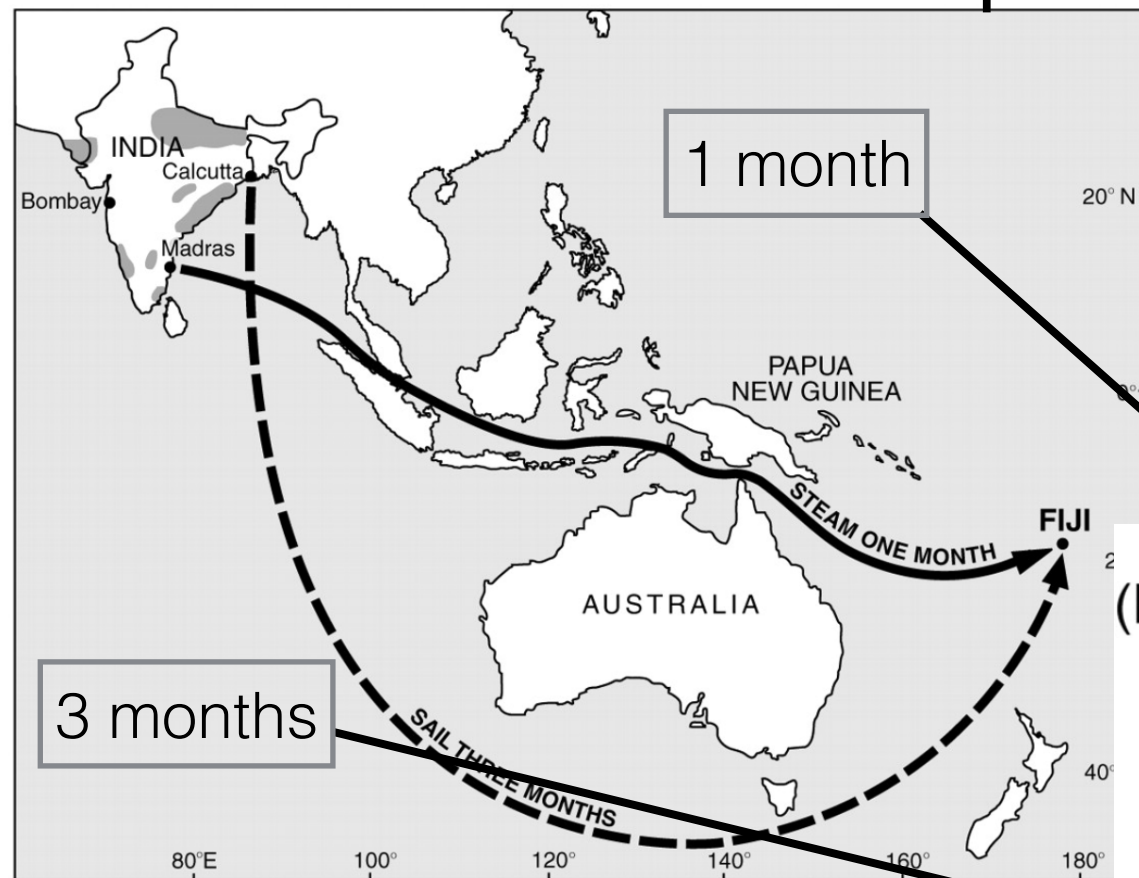
Human travel can introduce pathogens into susceptible populations

(A)

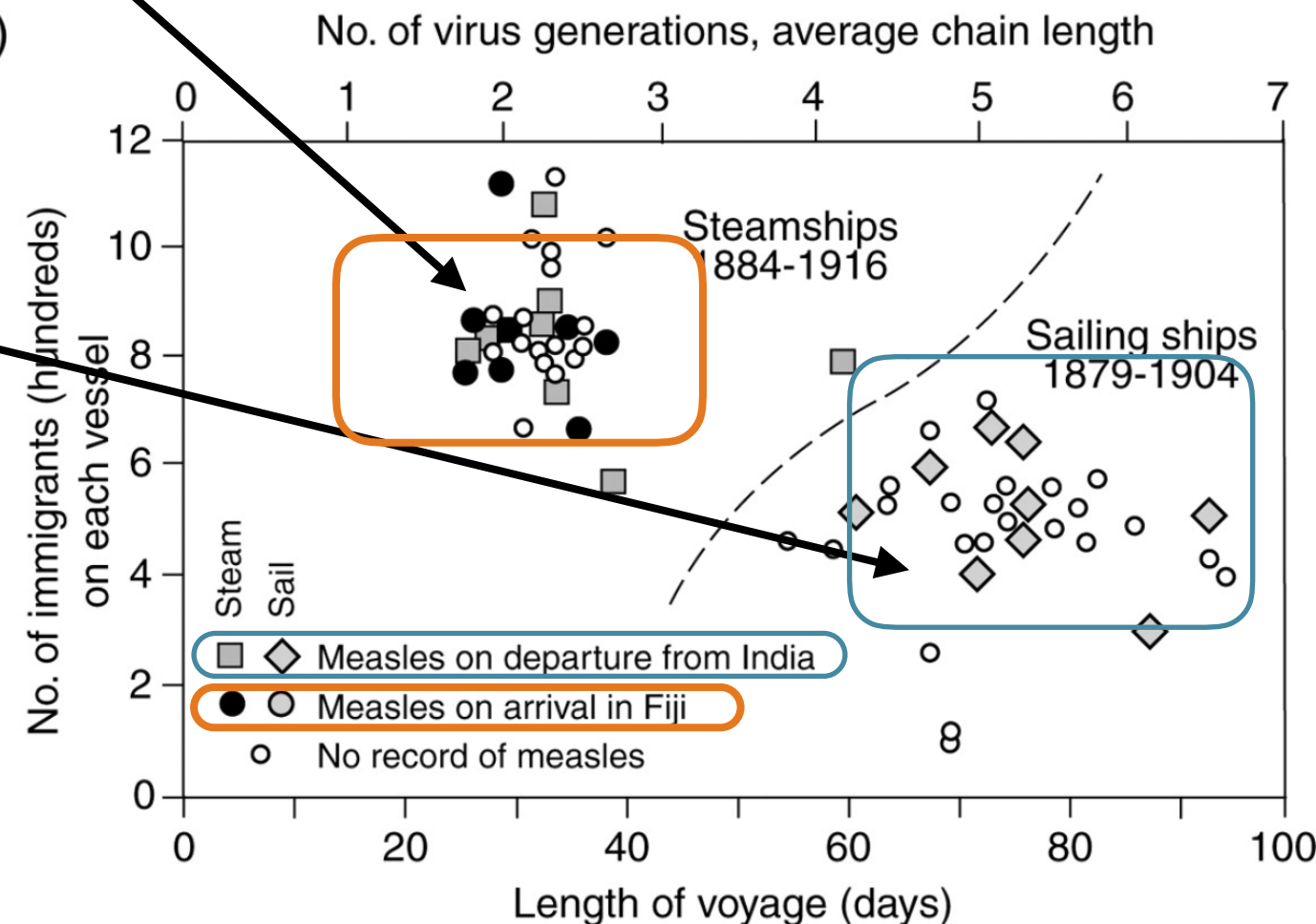


Human travel can introduce pathogens into susceptible populations

(A)



(B)



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

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

Bruce-Chwatt, 1972

Why do we care about human travel for malaria control?

Malaria resurgence

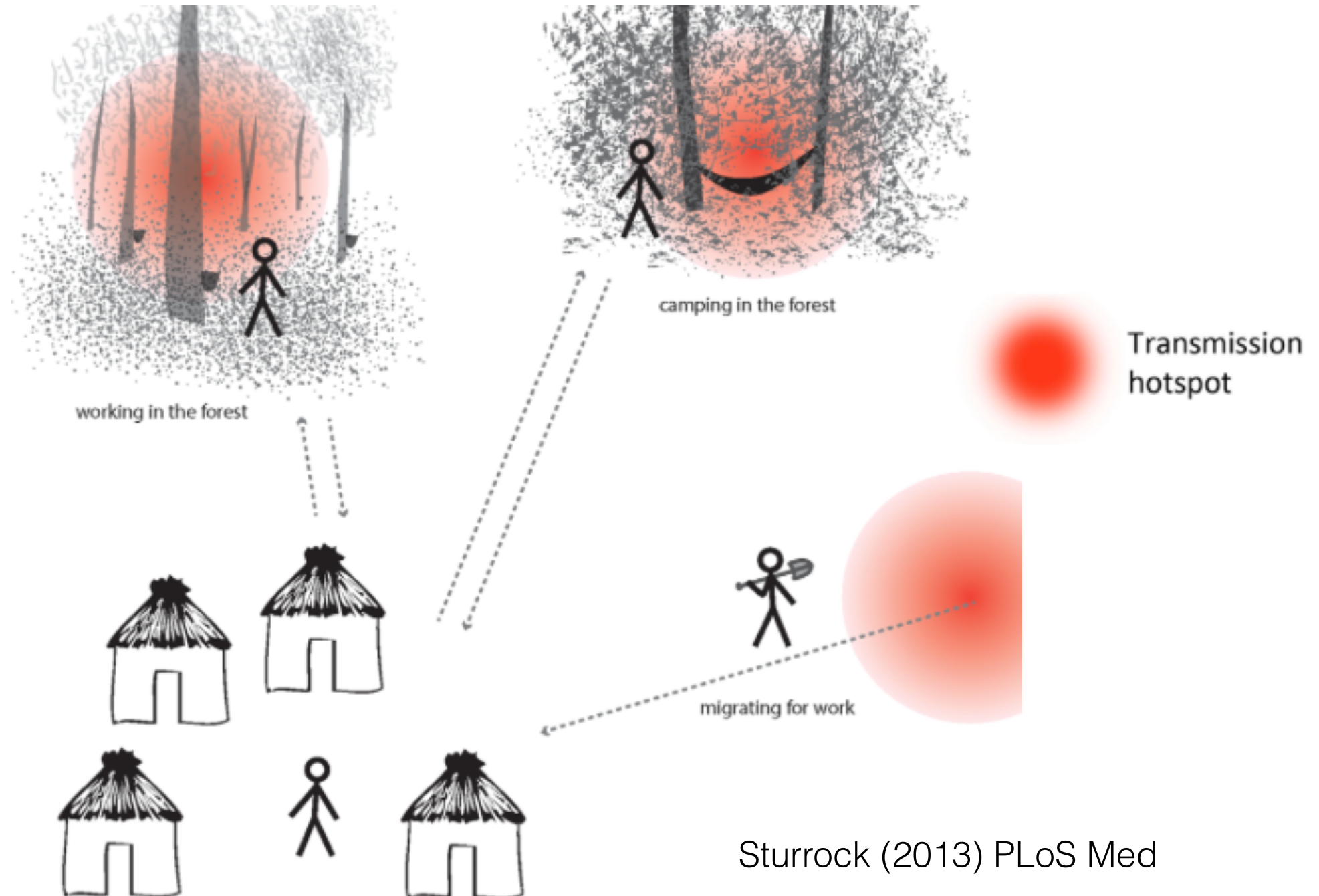
Targeted interventions

Spain 1936-1943	India 1965-1976
Russia 1960-	Myanmar 1968-2008
Afghanistan 1970-1978	Thailand 1970-1981
Azerbaijan 1990-1996	Bangladesh 1971-1994
Turkey 1990-1994	Vietnam 1979-1991
Iran 1991-1999	Pakistan 1980-1992
Liberia 1948-1951	Sri Lanka 1982-1987
Swaziland 1971-1996	French Guiana 1975-1990
Mauritius 1975-1982	Peru 1981-1998
Ethiopia 1980-1991	Indonesia 1963-1973
Sudan 1981-1993	Malaysia 1967-1978
Uganda 1990	

Why do we care about human travel for malaria control?

Malaria resurgence

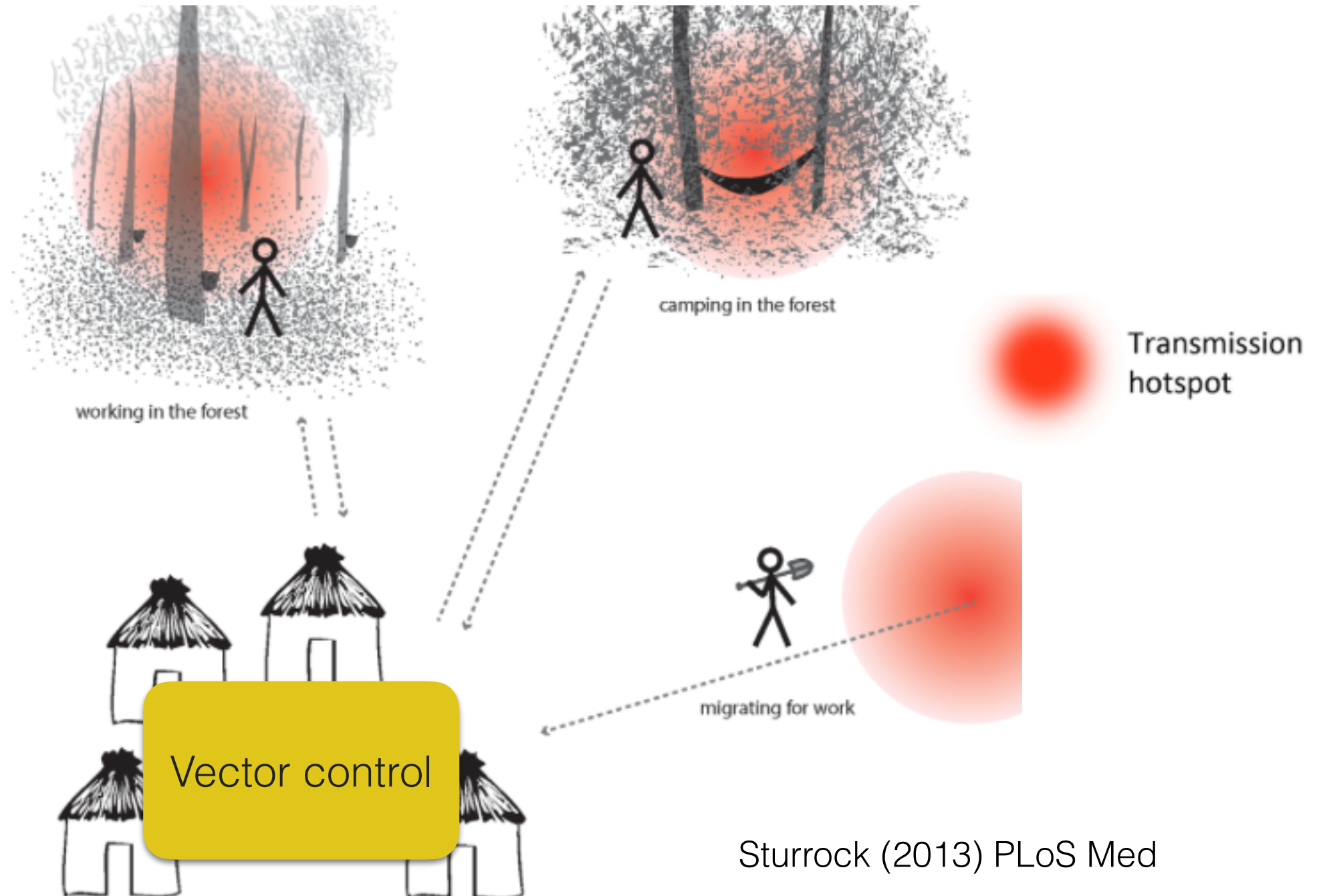
Targeted interventions



Why do we care about human travel for malaria control?

Malaria resurgence

Targeted interventions

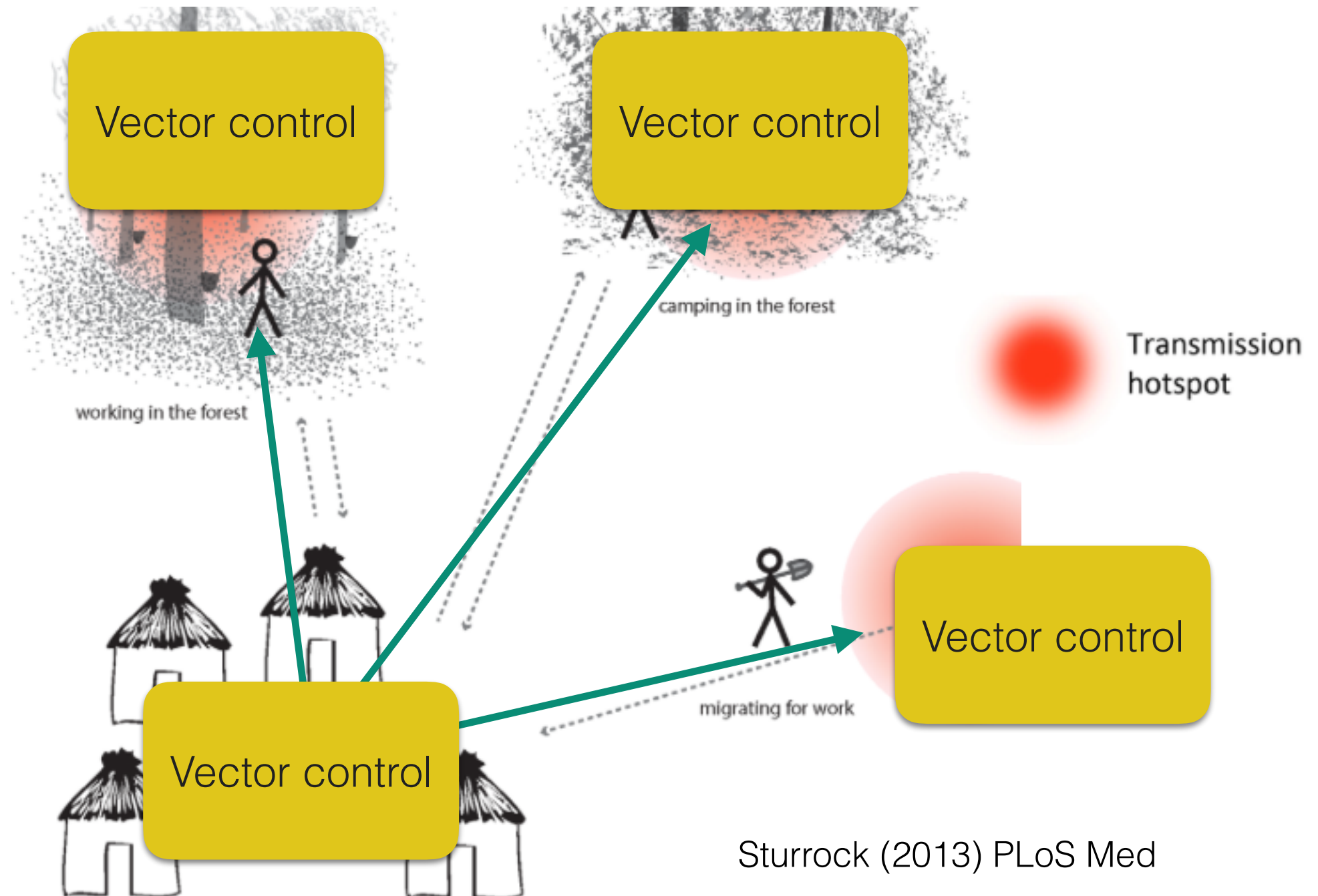


Sturrock (2013) PLoS Med

Why do we care about human travel for malaria control?

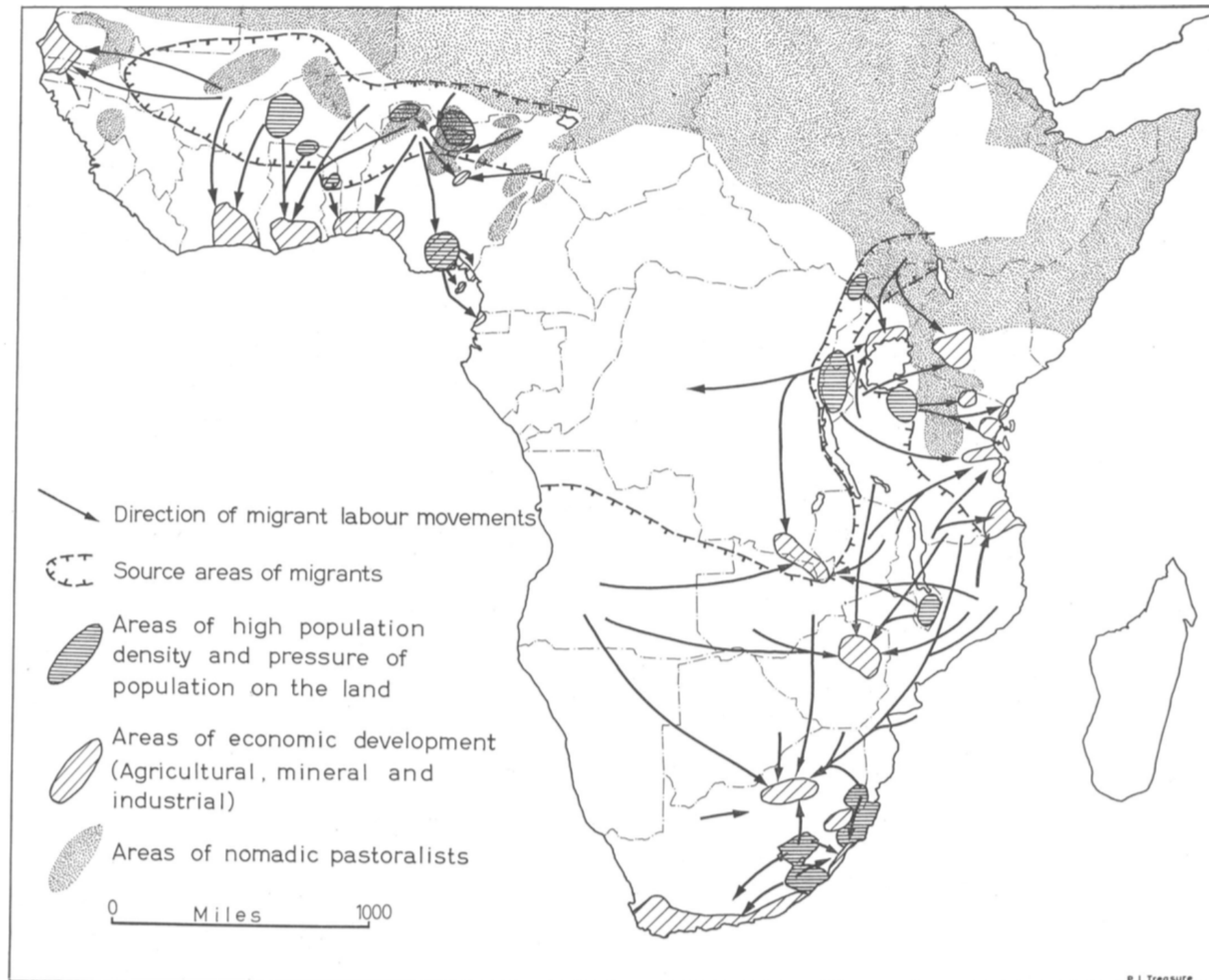
Malaria resurgence

Targeted interventions



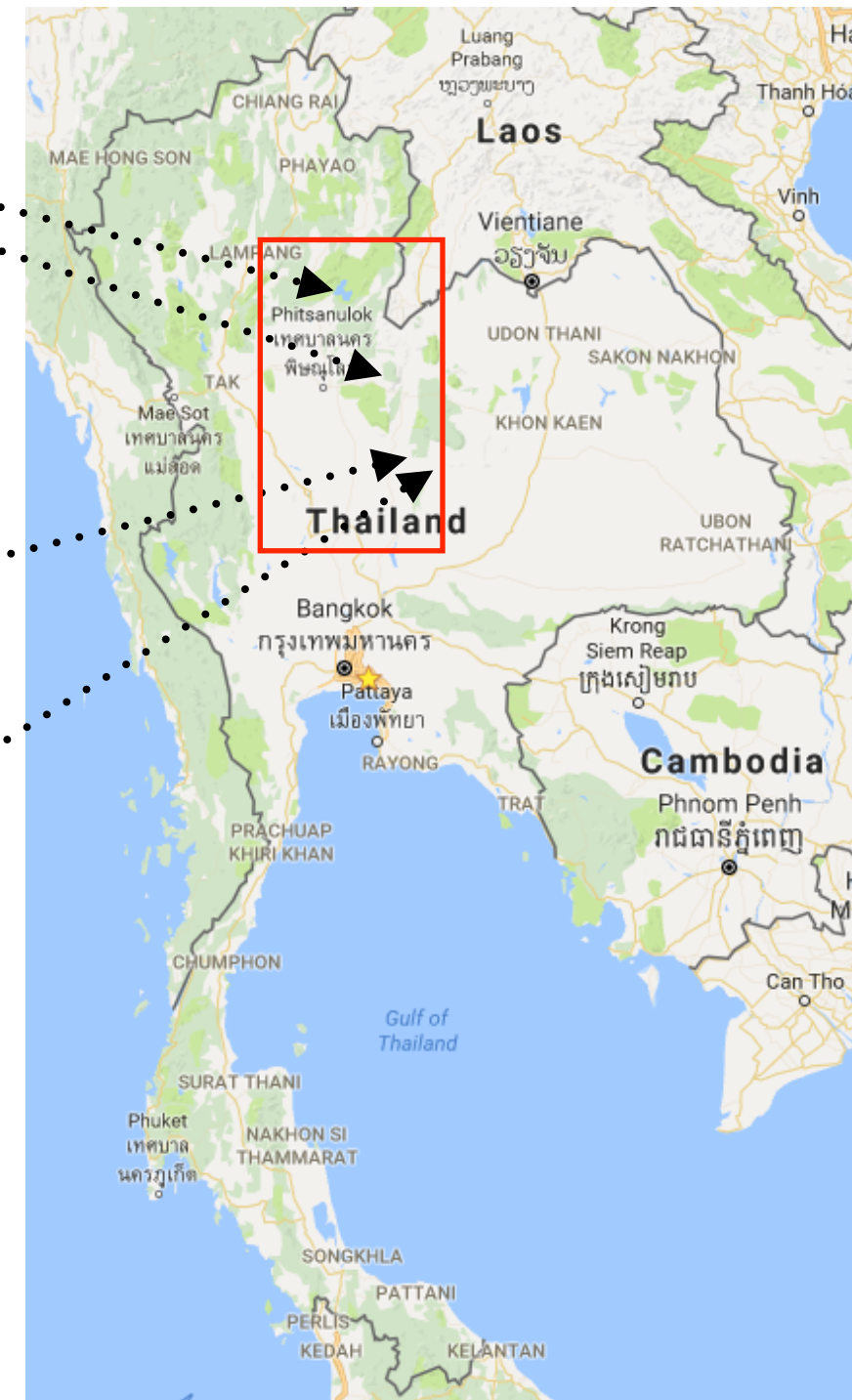
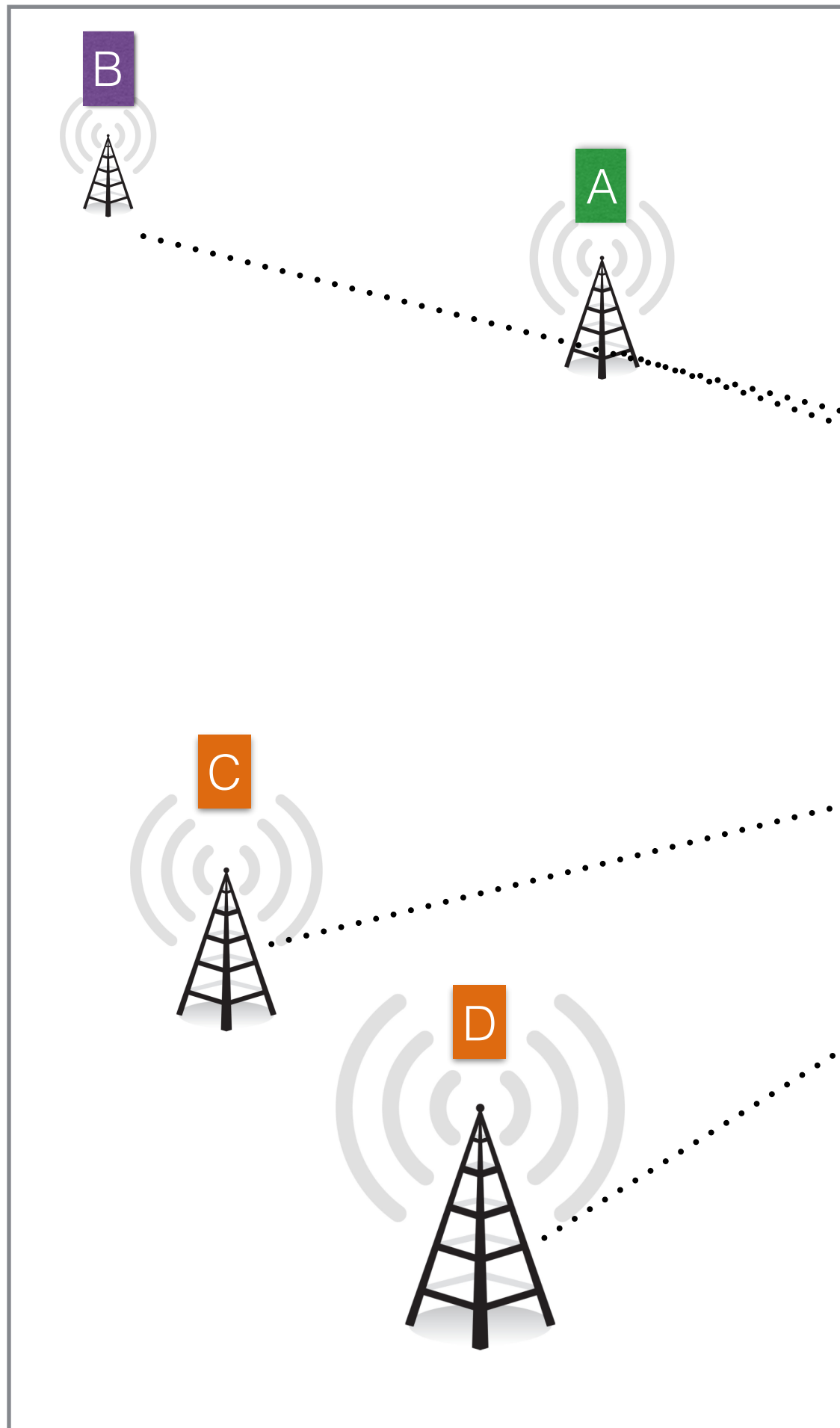
How do we measure human travel patterns?

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



Measuring mobility patterns

Mobile phone data

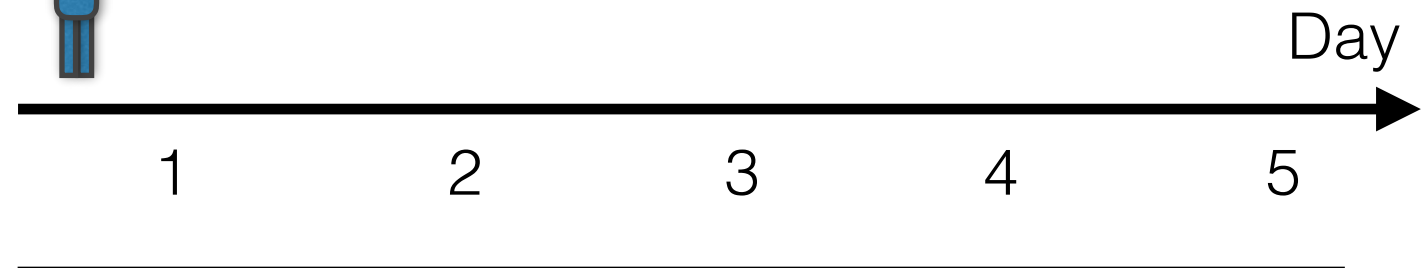


	A_NU...	B_NU...	CELL_ID	LOCATION	TIER3_NAME	MAIN_GROUP	CALLI...	CALLI...	EVENT_...	EVENT...	TWIN	DESTINATI...	COST_...	PRODUCT
423	20923...	23214...	(null)	Norge	SMS i Norge	SMS	(null)	242013...	15.02.2011	(null)	(null)	(null)	(null)	04720
424	20923...	23214...	(null)	Norge	SMS i Norge	SMS	(null)	242013...	15.02.2011	(null)	(null)	(null)	(null)	04720
425	20923...	23214...	(null)	Norge	SMS i Norge	SMS	(null)	242013...	15.02.2011	(null)	(null)	(null)	(null)	04720
426	24115...	46230...	242012040141314	Utland	NR - Utgående tale	Tale	35526...	242050...	15.02.2011	(null)	(null)	NOR	Z-NR-MOC	(null)
427	46240...	30623...	242011170104261	Norge	Til fastnett	Tale	12164...	242010...	15.02.2011	(null)	(null)	(null)	F-FAST...	04720
428	46240...	24002...	242012070143948	Norge	Til operatører hos Netcom	Tale	12164...	242010...	15.02.2011	(null)	(null)	(null)	X-NETW...	04720
429	46240...	30598...	242012070143948	Norge	Til fastnett	Tale	12164...	242010...	15.02.2011	(null)	(null)	(null)	F-FAST...	04720
430	46240...	24002...	242012070143948	Norge	Til operatører hos Netcom	Tale	12164...	242010...	15.02.2011	(null)	(null)	(null)	X-NETW...	04720
431	46240...	24002...			Til operatører hos Netcom	Tale	12164...	242010...	15.02.2011	(null)	(null)	(null)	X-NETW...	04720
432	46240...	11168...			Til fastnett	Tale	12164...	242010...	15.02.2011	(null)	(null)	(null)	F-FAST...	04720
433	48311...	45754...			Viderekobling i Telenors Nett	Tale	(null)	242010...	15.02.2011	(null)	(null)	NOR	M-MOBI...	04577
434	48311...	(null)			Internett	Internett	(null)	242010...	14.02.2011	45259	(null)	(null)	T3-VOT	04577
435	48311...	(null)			Internett	Internett	(null)	242010...	14.02.2011	297421	(null)	(null)	T3-VOT	04577
436	48311...	(null)	(null)	Norge	Internett	Internett	(null)	242010...	14.02.2011	468	(null)	(null)	T3-VOT	04577
437	48311...	(null)	(null)	Norge	Internett	Internett	(null)	242010...	15.02.2011	7854	(null)	(null)	T3-VOT	04577
438	48311...	(null)	(null)	Norge	Internett	Internett	(null)	242010...	15.02.2011	352	(null)	(null)	T3-VOT	04577
439	48311...	(null)			Internett	Internett	(null)	242010...	14.02.2011	152	(null)	(null)	T3-VOT	04577
440	48311...	(null)			Internett	Internett				70509	(null)	(null)	T3-VOT	04577
441	48311...	(null)			Internett	Internett				144	(null)	(null)	T3-VOT	04577
442	48311...	(null)			Internett	Internett				3711	(null)	(null)	T3-VOT	04577
443	48311...	(null)			Internett	Internett				3202	(null)	(null)	T3-VOT	04577
444	48311...	(null)	(null)	Norge	Internett	Internett				152	(null)	(null)	T3-VOT	04577
445	45047...	49639...	(null)	Norge	SMS i Norge	SMS	(null)	242010...	15.02.2011	(null)	(null)	(null)	(null)	04747
446	22637...	(null)	(null)	Utland	GPRS i utlandet	Internett	(null)	238209...	15.02.2011	341	(null)	(null)	T3-VOT	(null)
447	46835...	23959...	242012080150195	Norge	NR - Utgående SMS	SMS	35821...	242050...	14.02.2011	(null)	(null)	(null)	Z-MO	(null)
448	23170...	(null)	242011450118026	Utland	NR - Inngående tale/data/fax	Tale	35492...	242059...	14.02.2011	(null)	(null)	(null)	Z-MTC	(null)
449	23698...	(null)	242011560112573	Utland	NR - Inngående tale/data/fax	Tale	35489...	242050...	15.02.2011	(null)	(null)	(null)	Z-MTC	(null)
450	29651...	(null)	(null)	Norge	Internett	Internett	(null)	242059...	14.02.2011	28754	(null)	(null)	T3-VOT	(null)
451	48376...	23959...	(null)	Norge	SMS	SMS	35536...	242059...	15.02.2011	(null)	(null)	(null)	T3-TA2...	(null)
1792	23825...	36243...	0	Norge	Tale	Tale	(null)	(null)	15.02.2011	(null)	(null)	(null)	F-FAST...	04008
1793	23825...	45754...	0	Norge	Tale	Tale	(null)	(null)	15.02.2011	(null)	(null)	(null)	M-MOBI...	04008
1794	130055	45558...	(null)	Norge	SMS	SMS	(null)	(null)	15.02.2011	(null)	(null)	(null)	(null)	02092
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1796	47589...	24063...	(null)	Norge	SMS i Norge	SMS	(null)	242013...	14.02.2011	(null)	(null)	(null)	(null)	04140
1797	47589...	24063...	(null)	Norge	SMS i Norge	SMS	(null)	242013...	14.02.2011	(null)	(null)	(null)	(null)	04140
1798	47589...	49864...	(null)	Norge	SMS i Norge	SMS	(null)	242013...	15.02.2011	(null)	(null)	(null)	(null)	04140
1799	47589...	45797...	(null)	Norge	SMS i Norge	SMS	(null)	242013...	15.02.2011	(null)	(null)	(null)	(null)	04140
1800	47589...	45006...	(null)	Norge	SMS i Norge	SMS	(null)	242013...	15.02.2011	(null)	(null)	(null)	(null)	04140
1801	47589...	45872...	(null)	Norge	Internt til kollega - SMS	SMS	(null)	242013...	15.02.2011	(null)	(null)	(null)	(null)	04140
1802	46633...	47516...	242015040147145	Utland	NR - Utgående tale	Tale	35629...	242050...	14.02.2011	(null)	(null)	NOR	Z-NR-MOC	(null)
1803	22600...	45001...	(null)	Norge	NR - Inngående SMS	SMS	35486...	242059...	14.02.2011	(null)	(null)	(null)	T3-TA2...	(null)
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1805	46809...	49792...	(null)	Utland	Fri bruk SMS i	SMS	(null)	242013...	14.02.2011	(null)	(null)	(null)	(null)	04712
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1807	46809...	20022...	(null)	Utland	Fri bruk SMS i	SMS	(null)	242013...	14.02.2011	(null)	(null)	(null)	(null)	04712



Measuring mobility patterns

Mobile phone data



Day	Tower per day	Location per day
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1	▶	▶
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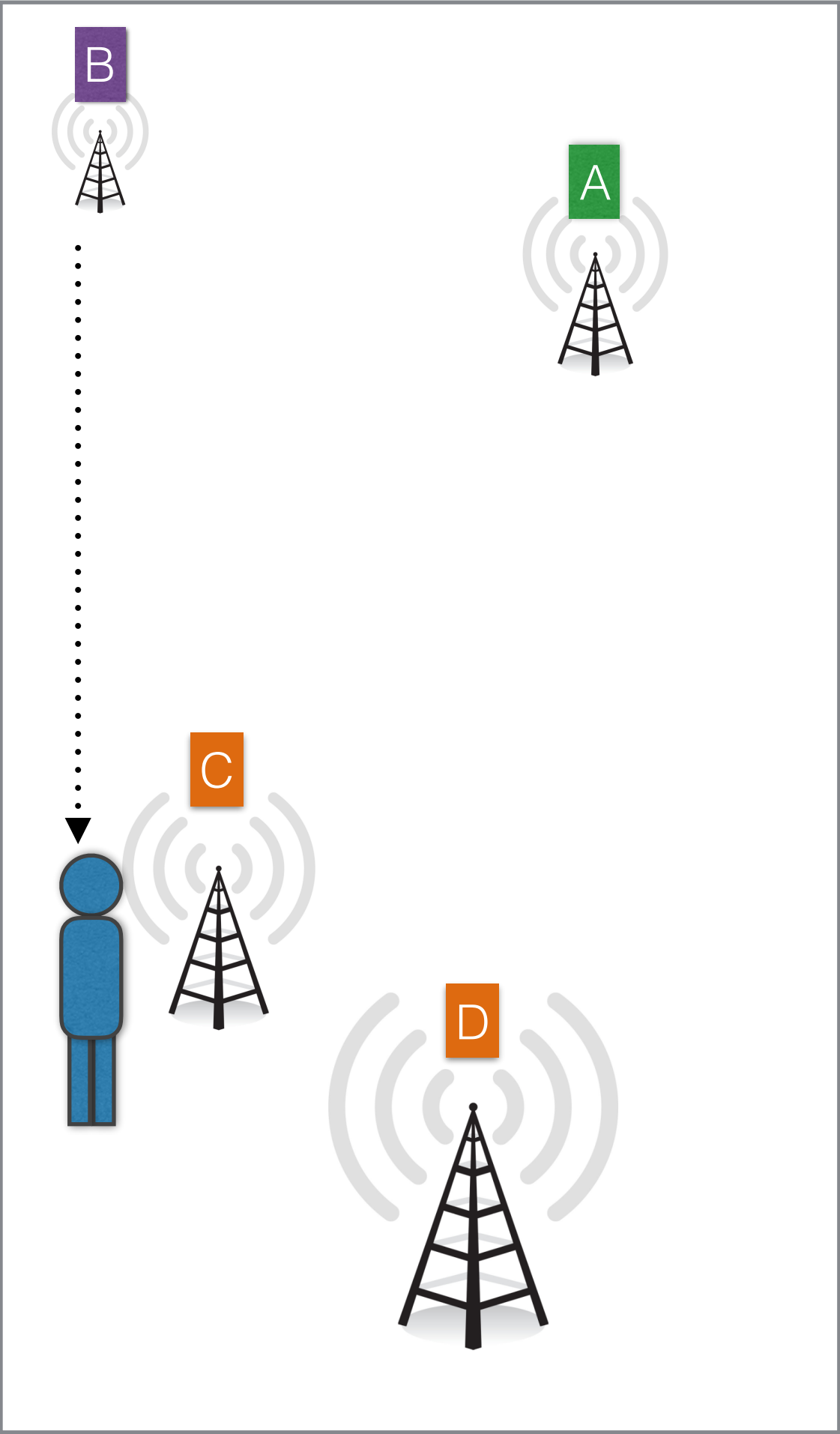
2	▶	▶
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3	▶	▶
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4	▶	▶
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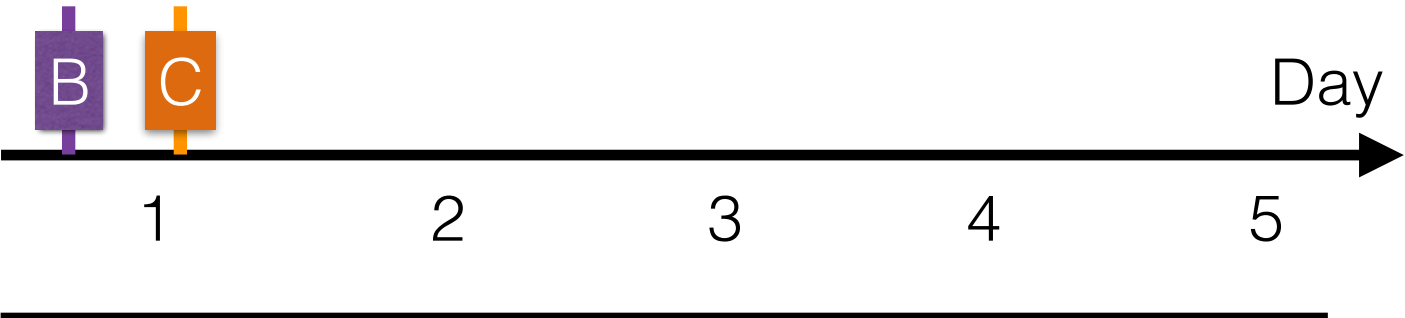
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Trips

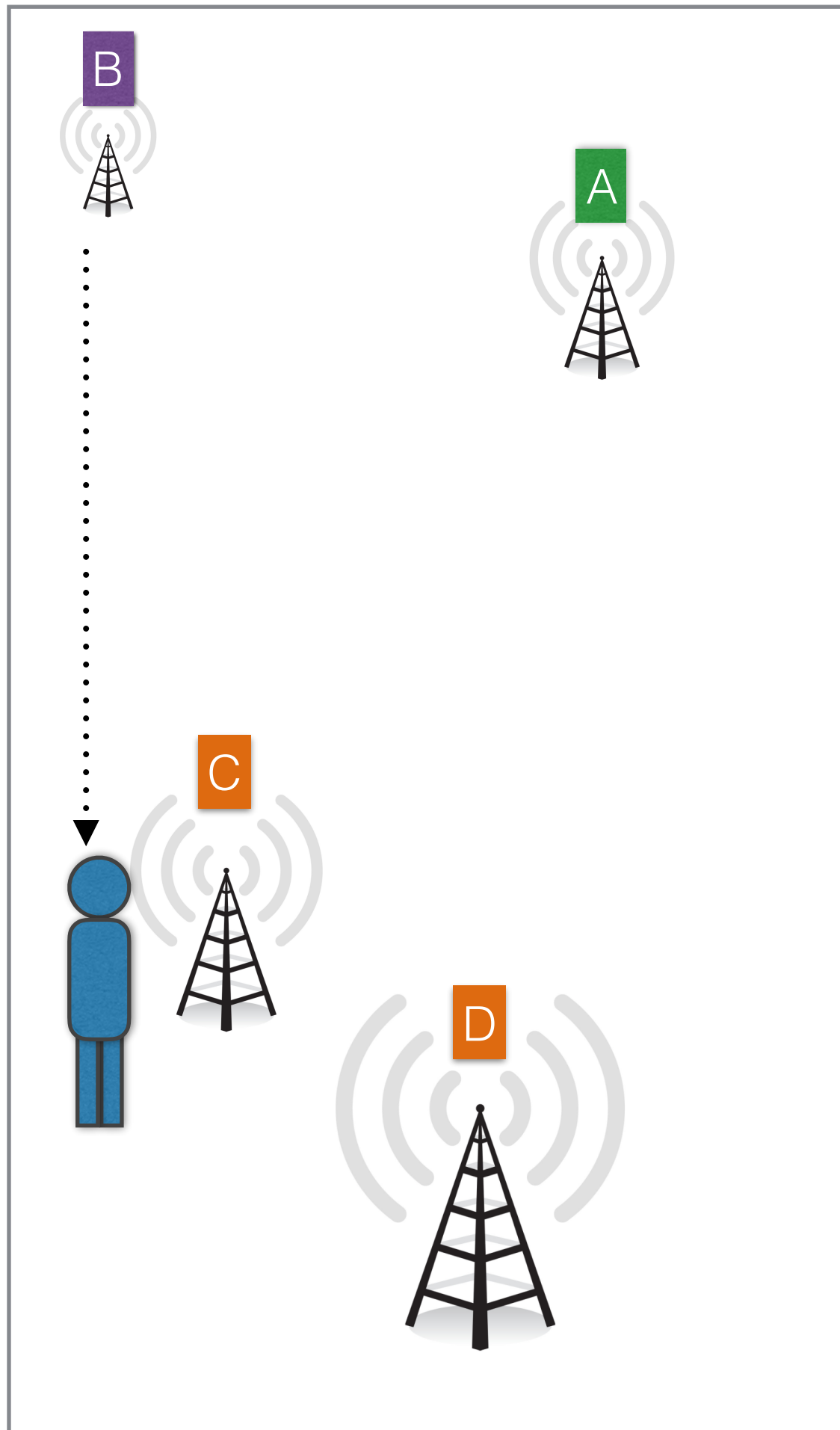


Measuring mobility patterns

Mobile phone data

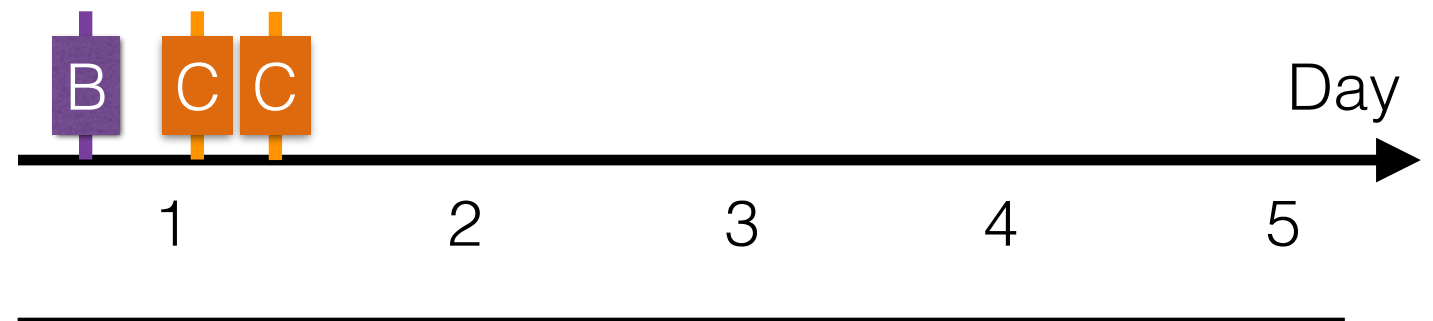


Day	Tower per day	Location per day	Trips
1	▶	▶	
2	▶	▶	
3	▶	▶	
4	▶	▶	
5	▶	▶	



Measuring mobility patterns

Mobile phone data



Day	Tower per day	Location per day
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1	▶	▶
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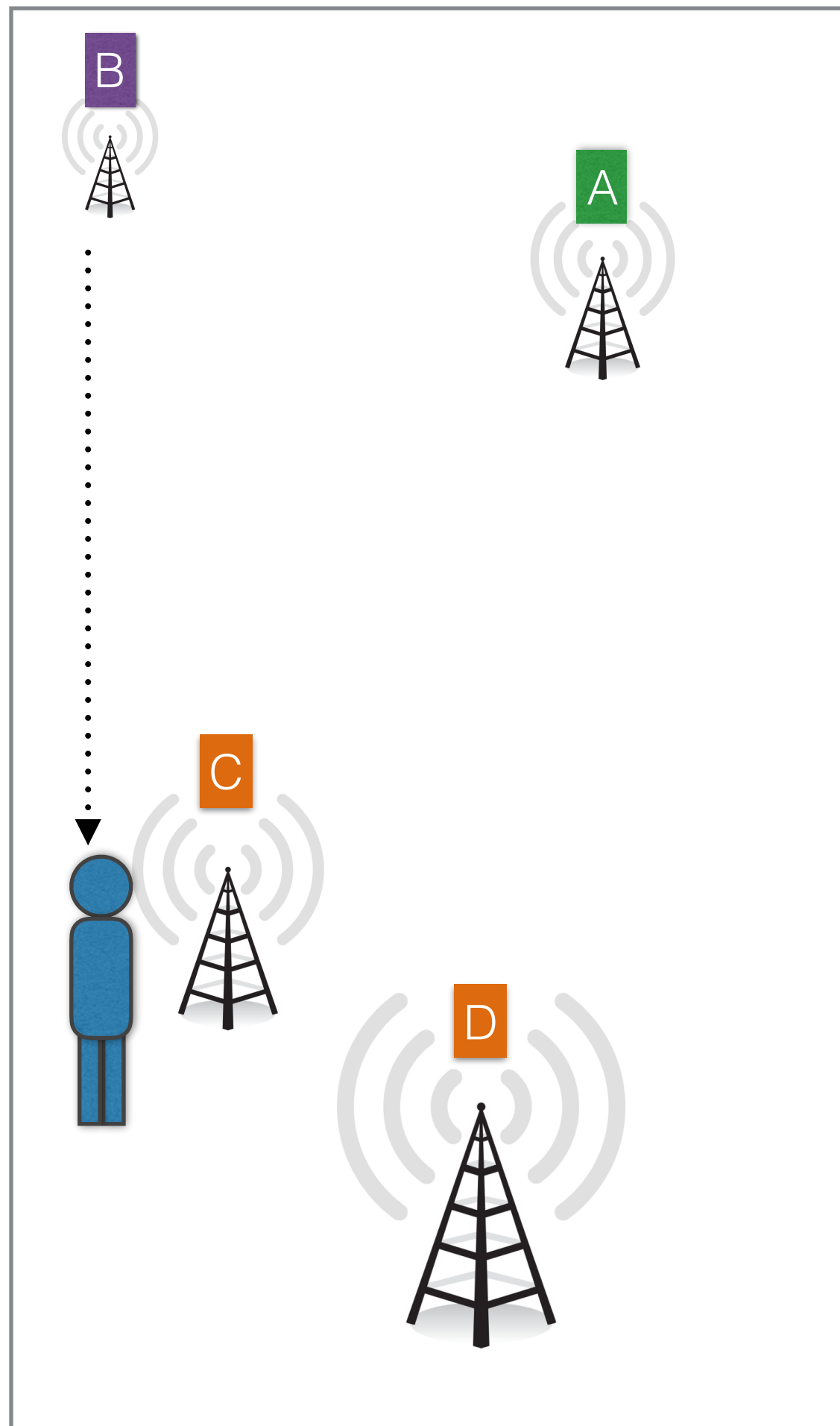
2	▶	▶
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3	▶	▶
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4	▶	▶
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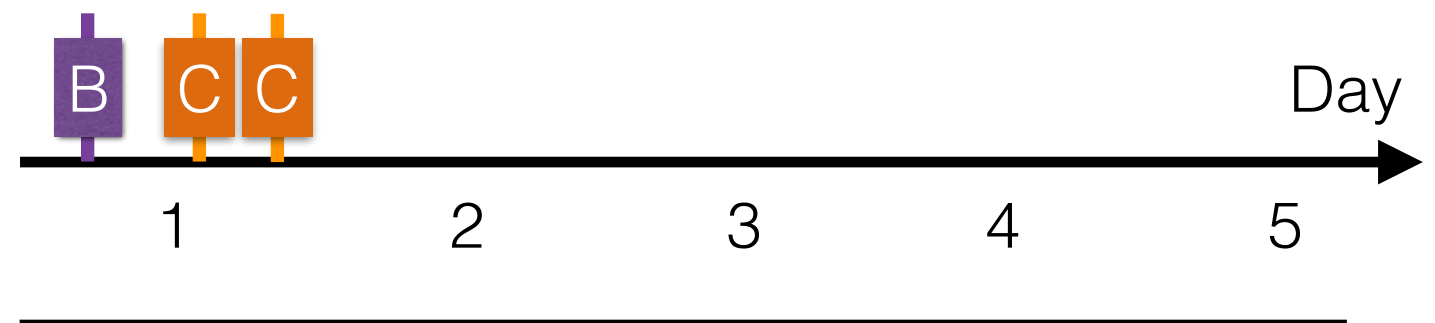
5	▶	▶
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Trips



Measuring mobility patterns

Mobile phone data



Day	Tower per day	Location per day
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1	▶ C	▶
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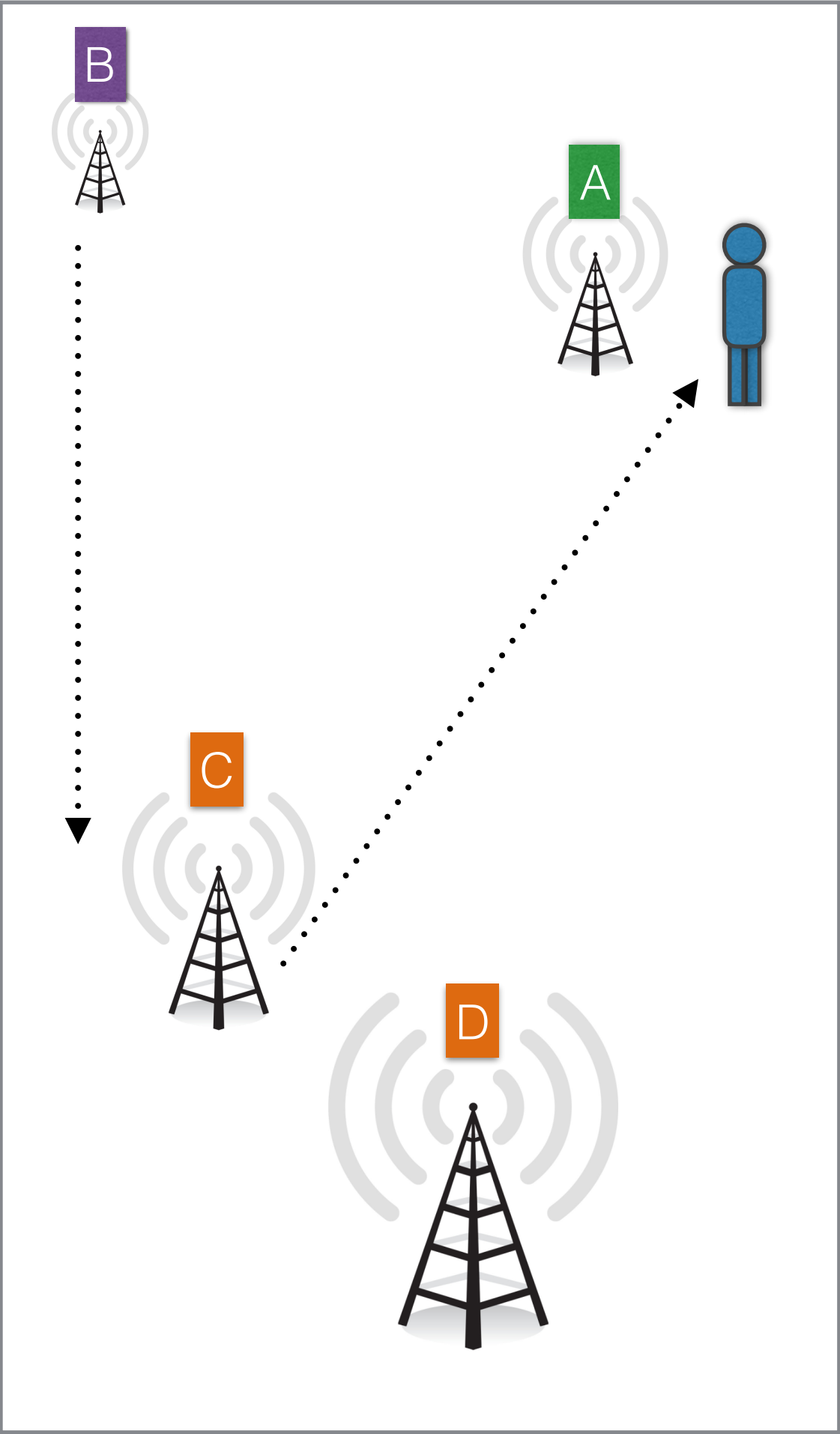
2	▶	▶
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3	▶	▶
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4	▶	▶
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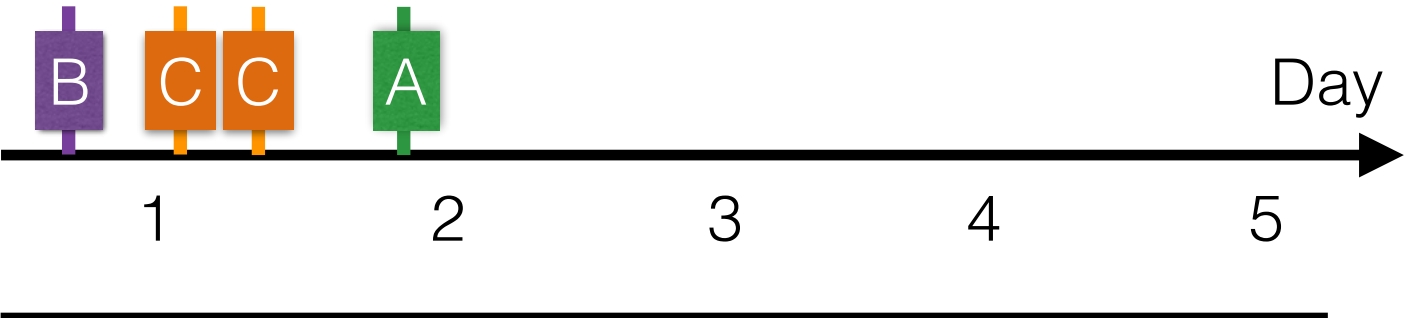
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Trips



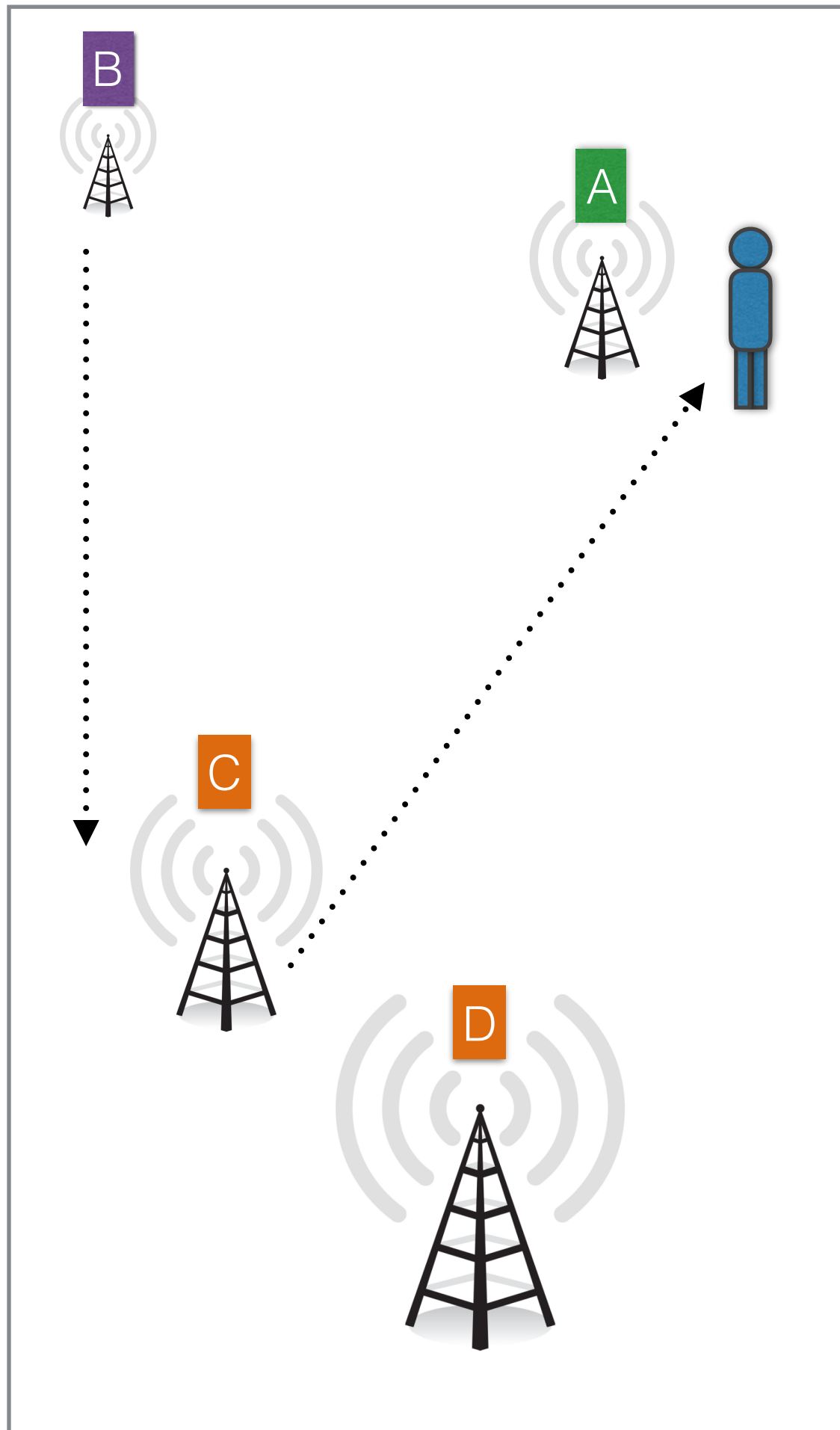
Measuring mobility patterns

Mobile phone data



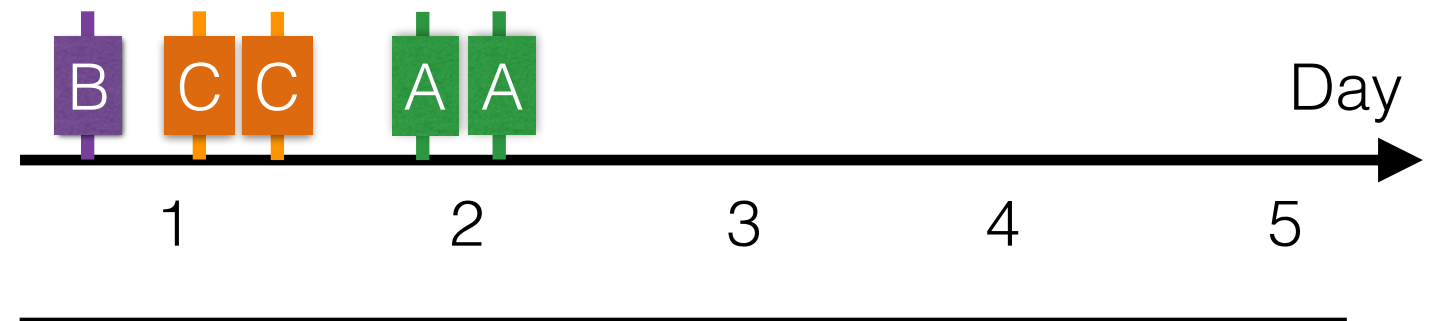
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Trips



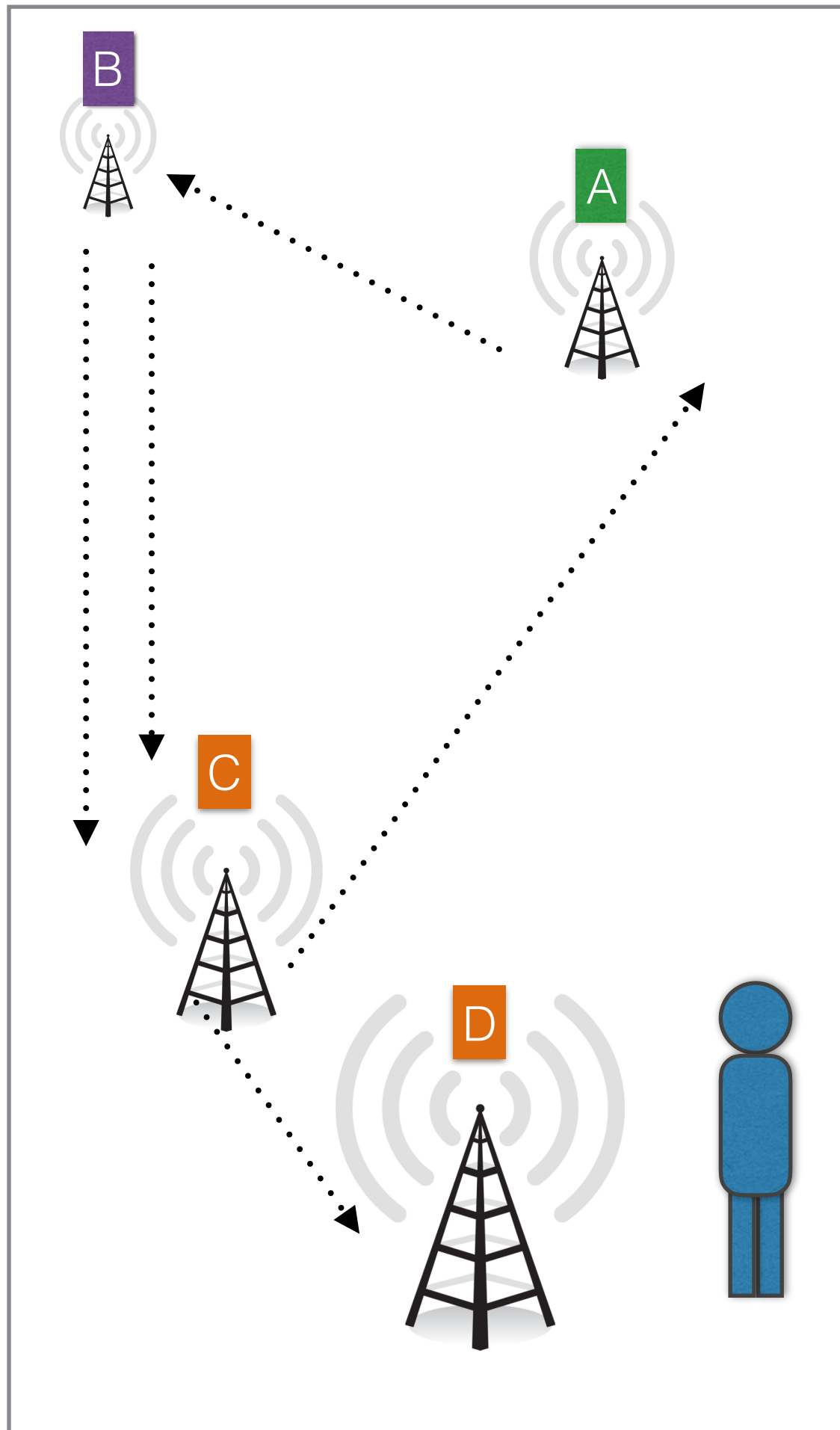
Measuring mobility patterns

Mobile phone data



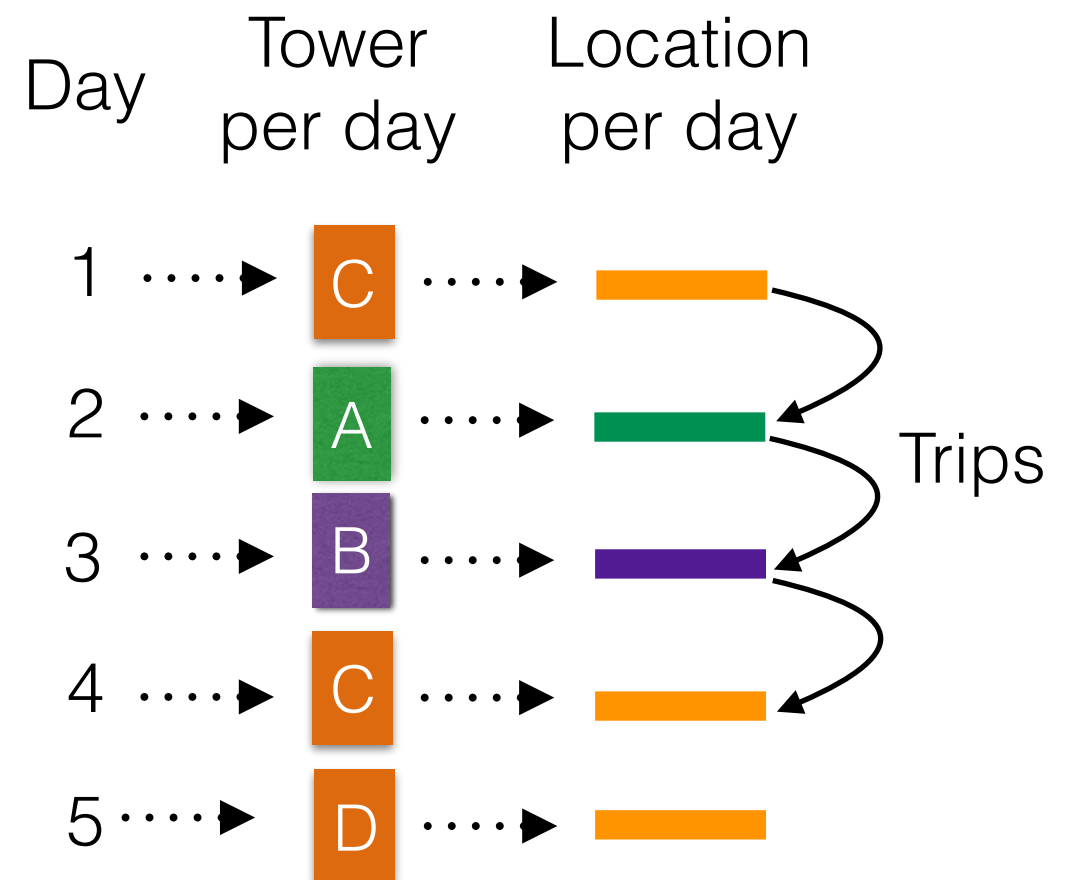
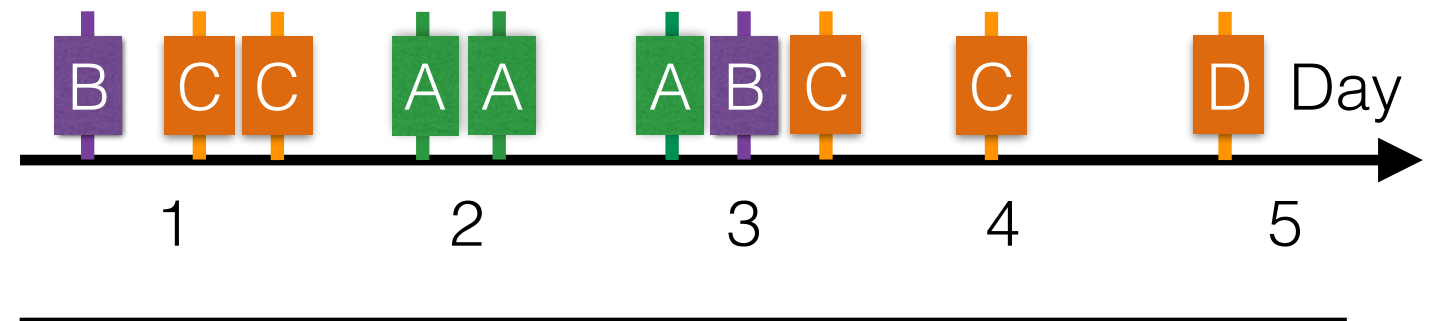
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3		
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5		

Trips

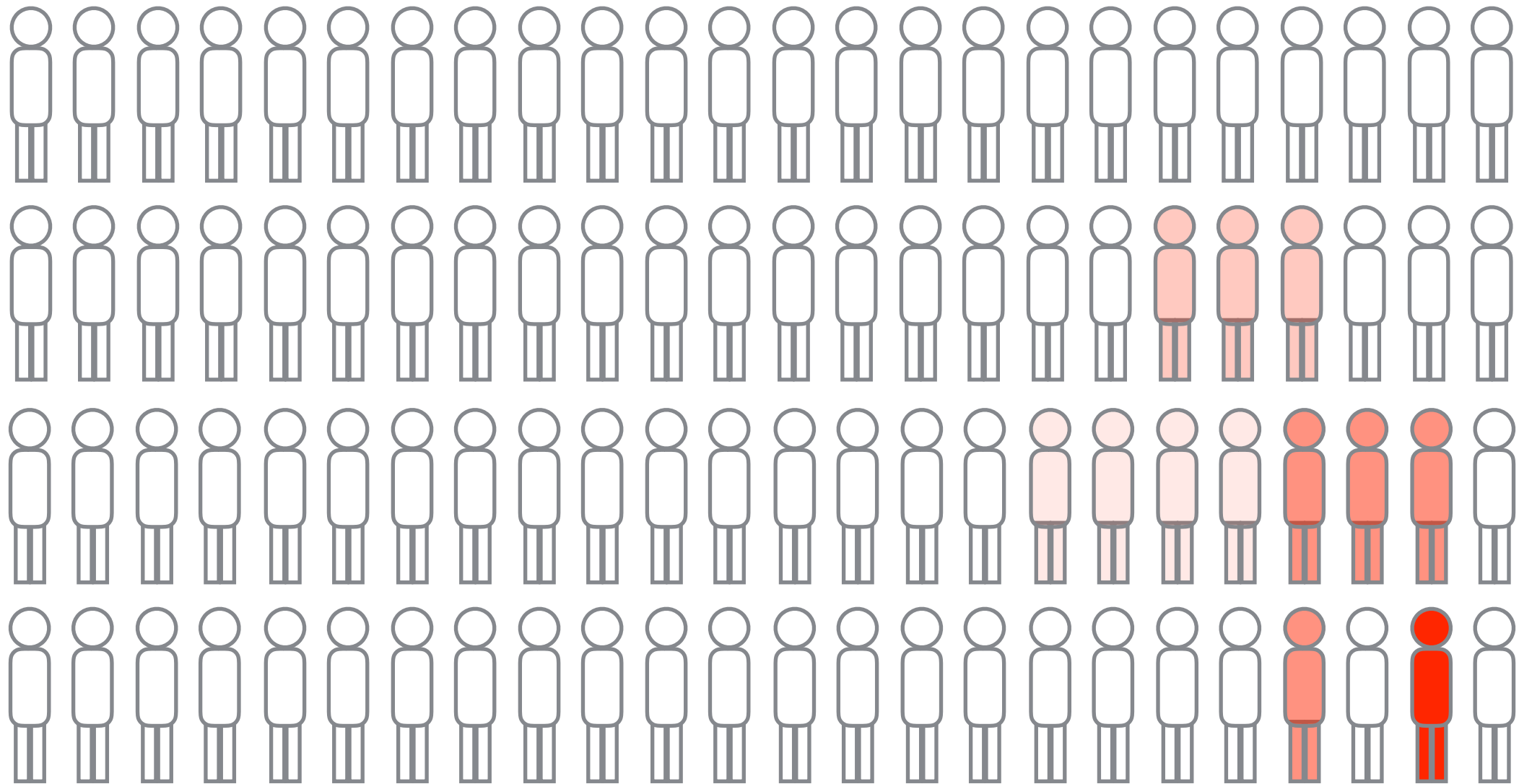


Measuring mobility patterns

Mobile phone data



Incorporating mobility into transmission models

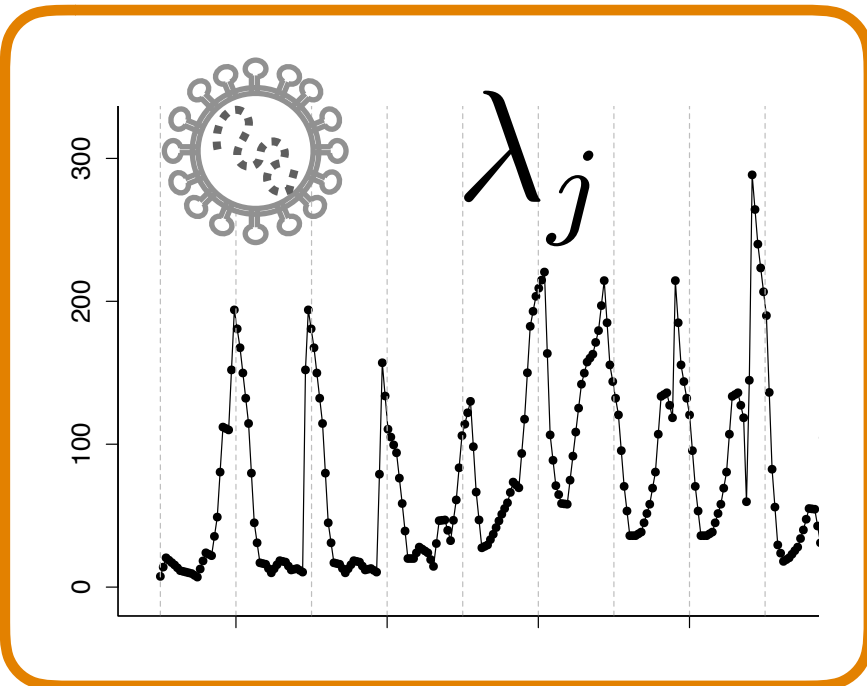
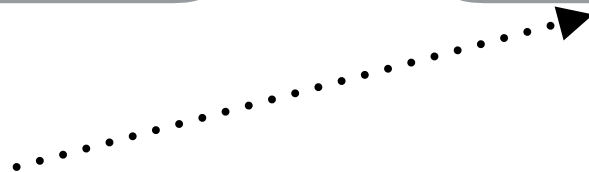


For a directly-transmitted immunizing infection

$$P(\text{import}) = \text{Prevalence (FOI) in source} * \text{Source contact rate} * P(\text{infect} | \text{contact})$$

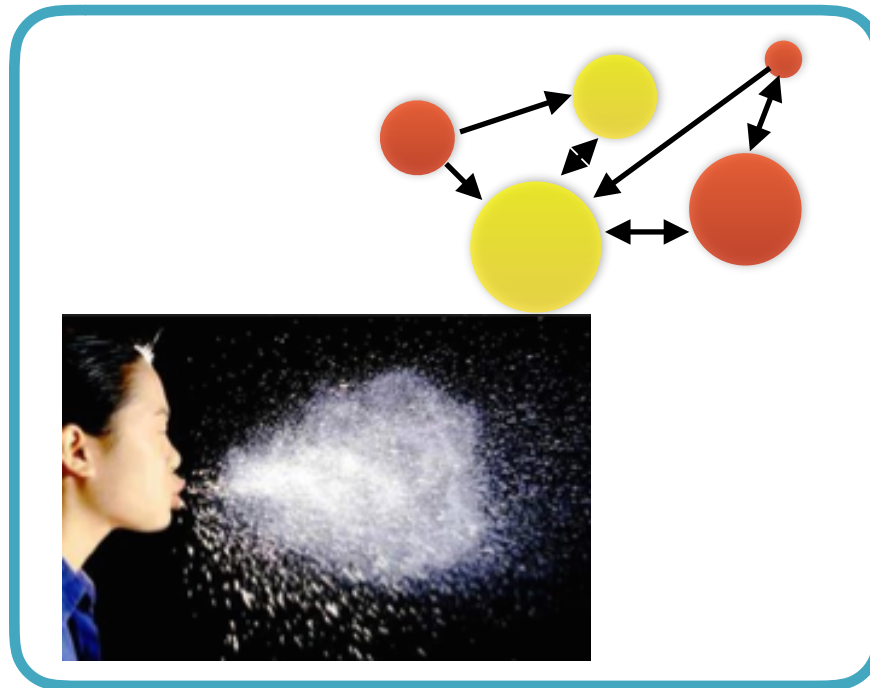
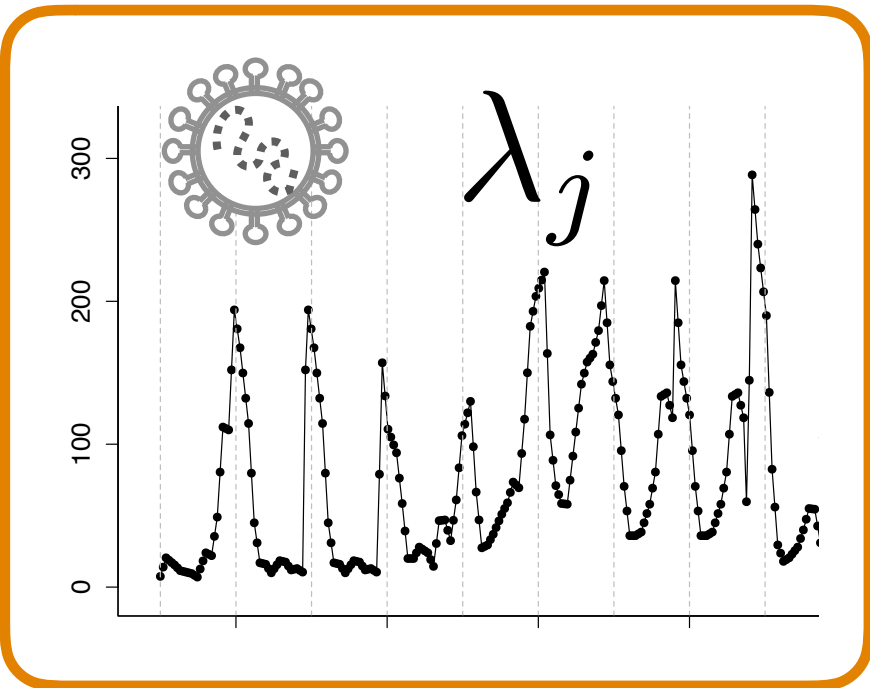
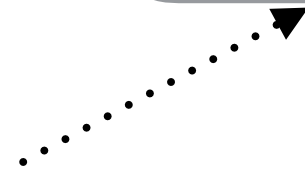
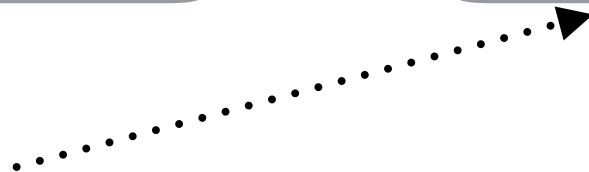
For a directly-transmitted immunizing infection

$$P(\text{import}) = \text{Prevalence (FOI) in source} * \text{Source contact rate} * P(\text{infect} | \text{contact})$$



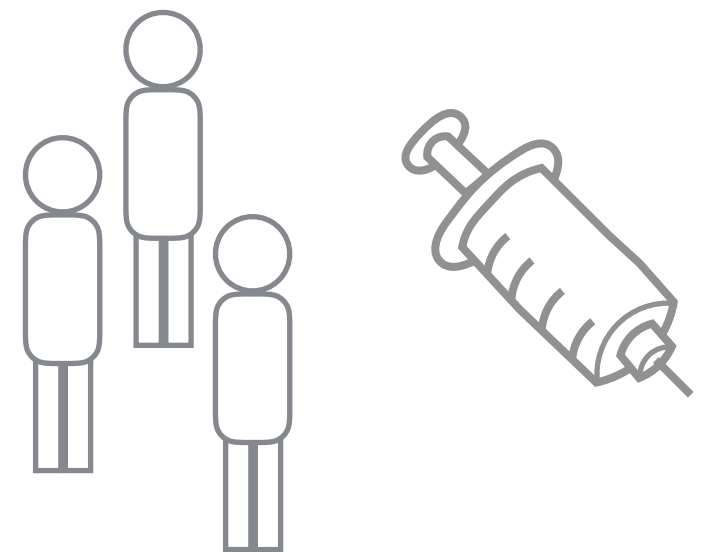
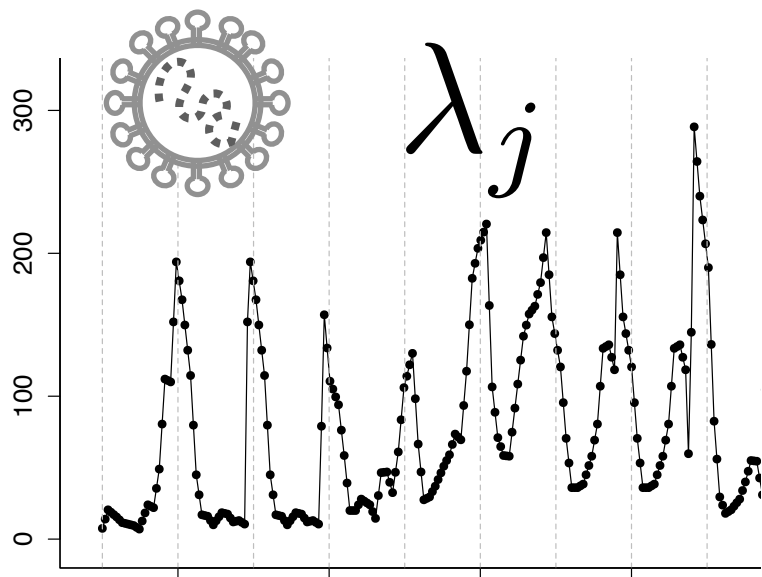
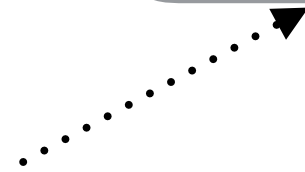
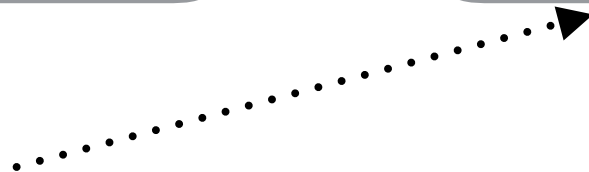
For a directly-transmitted immunizing infection

$$P(\text{import}) = \text{Prevalence (FOI) in source} * \text{Source contact rate} * P(\text{infect} | \text{contact})$$

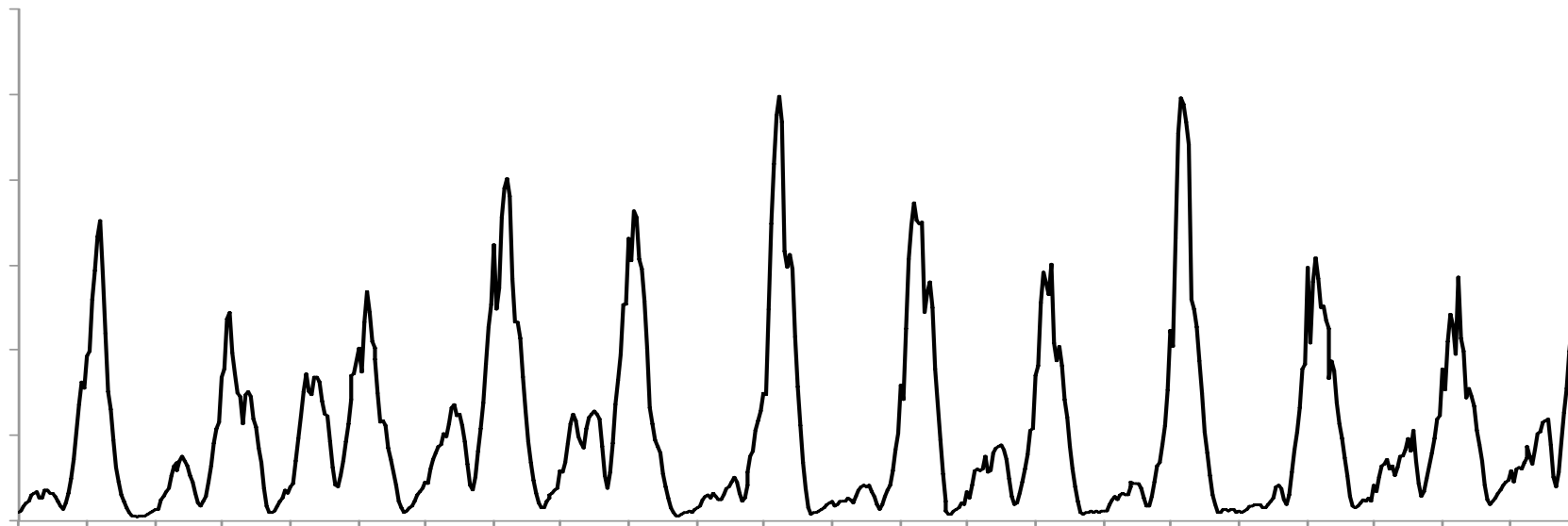


For a directly-transmitted immunizing infection

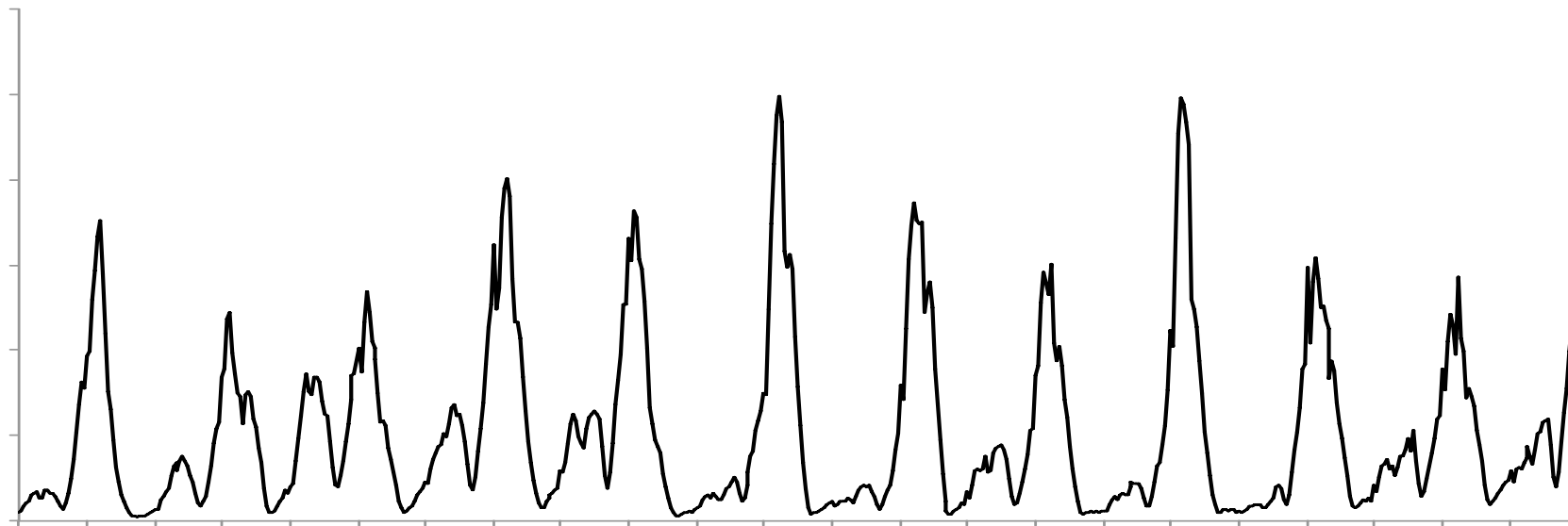
$$P(\text{import}) = \text{Prevalence (FOI) in source} * \text{Source contact rate} * P(\text{infect} | \text{contact})$$



For a directly-transmitted immunizing infection



For a directly-transmitted immunizing infection



$P(\text{import})$

=

Prevalence
(FOI) in
source

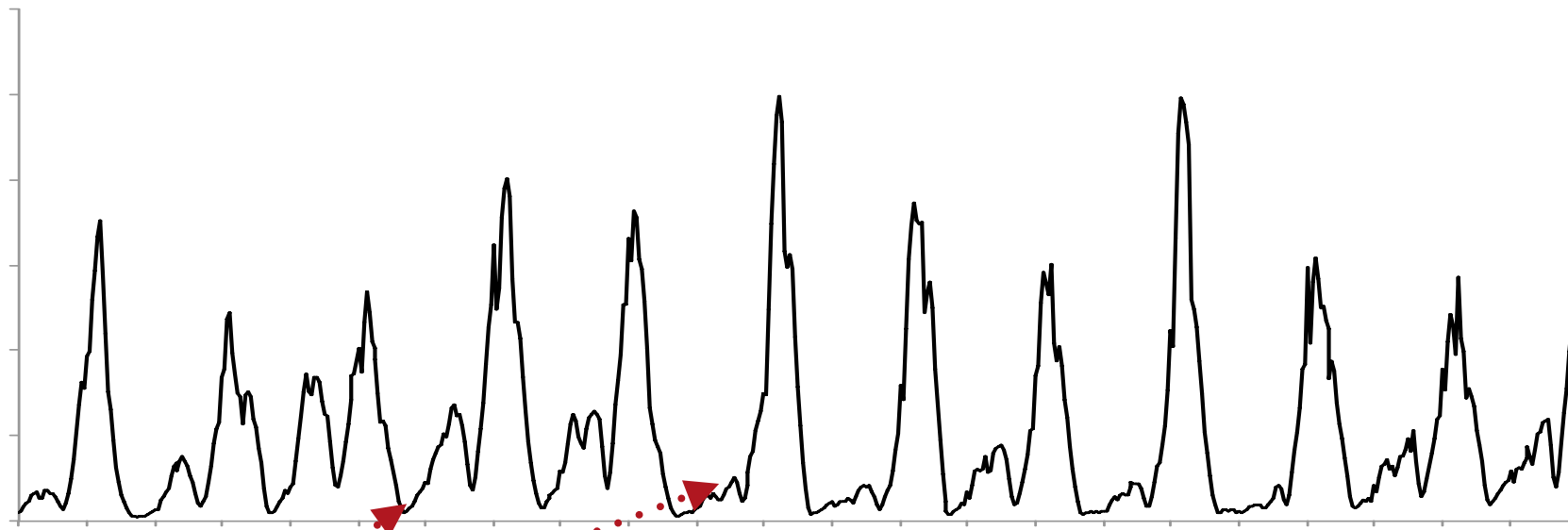
*

Source
contact rate

*

$P(\text{infect} \mid \text{contact})$

For a directly-transmitted immunizing infection



$P(\text{import})$

=

Prevalence
(FOI) in
source

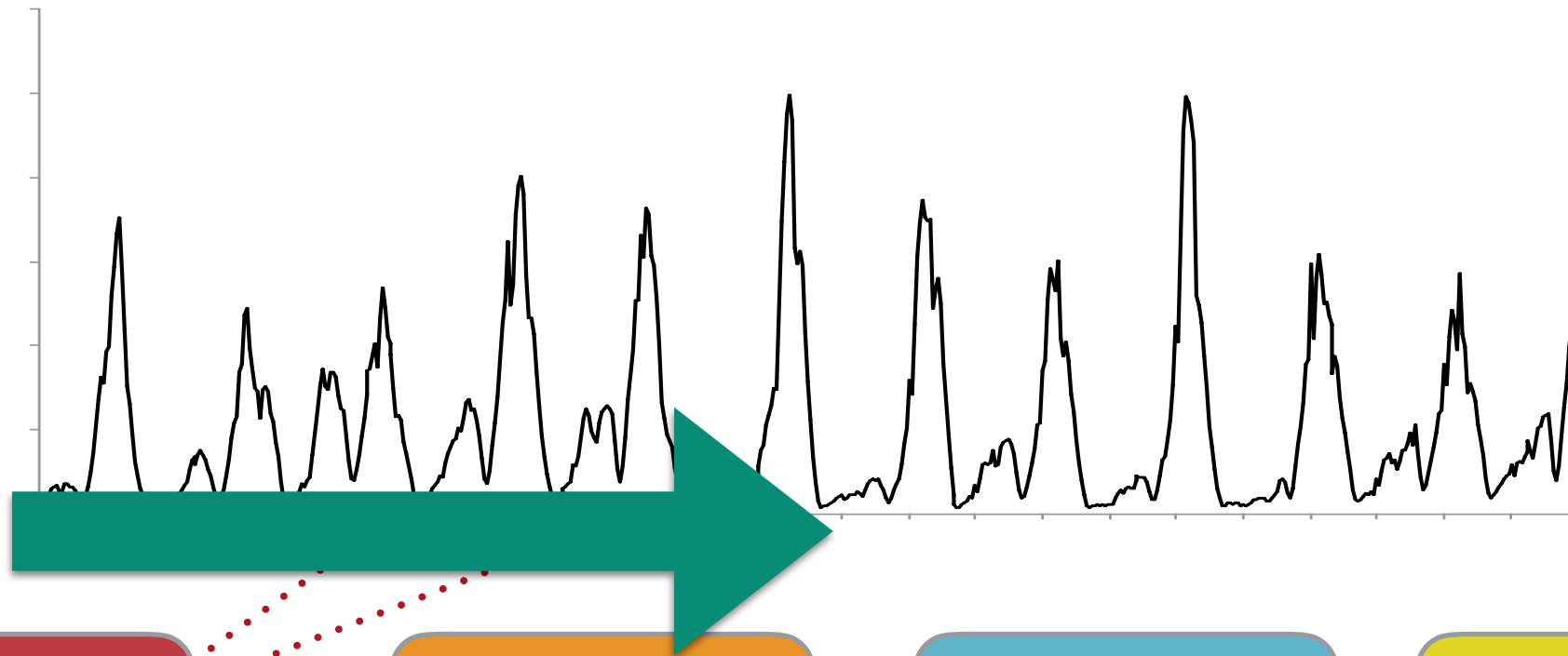
*

Source
contact rate

*

$P(\text{infect} \mid \text{contact})$

For a directly-transmitted immunizing infection



$P(\text{import})$

=

Prevalence
(FOI) in
source

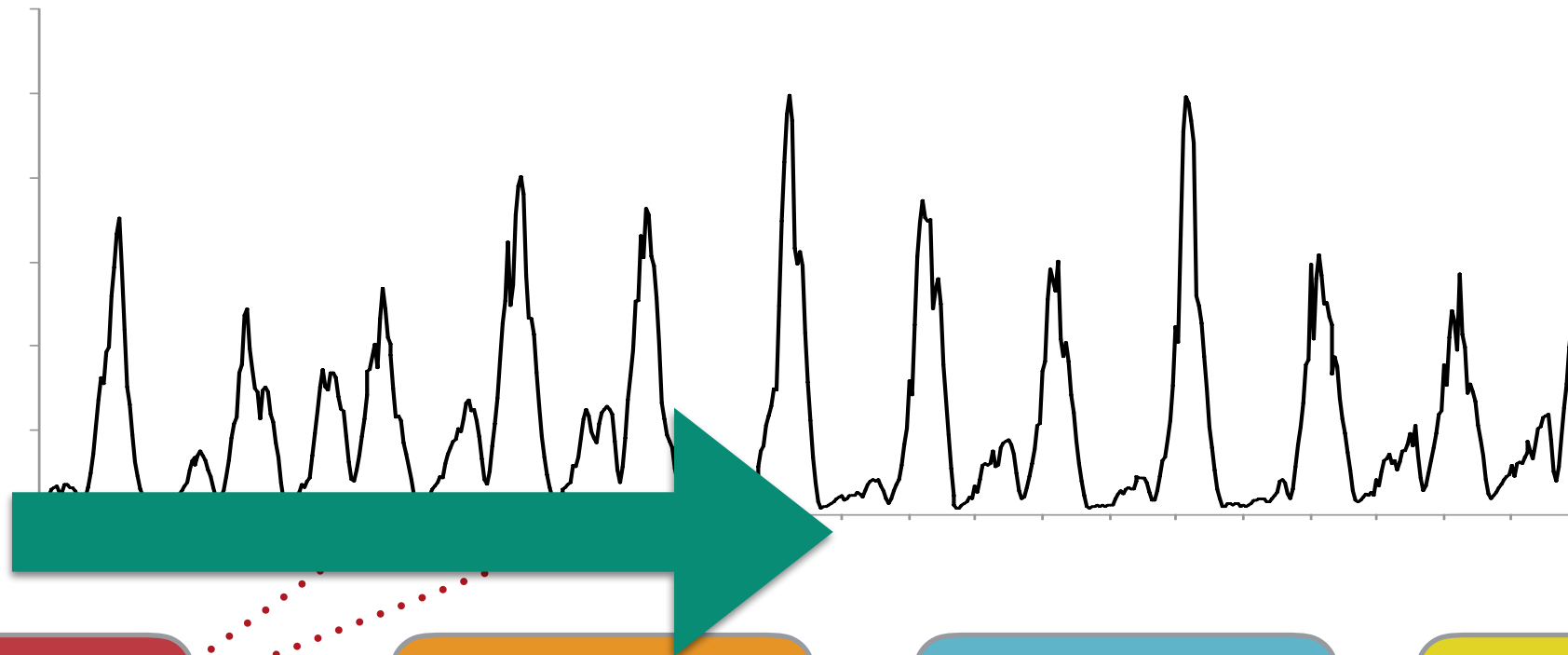
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Source
contact rate

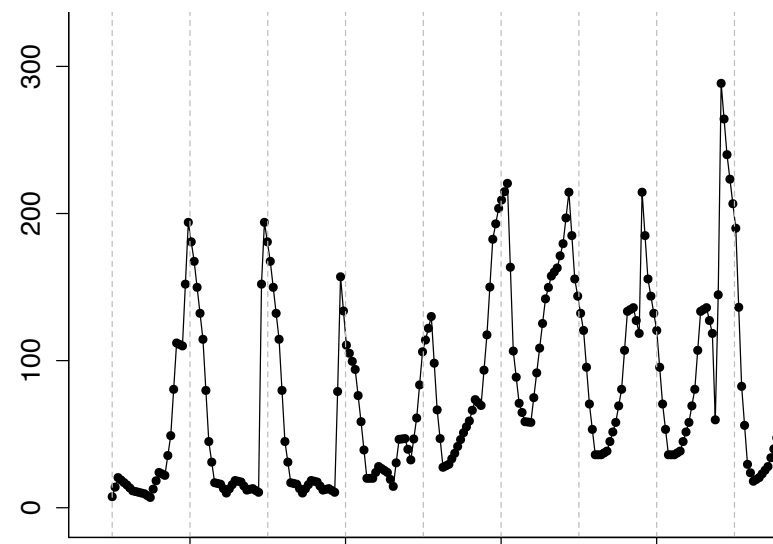
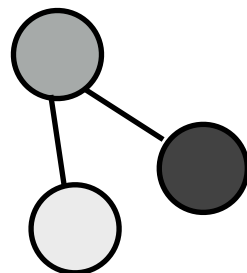
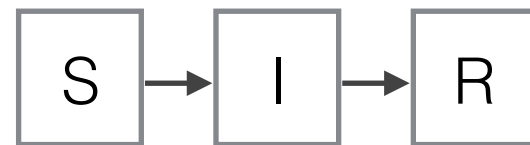
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$P(\text{infect} \mid \text{contact})$

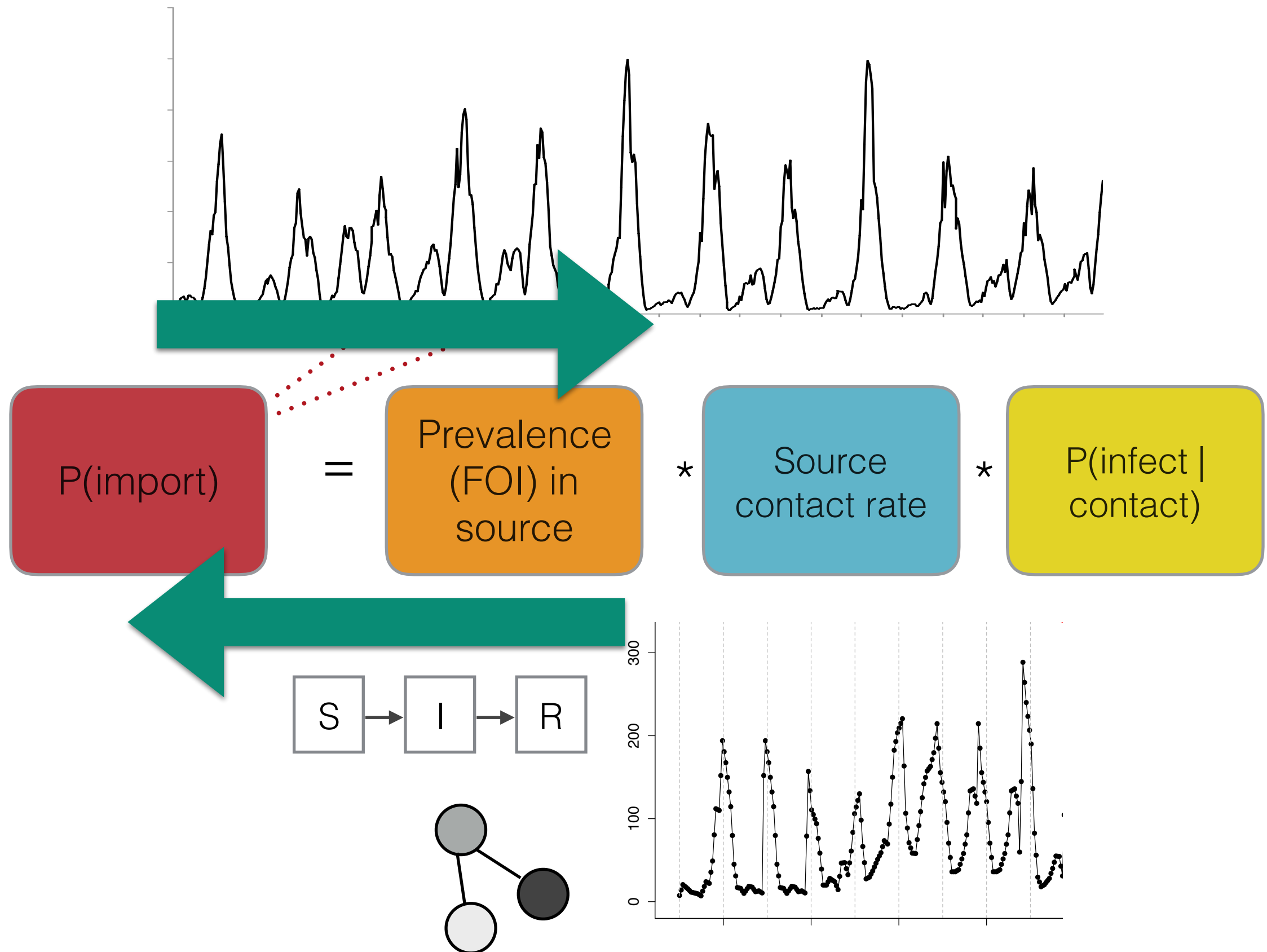
For a directly-transmitted immunizing infection



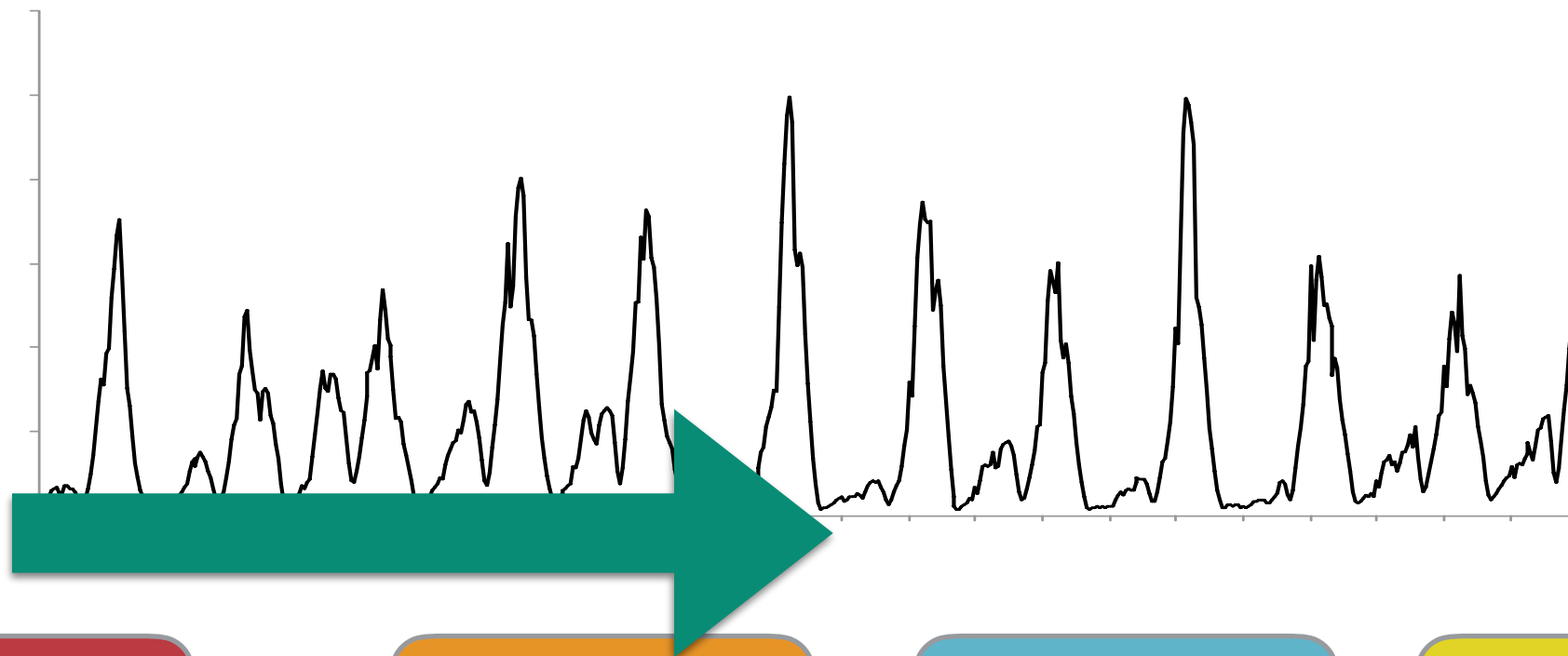
$$P(\text{import}) = \text{Prevalence (FOI) in source} * \text{Source contact rate} * P(\text{infect} | \text{contact})$$



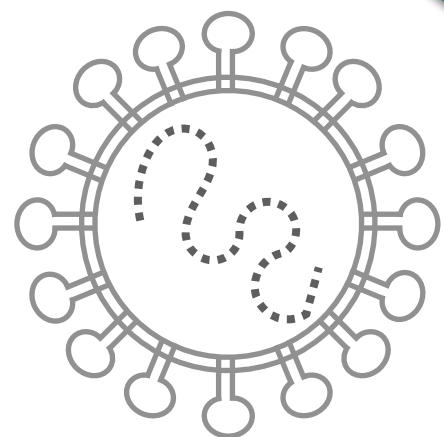
For a directly-transmitted immunizing infection



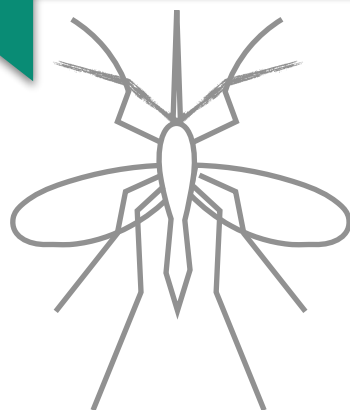
How can we extend this framework for malaria?



$$P(\text{import}) = \text{Prevalence (FOI) in source} * \text{Source contact rate} * P(\text{infect} | \text{contact})$$



Pathogen

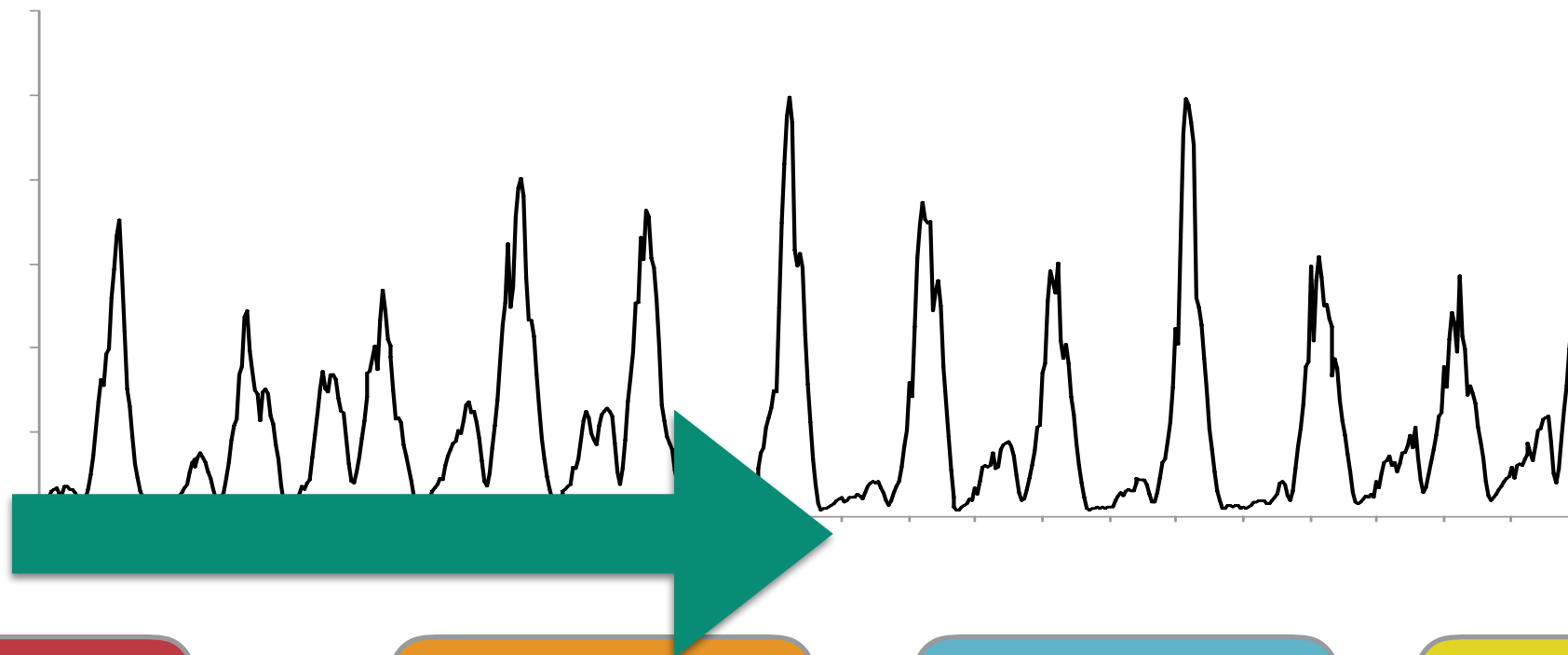


Vector



Environment

How can we extend this framework for malaria?



$P(\text{import})$

=

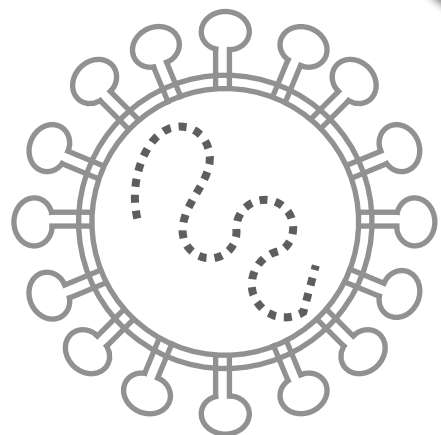
Prevalence
(FOI) in
source

*

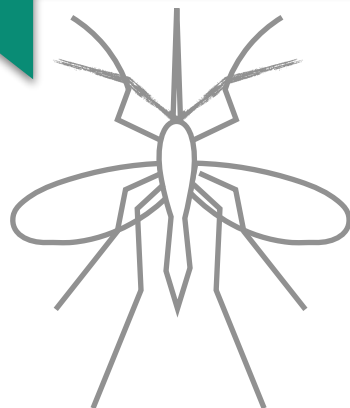
Source
contact rate

*

$P(\text{infect} \mid \text{contact})$



Pathogen



Vector



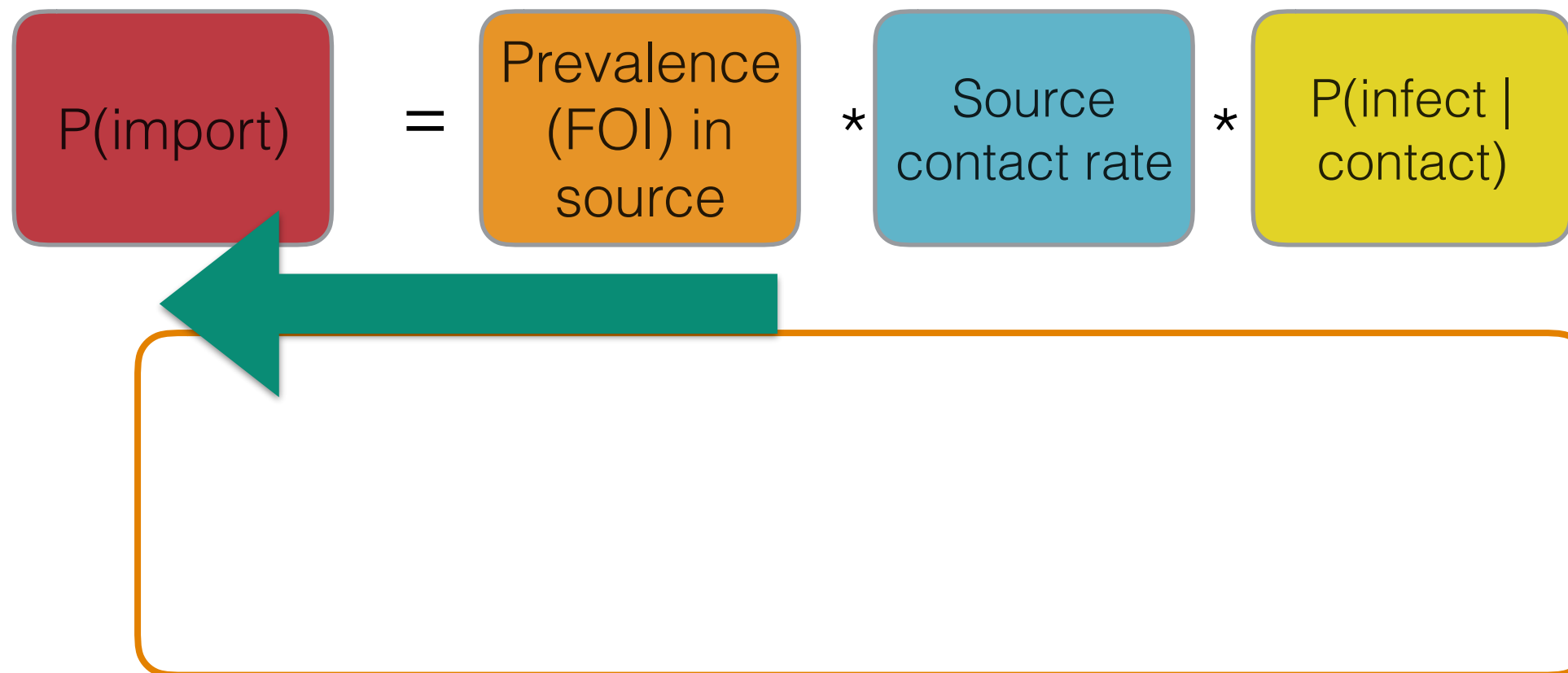
Environment

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?



Can we identify sources and sinks?

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

$$P(\text{import}) = \text{Prevalence (FOI) in source} * \text{Source contact rate} * P(\text{infect} | \text{contact})$$

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?

Can we identify sources and sinks?

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Malaria in Madagascar



Felana Ihantamalala



Jean Maurice Rakotondramanga

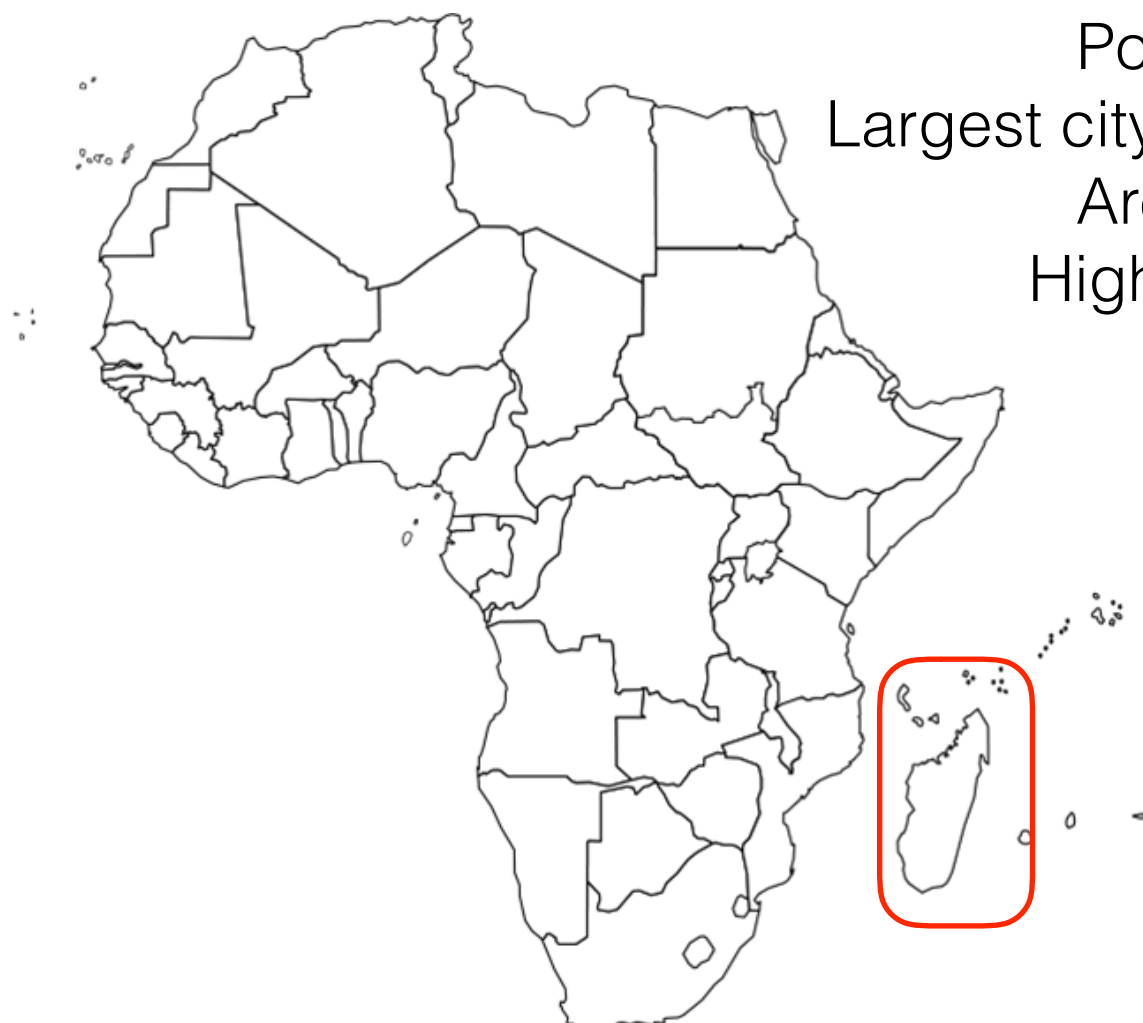
Malaria in Madagascar



Felana Ihantamalala



Jean Maurice Rakotondramanga



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

Malaria in Madagascar

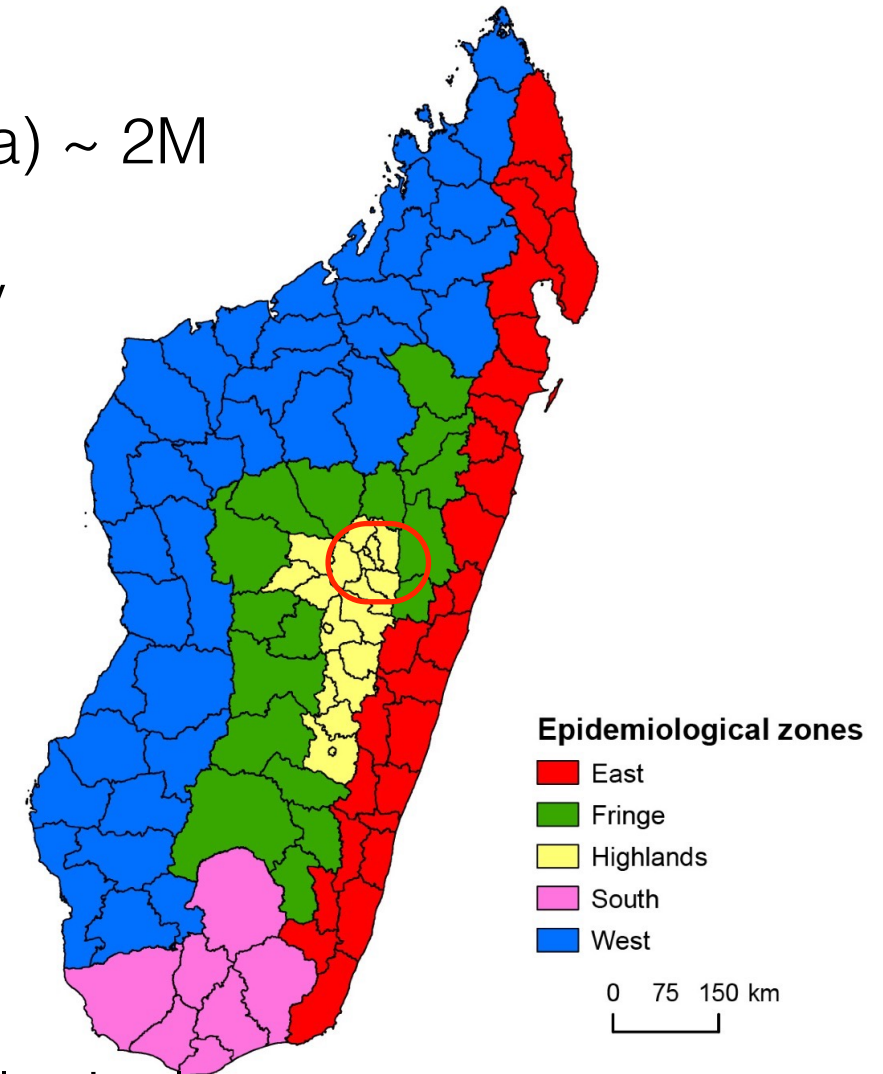


Felana Ihantamalala



Jean Maurice Rakotondramanga

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

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.

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

Correspondence.

MALARIA IN MADAGASCAR.

To the Editors of the JOURNAL OF TROPICAL MEDICINE AND HYGIENE.

Moramanga—have been made and are already in operation, leaving 122 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.

W. CARNEGIE BROWN.

Malaria in Madagascar

June 15, 1907.]

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W. CARNEGIE BROWN.

Mobility in Madagascar

Volume

Ratio Avg Incoming vs
Outgoing Trips

Number of Destinations



Data over 6 months (Jan - June 2015)
~3.5M subscribers

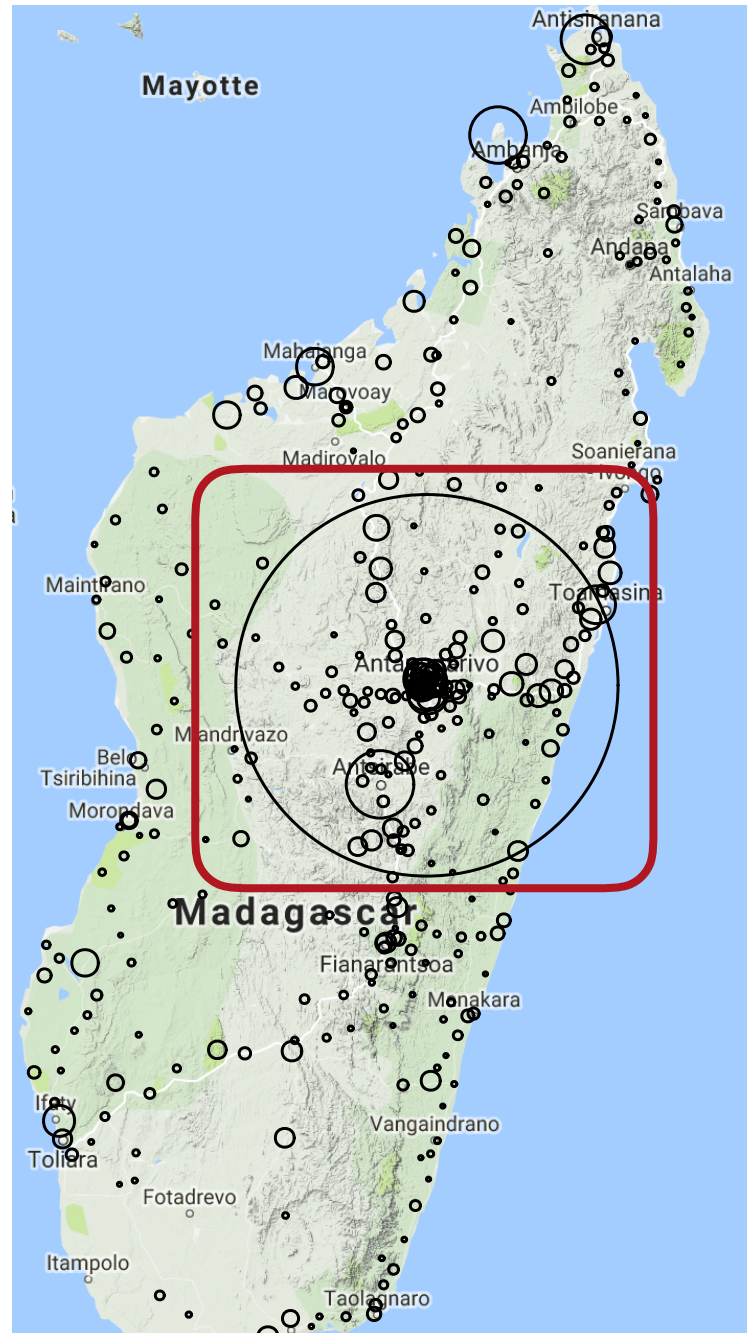
Mobile phone tower coverage in 102/112 districts

Mobility in Madagascar

Volume

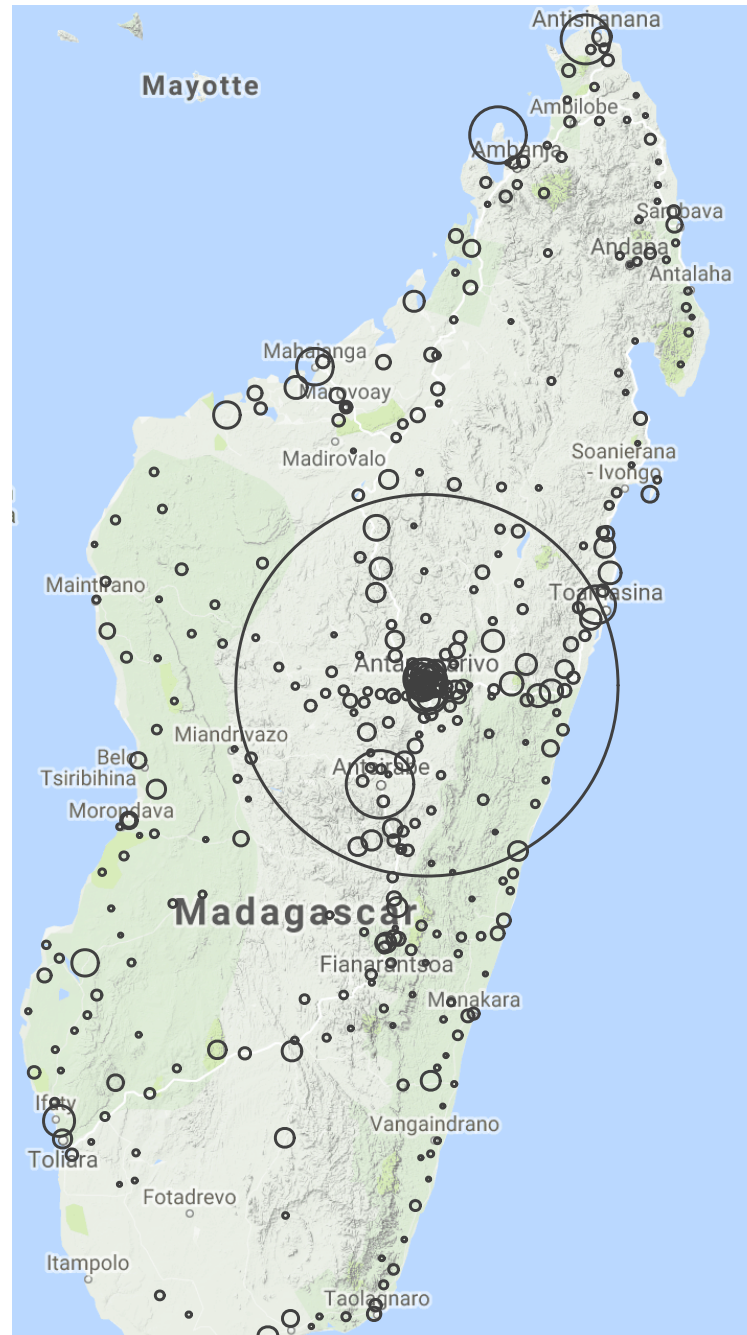
Ratio Avg Incoming vs Outgoing Trips

Number of Destinations

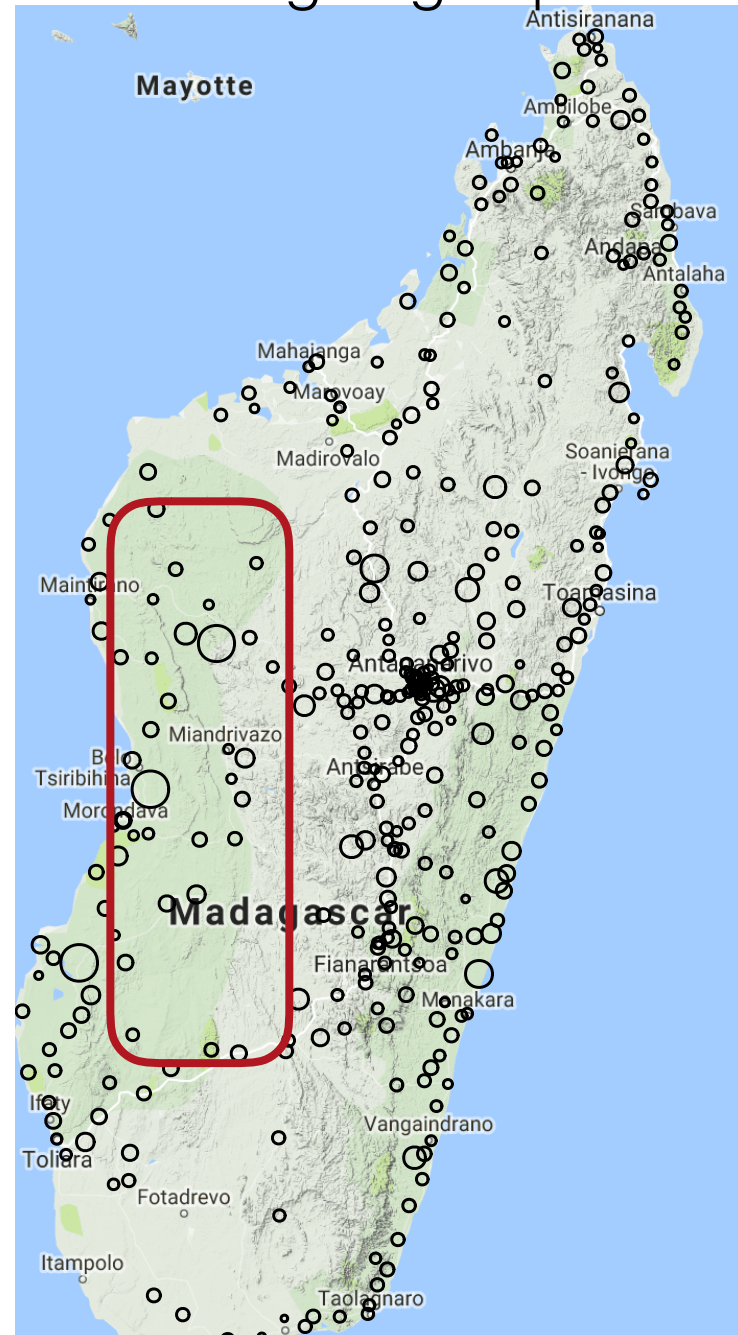


Mobility in Madagascar

Volume



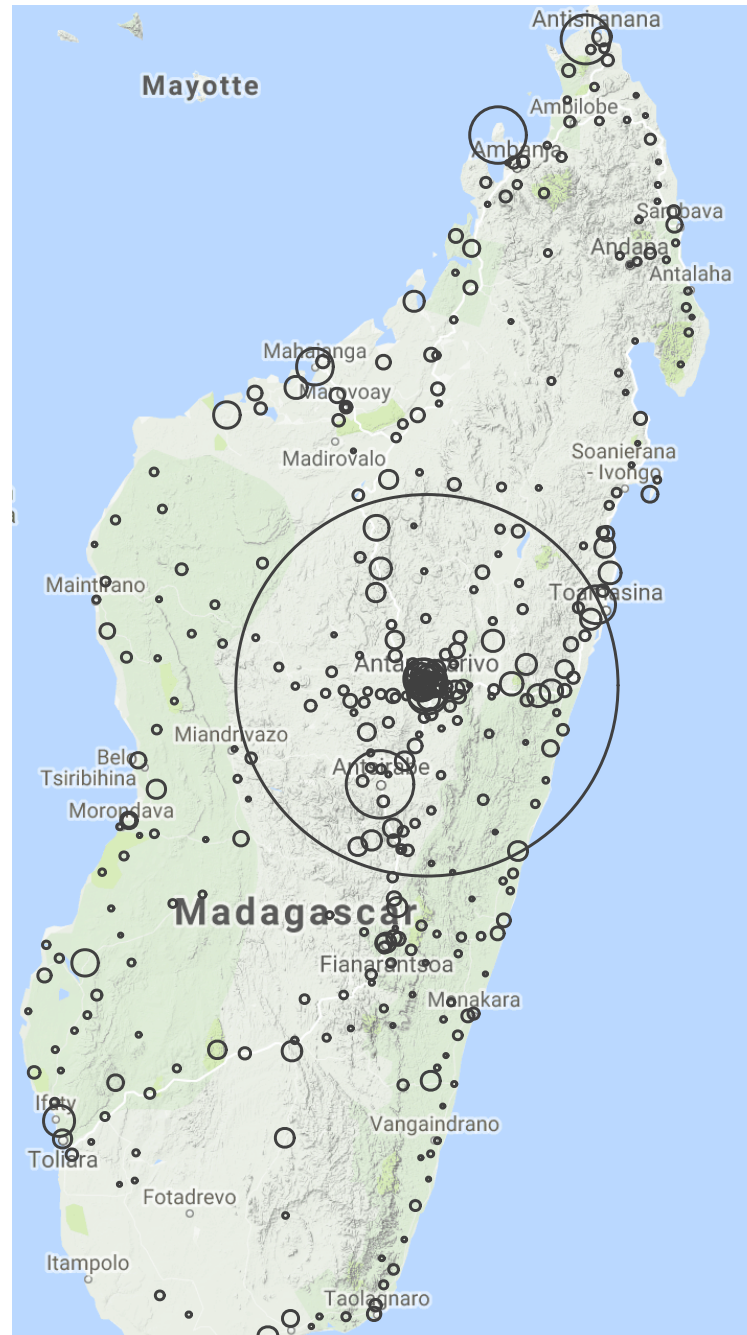
Ratio Avg Incoming vs
Outgoing Trips



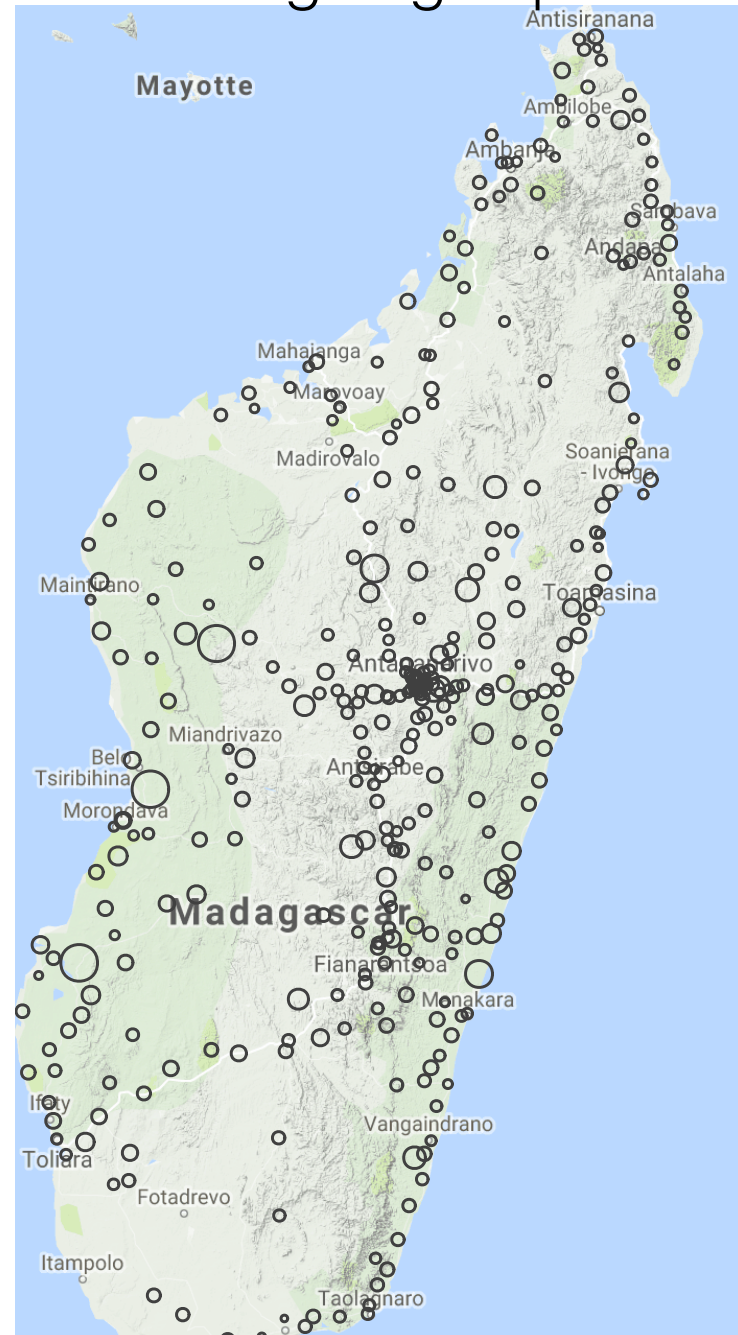
Number of Destinations

Mobility in Madagascar

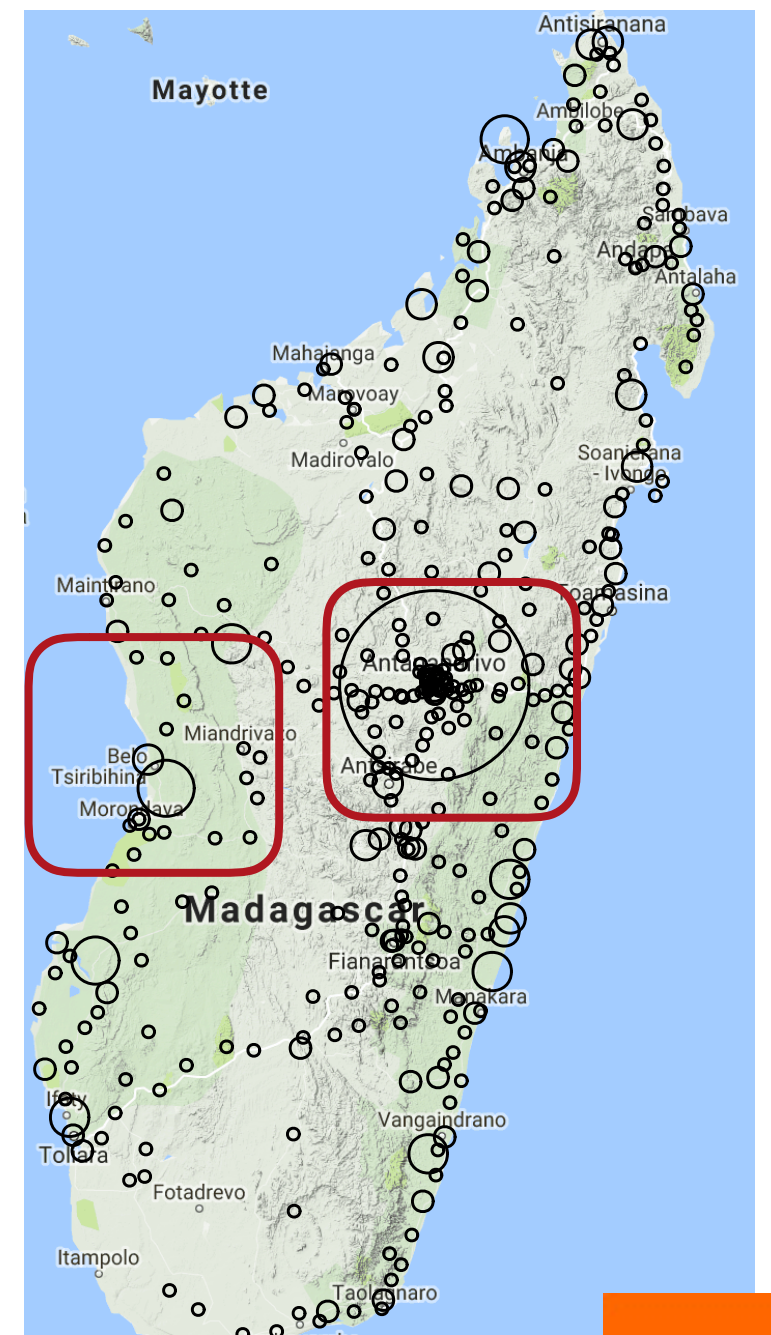
Volume



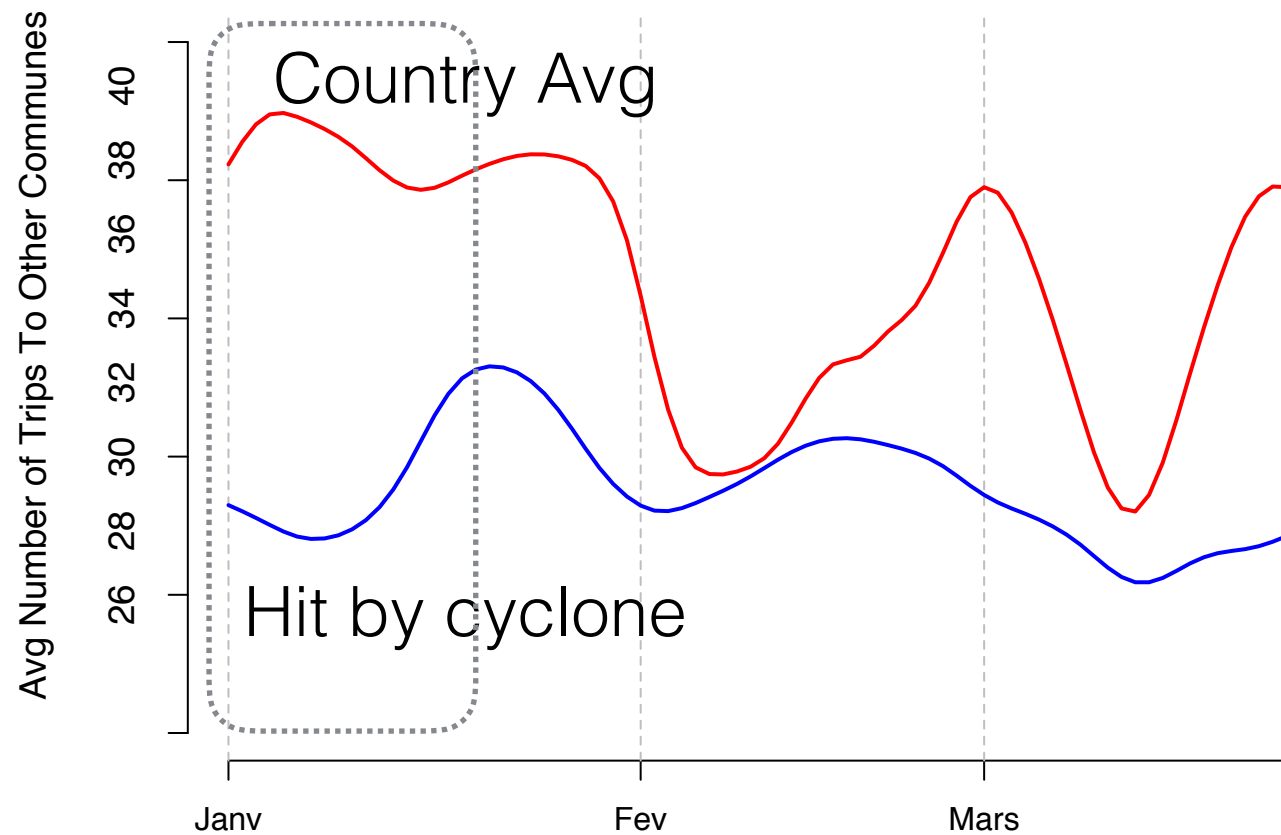
Ratio Avg Incoming vs
Outgoing Trips



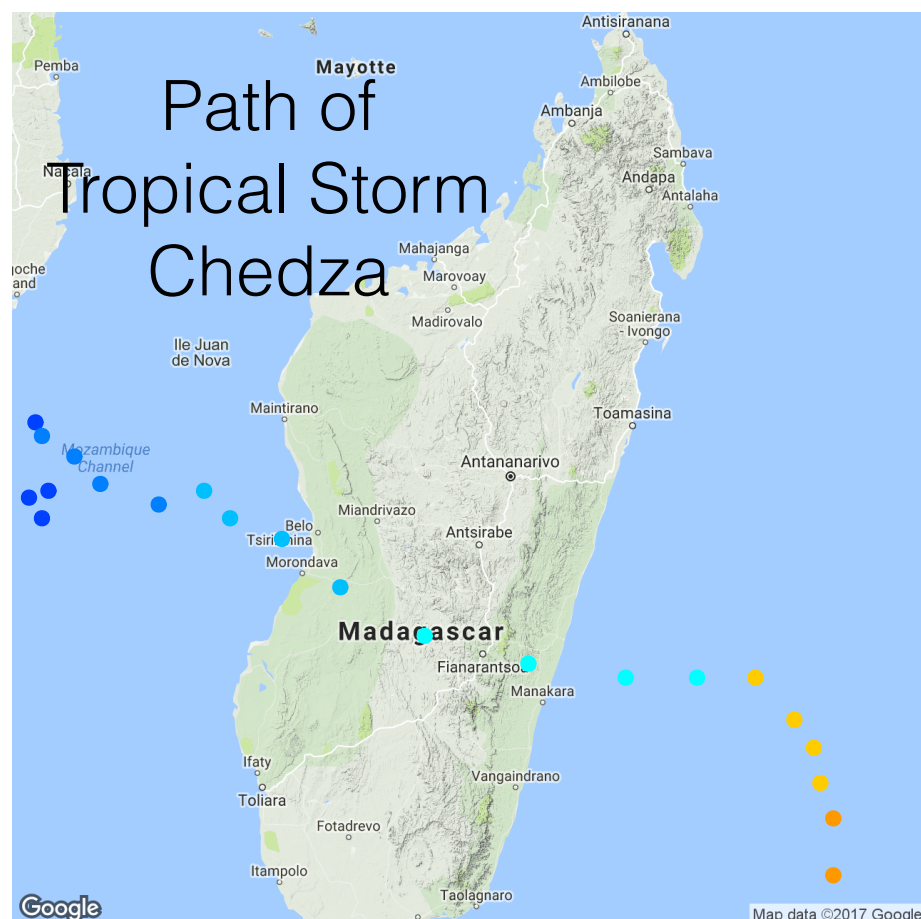
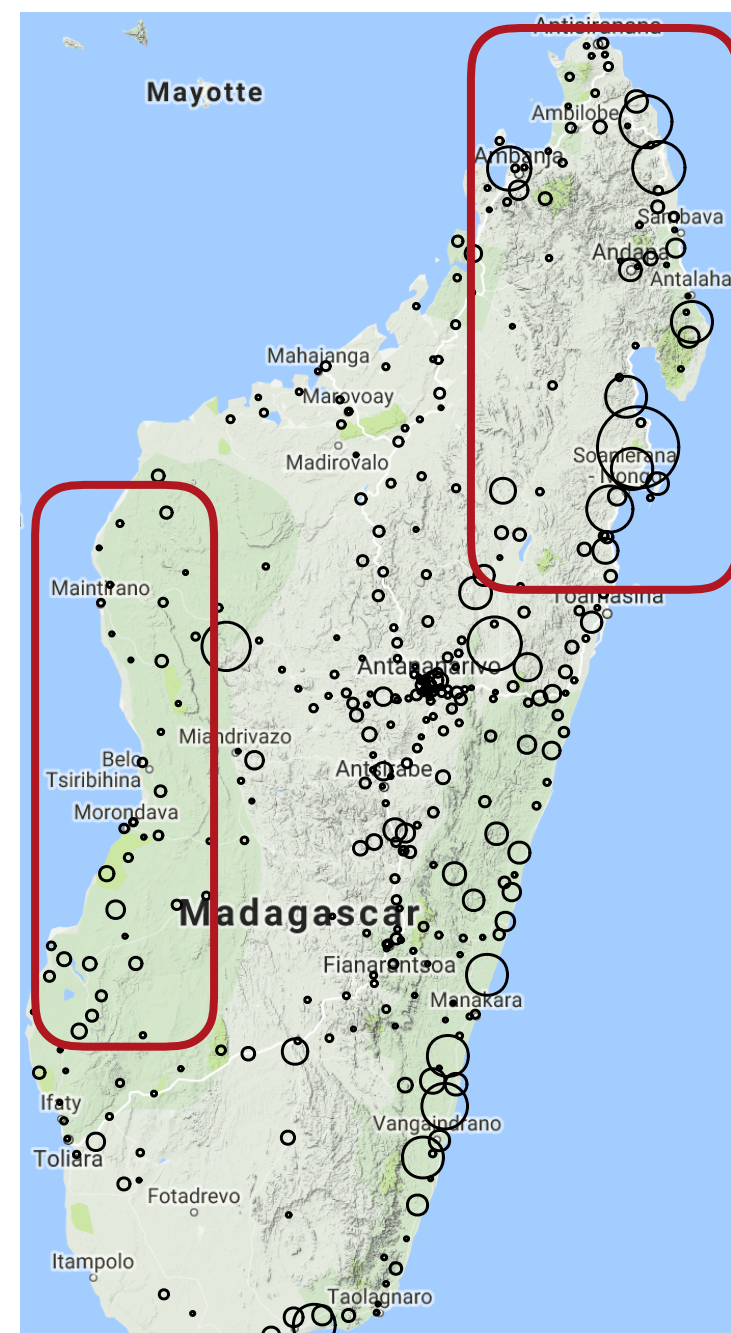
Number of Destinations



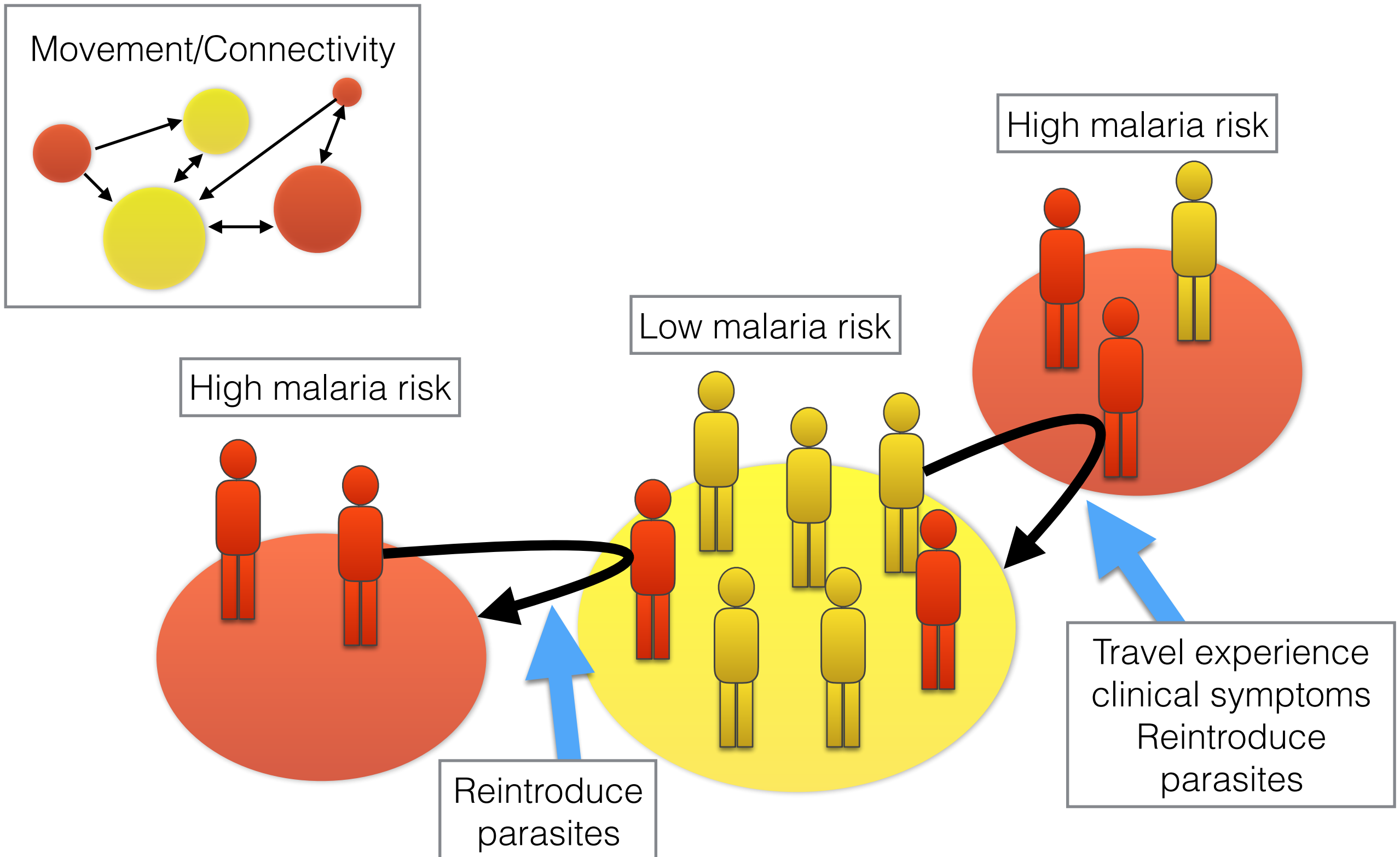
Mobility in Madagascar



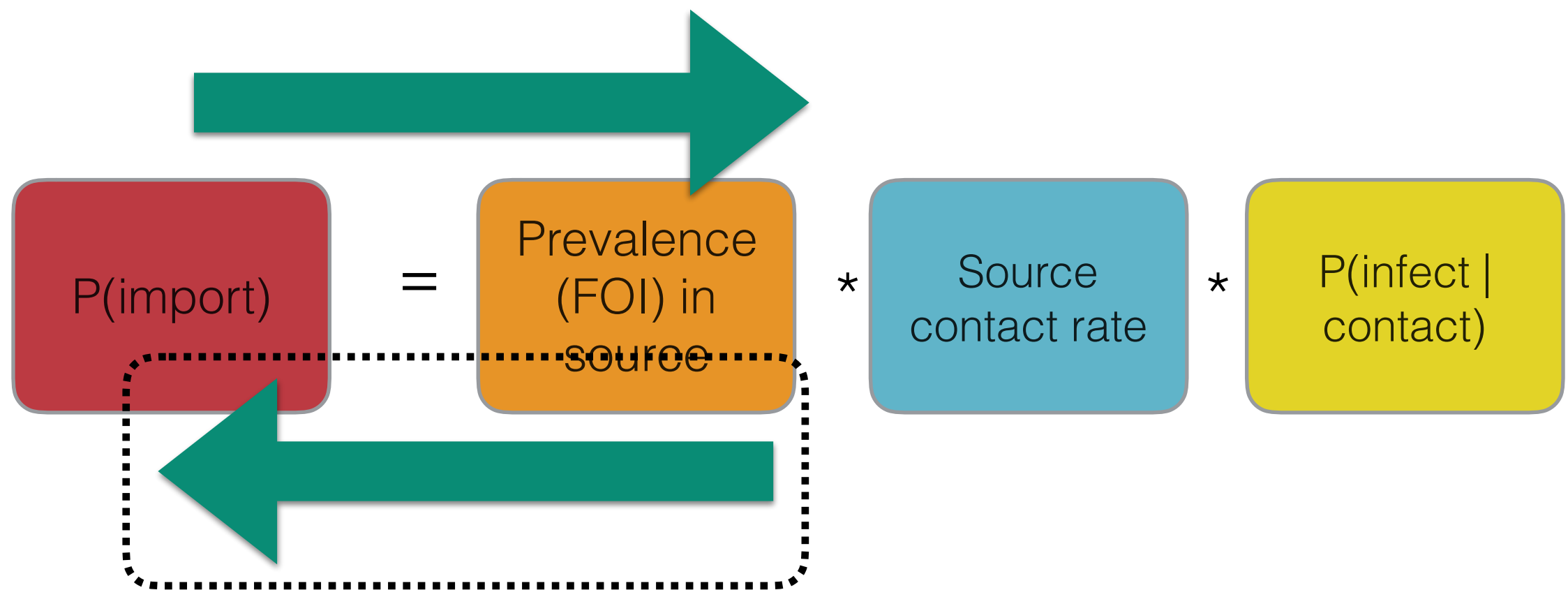
Coefficient of Variation of Daily Travel to Other Districts



How can we extend this framework for malaria?



How can we extend this framework for malaria?



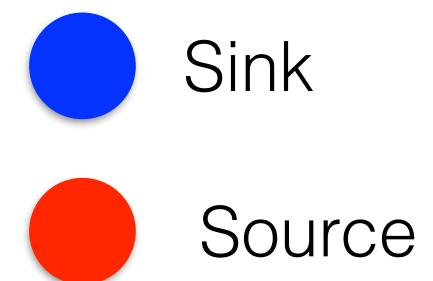
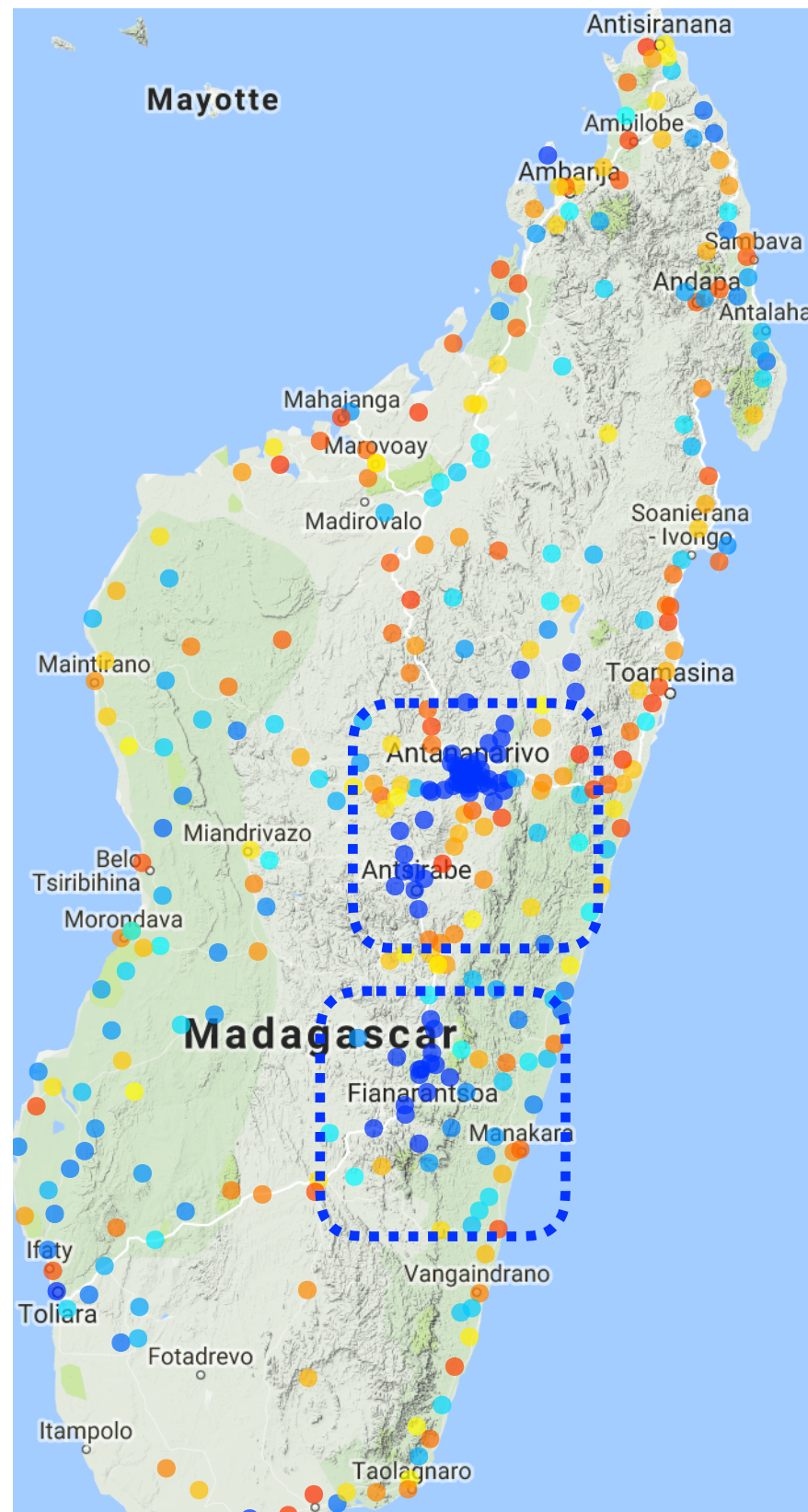
Sources (emitters) and sinks (receivers) of travel and parasite importation were identified

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

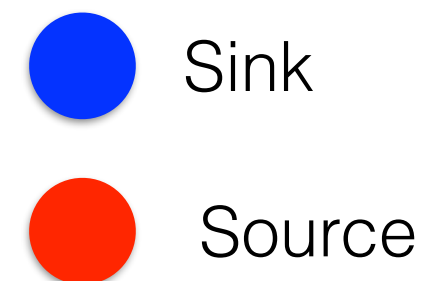
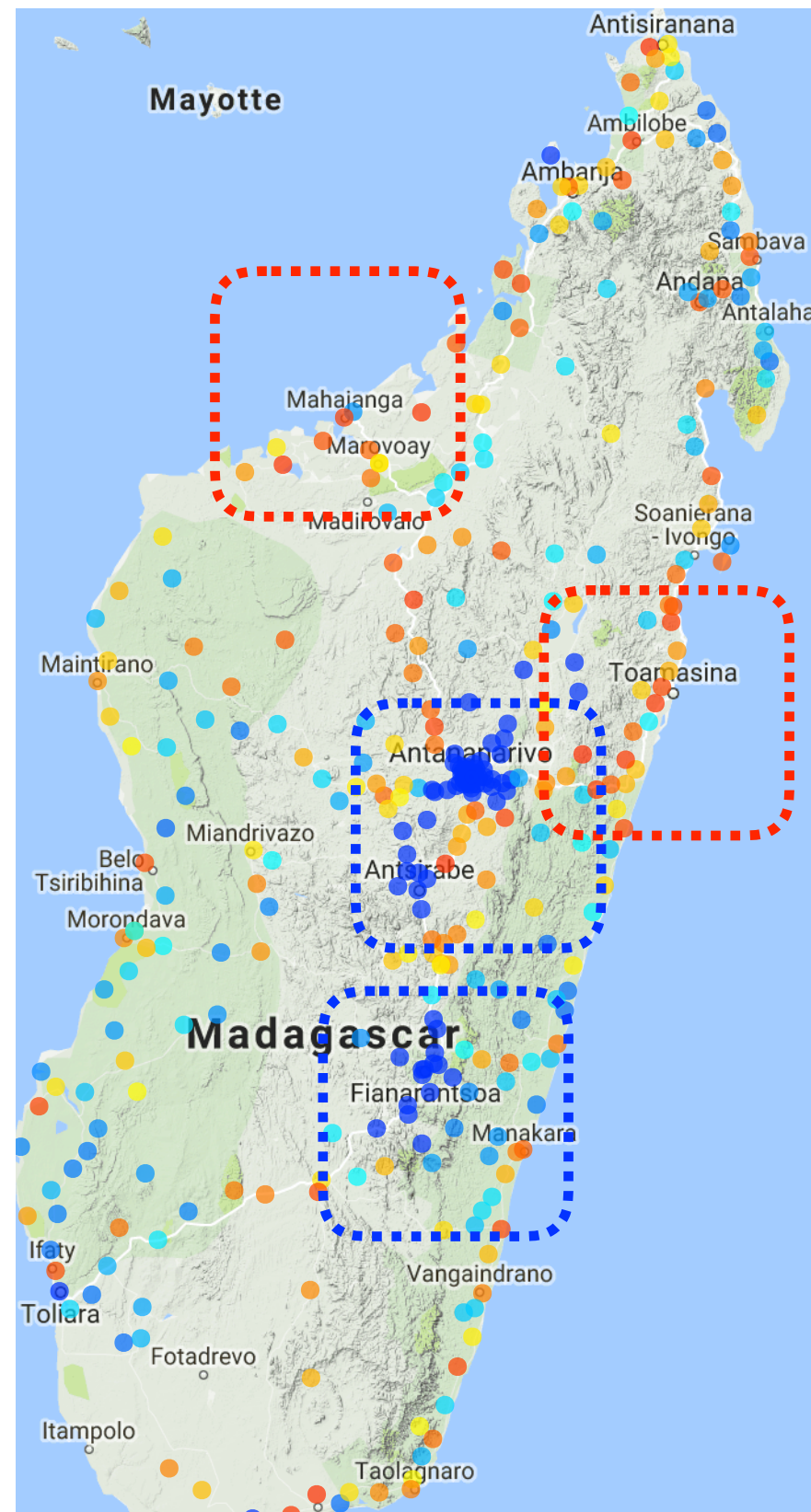
The great sources were communes that emitted a large amount of parasites.

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

Sources and sinks of malaria parasites



Sources and sinks of malaria parasites



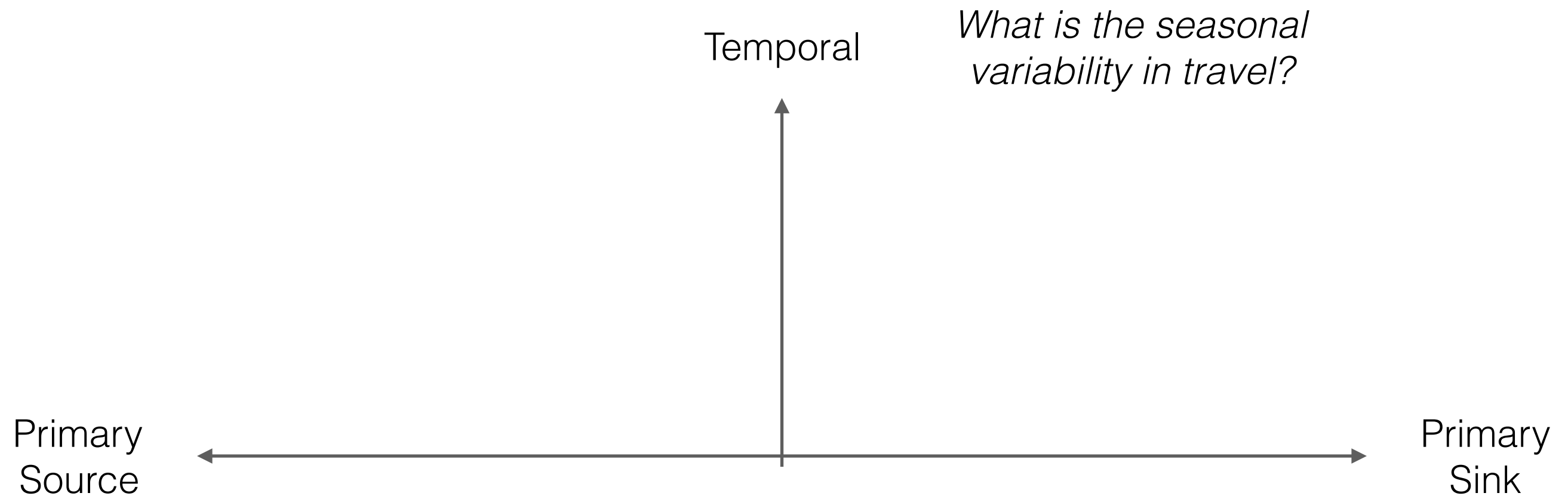
Sources and sinks of malaria parasites

Primary
Source

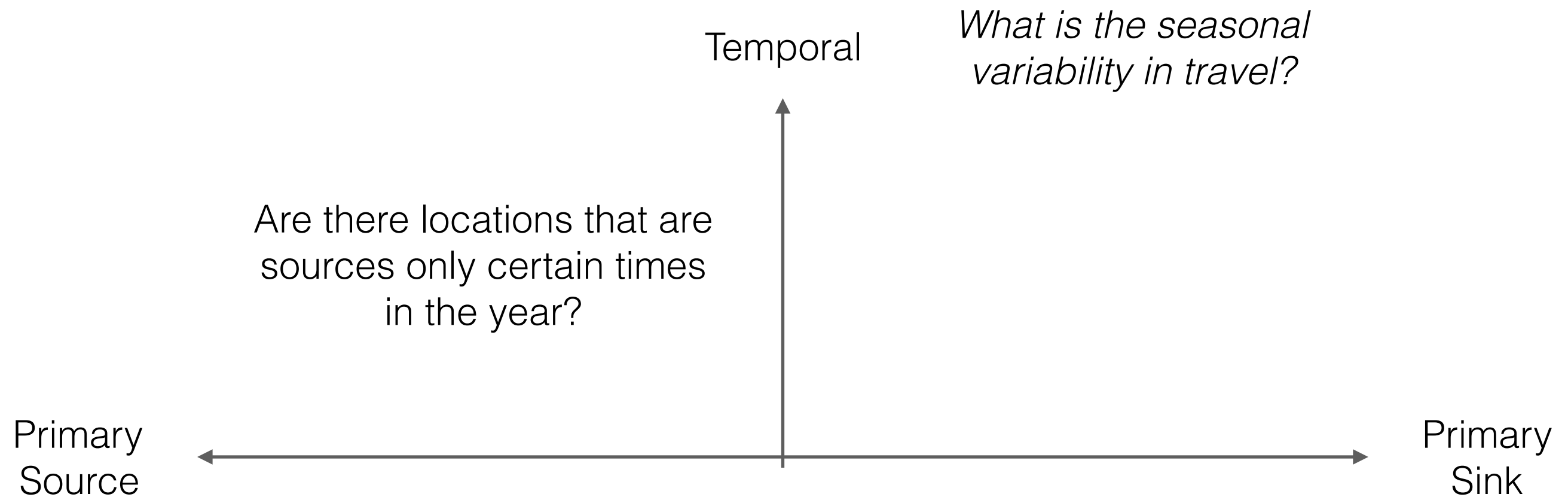


Primary
Sink

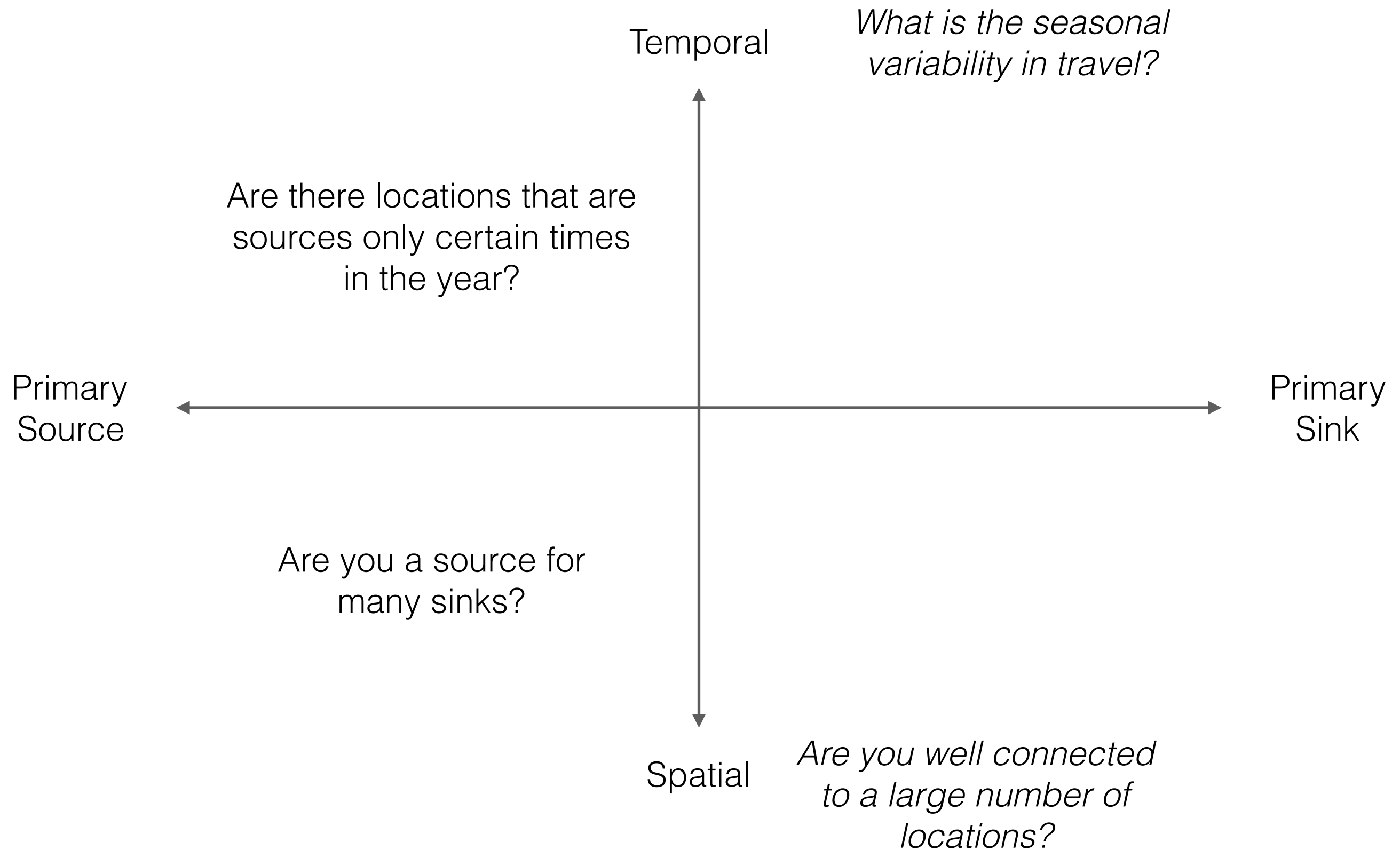
Sources and sinks of malaria parasites



Sources and sinks of malaria parasites



Sources and sinks of malaria parasites



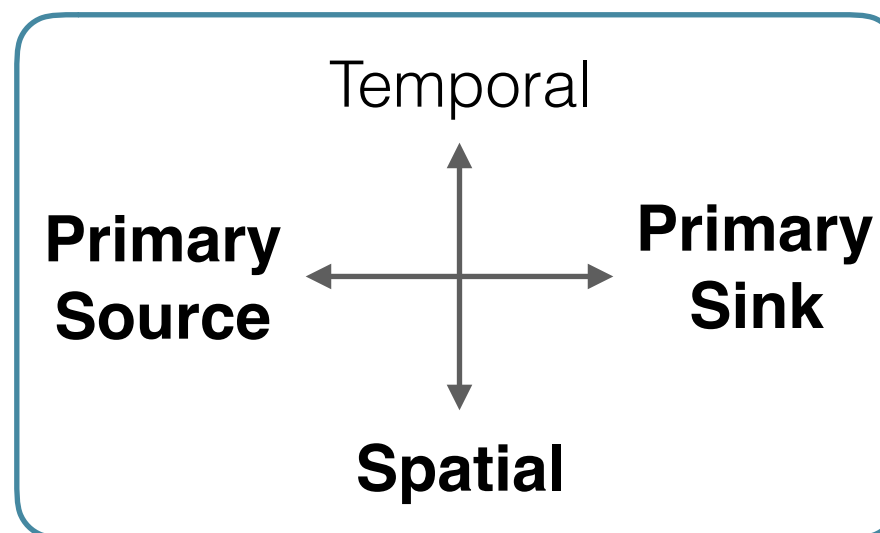
Sources and sinks of malaria parasites

Number of
Related Sinks

25
20
15
10
5
0

Neutral

Primary Source



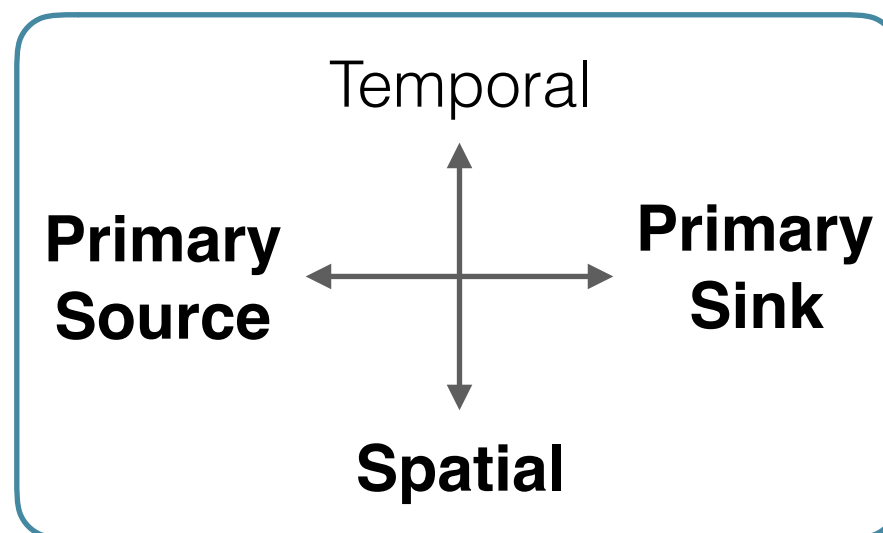
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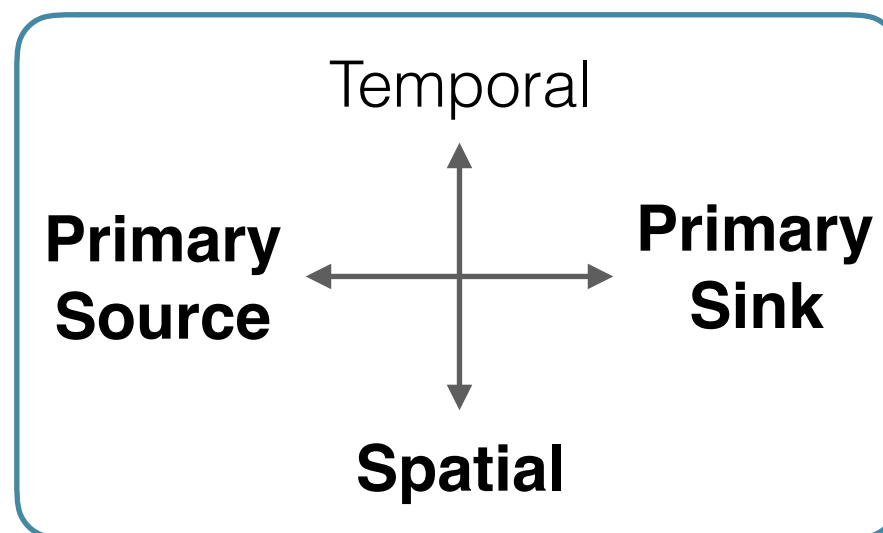
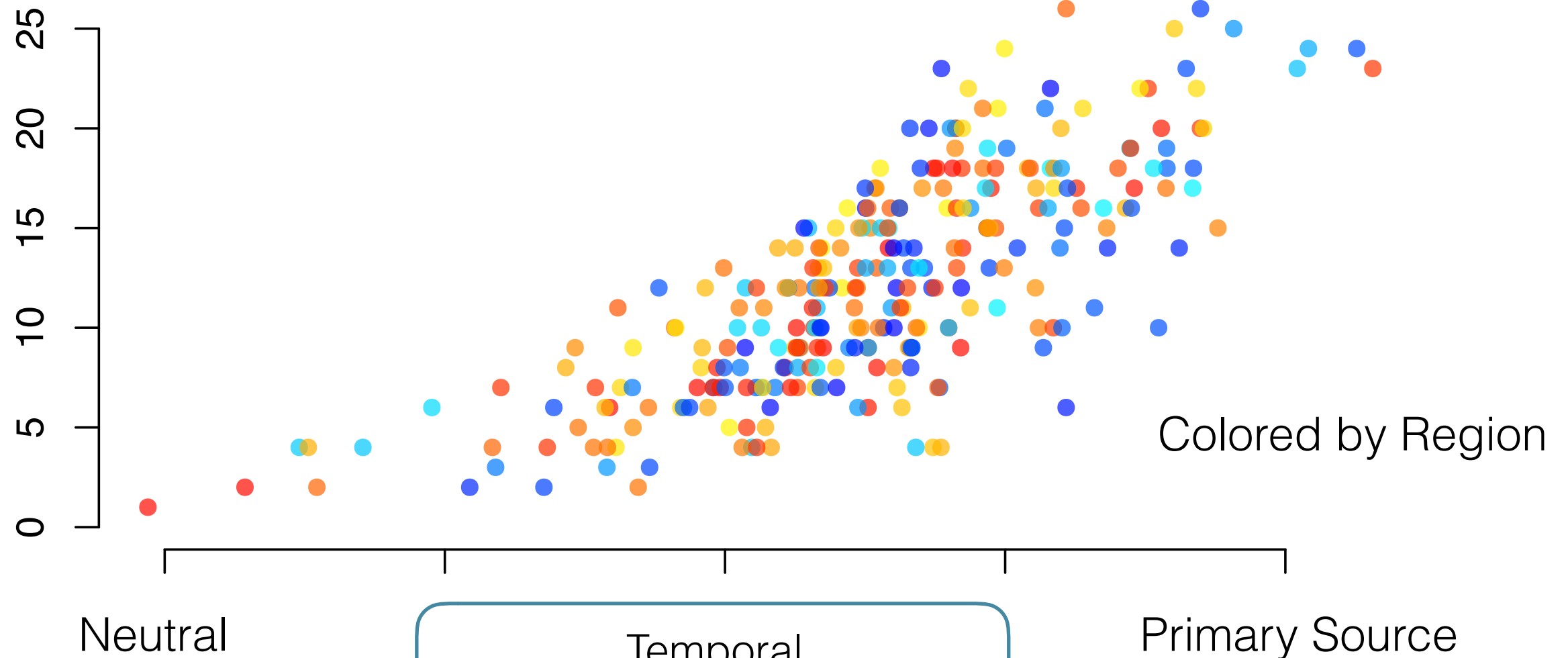
Neutral

Primary Source



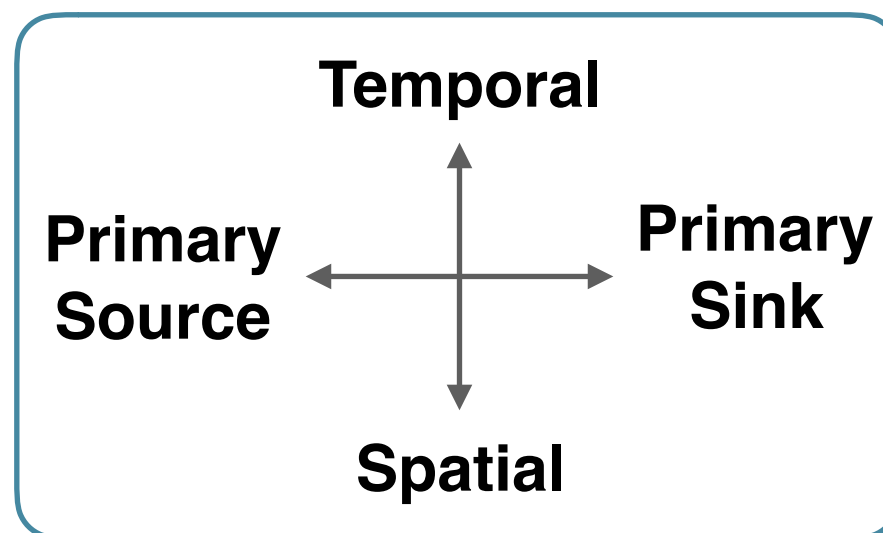
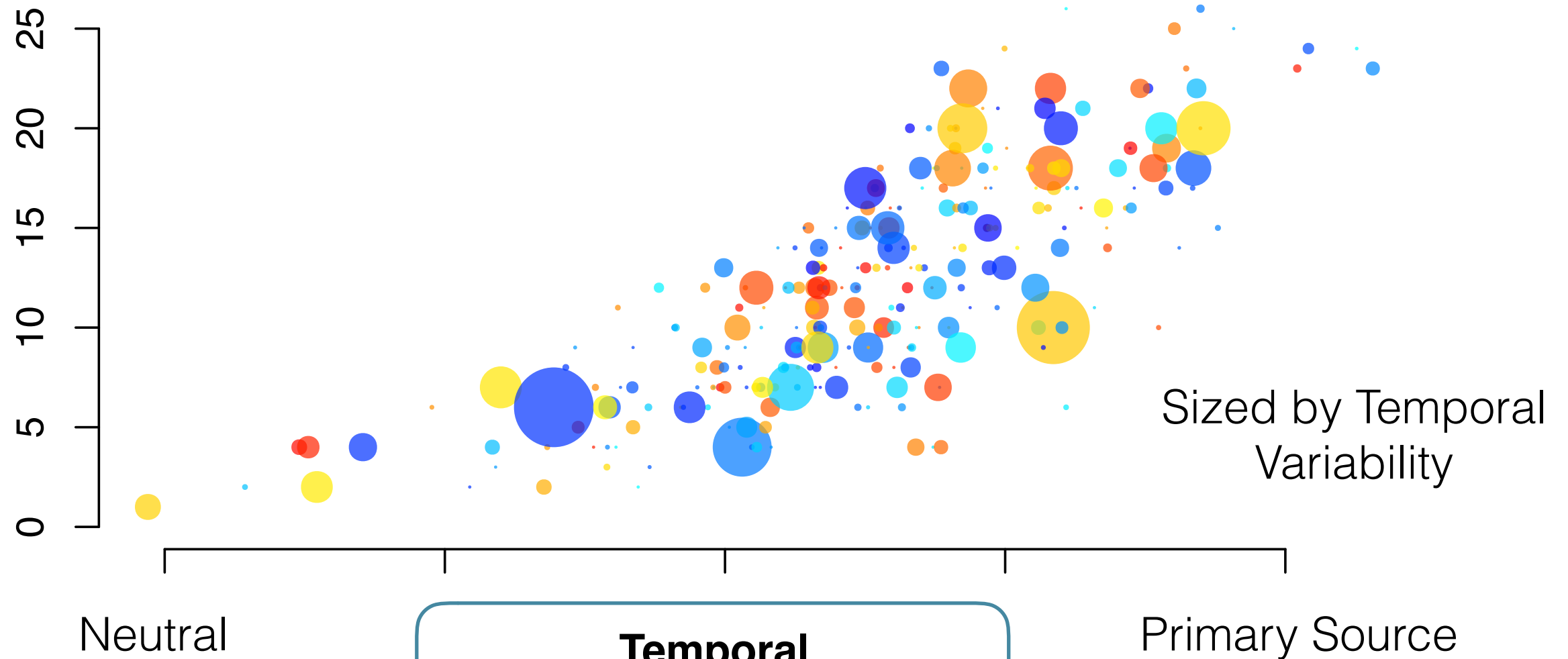
Sources and sinks of malaria parasites

Number of
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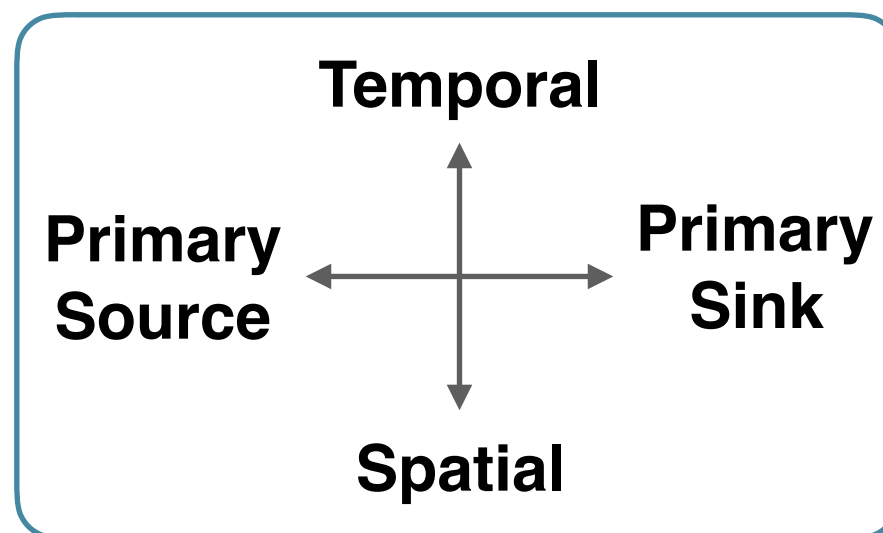
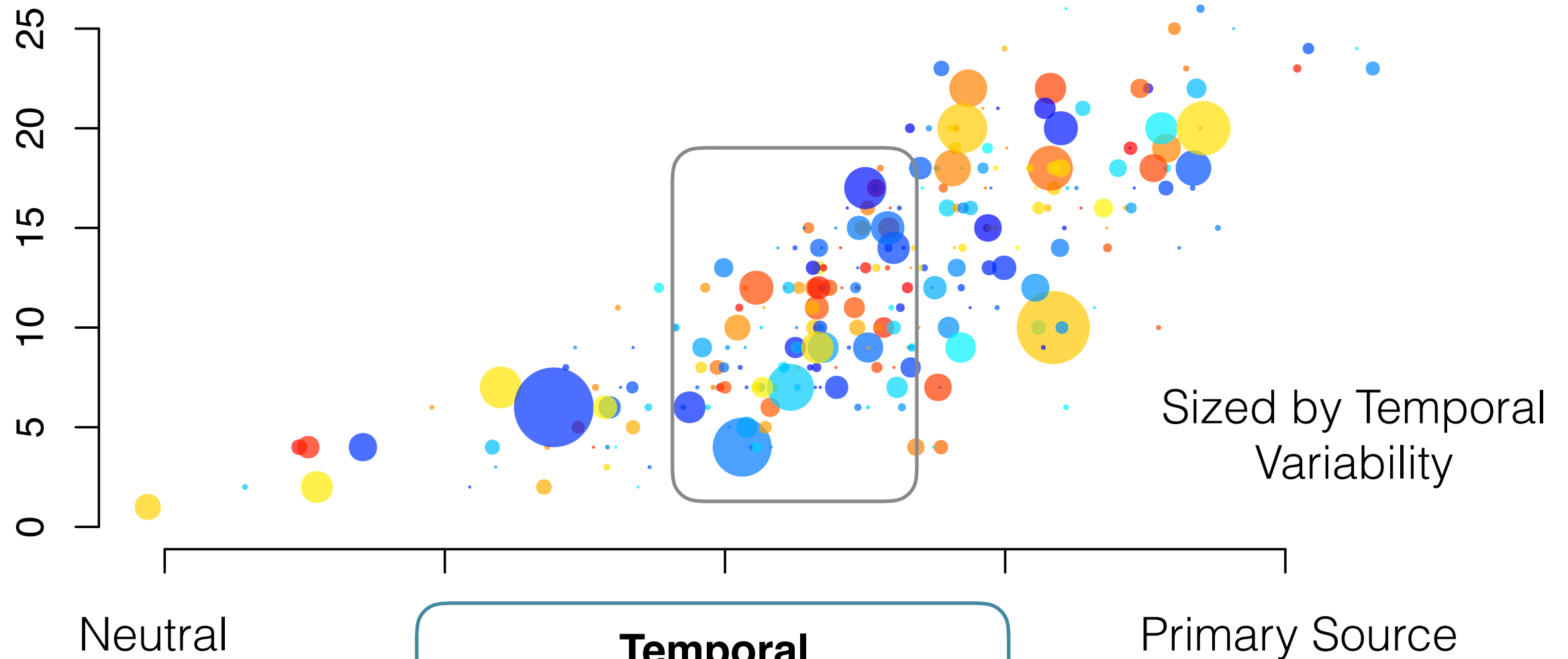
Sources and sinks of malaria parasites

Number of
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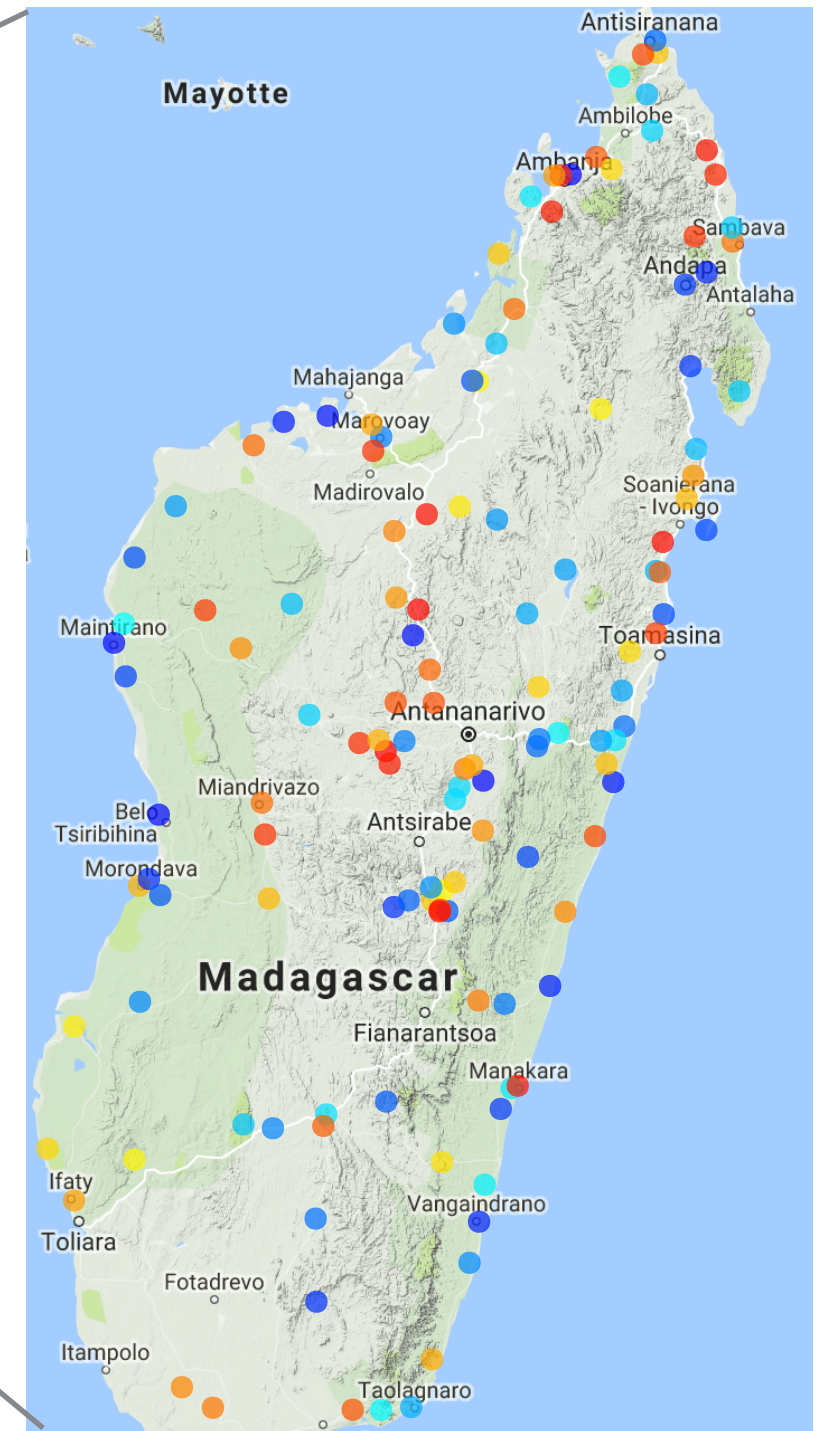
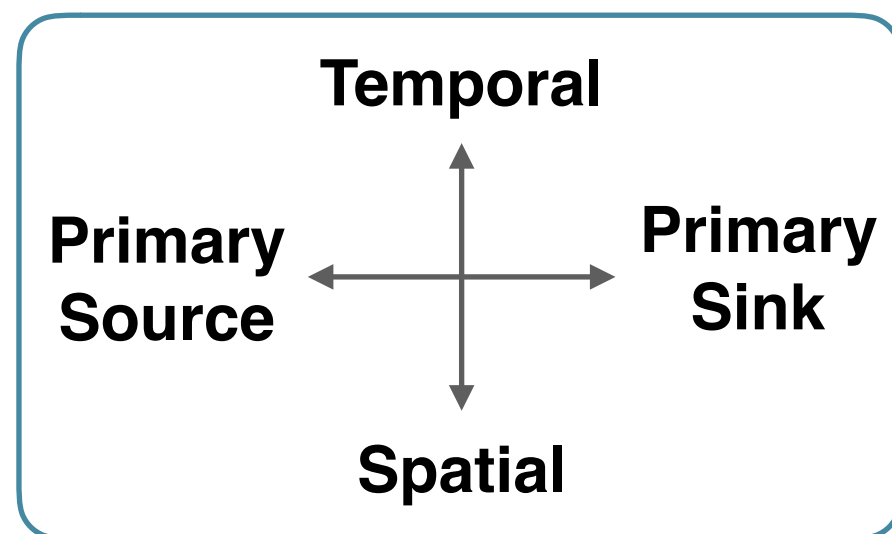
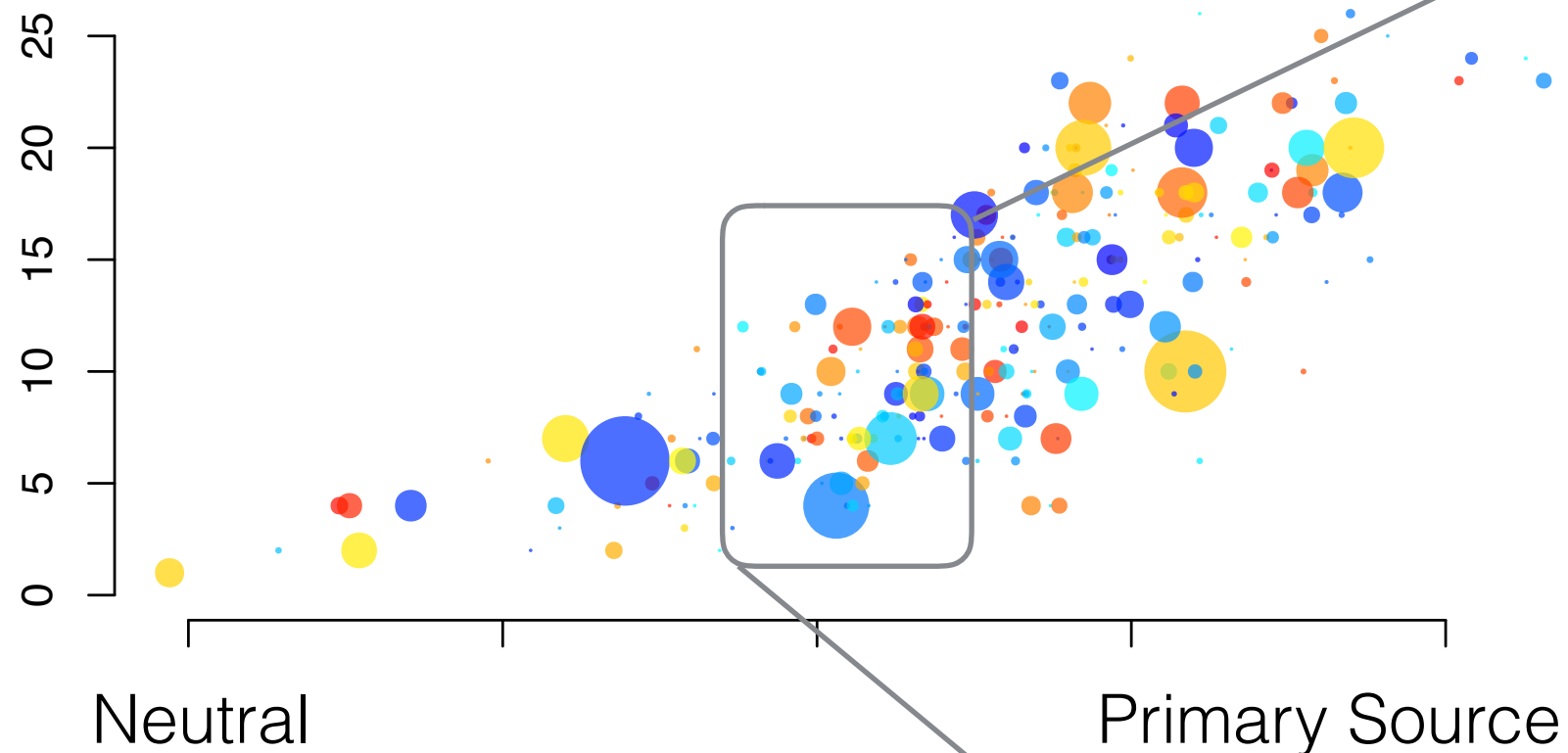
Sources and sinks of malaria parasites

Number of
Related Sinks

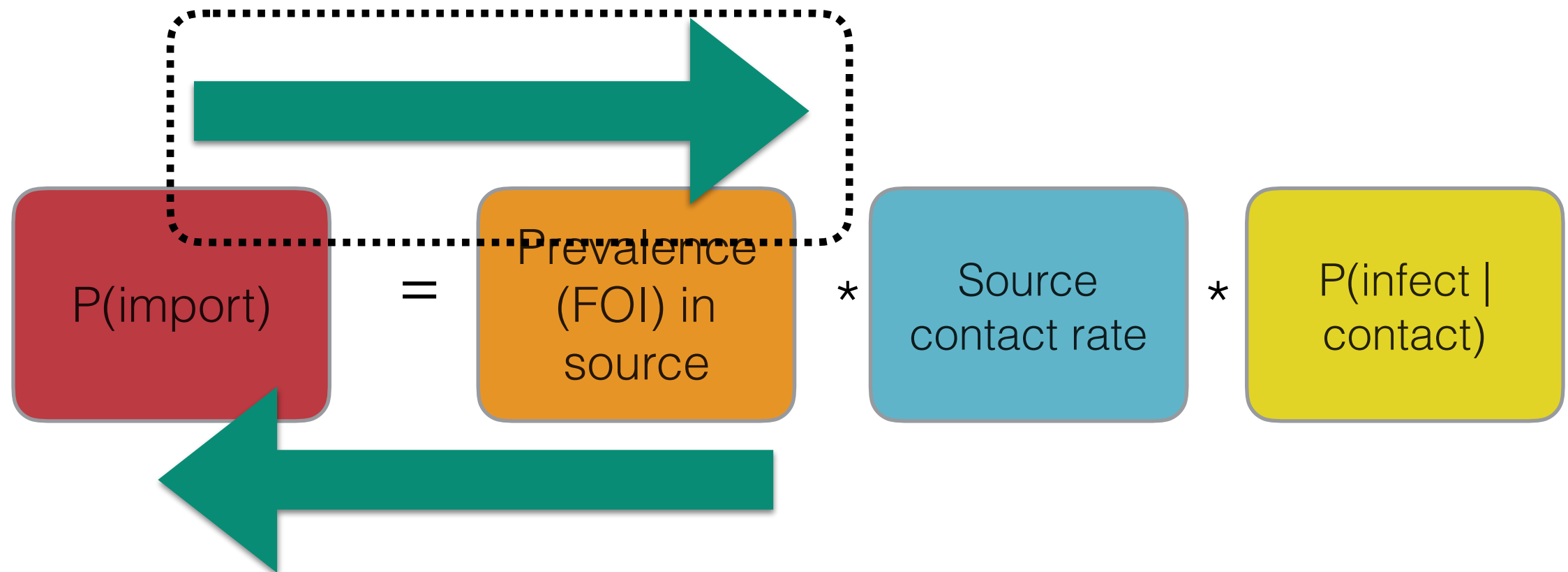


Sources and sinks of malaria parasites

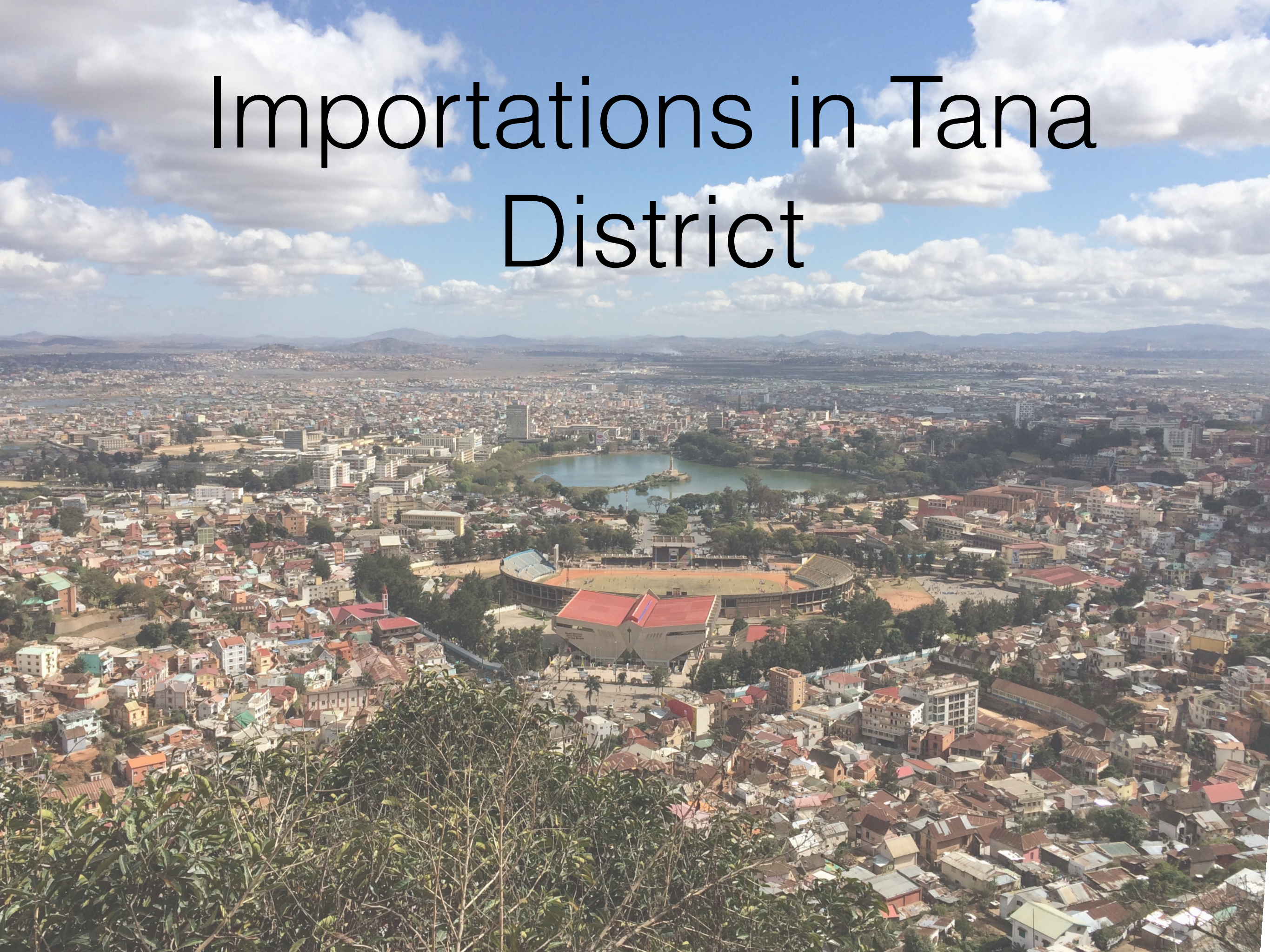
Number of
Related Sinks



How can we extend this framework for malaria?

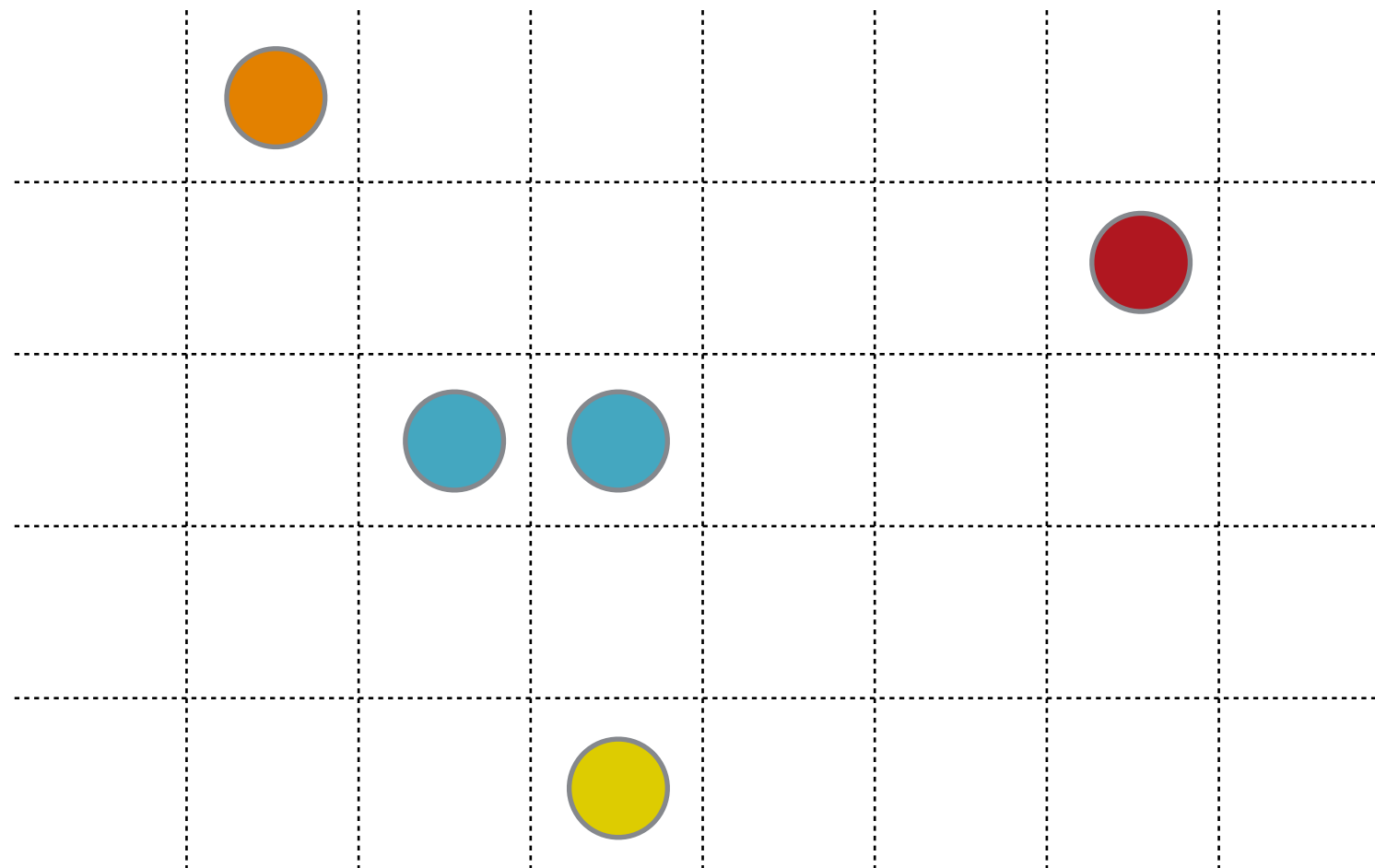


Importations in Tana District



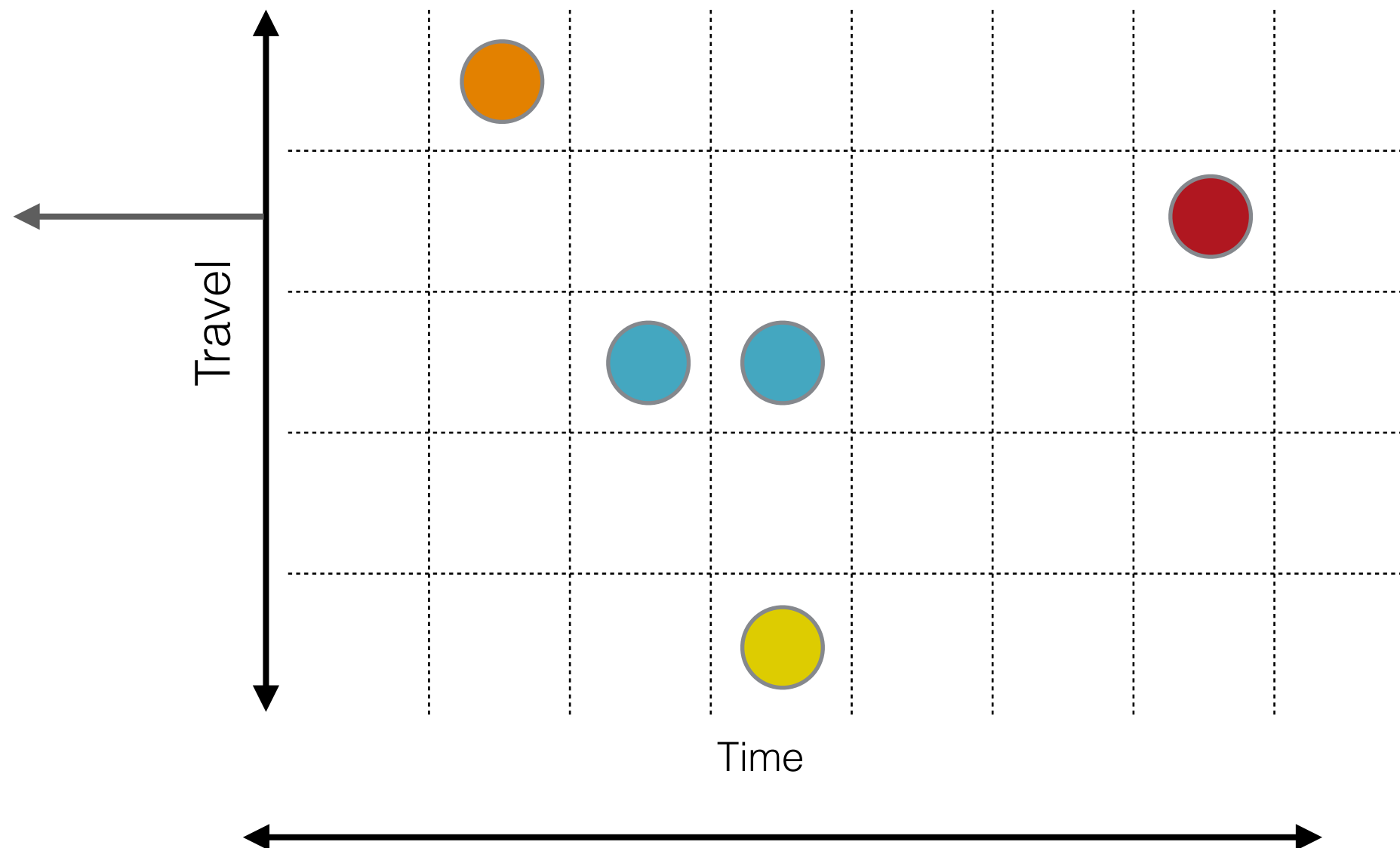
Sources and sinks of malaria parasites

Spatial Wallinga-Teunis Method



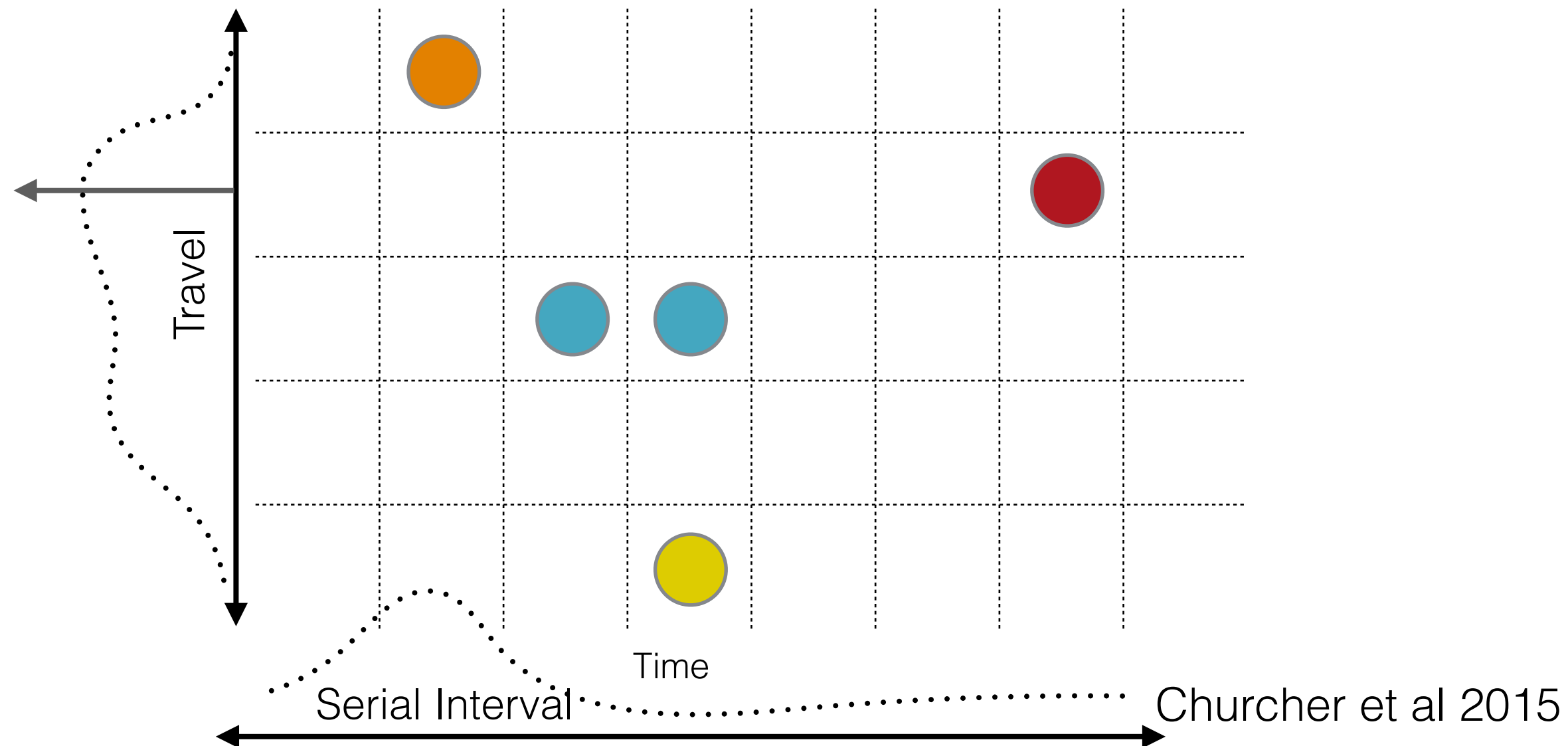
Sources and sinks of malaria parasites

Spatial Wallinga-Teunis Method



Sources and sinks of malaria parasites

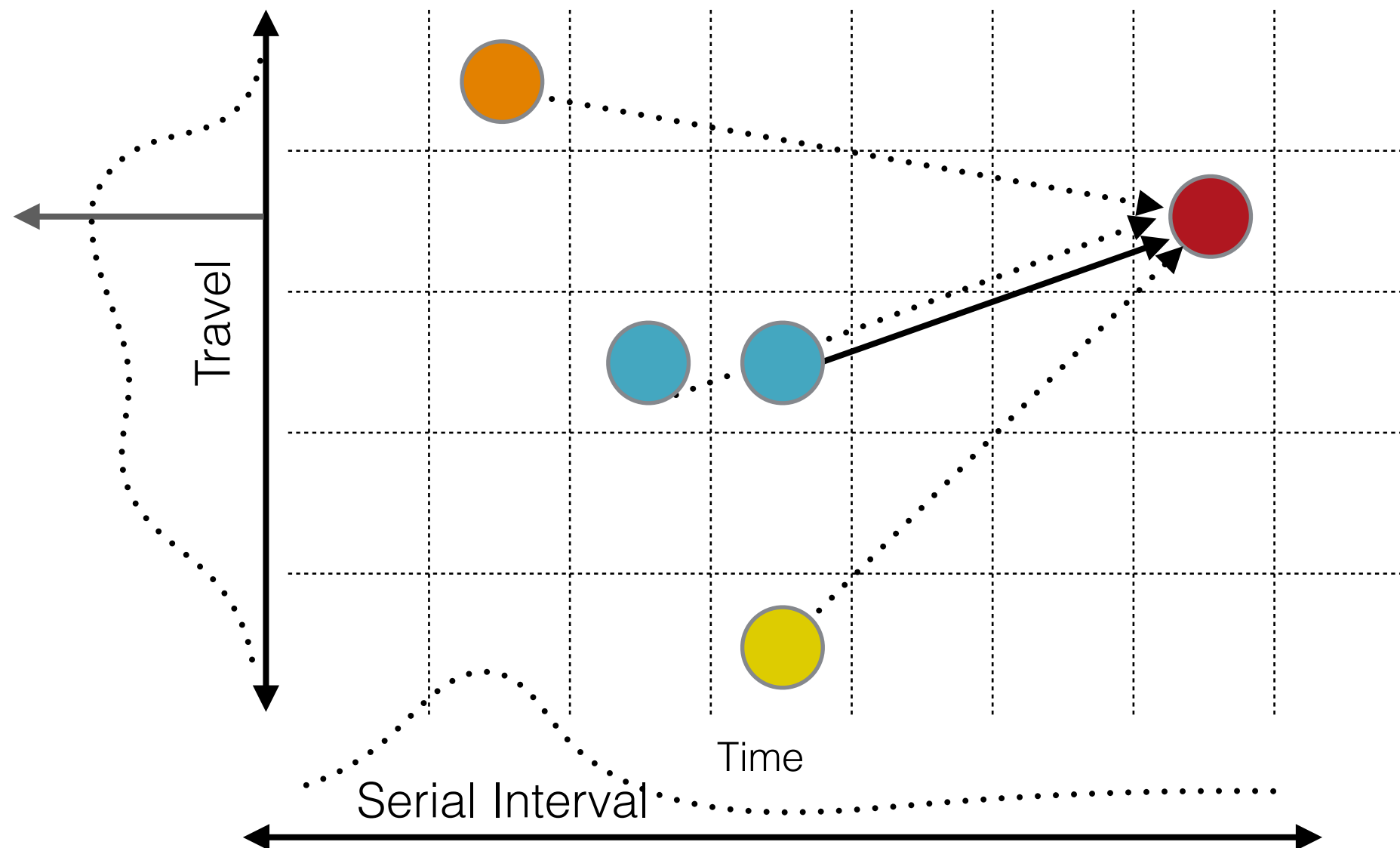
Spatial Wallinga-Teunis Method



White et al 2013

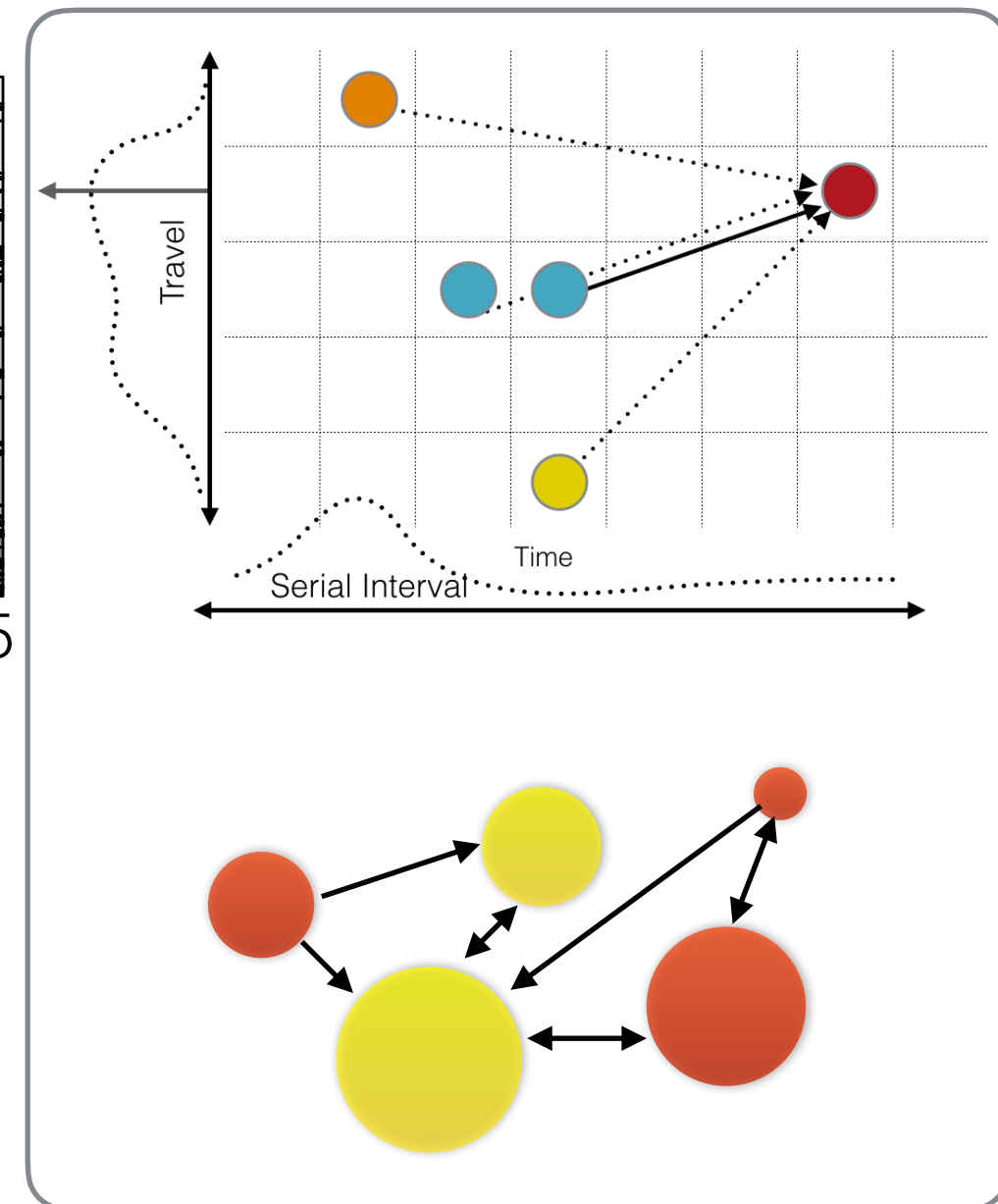
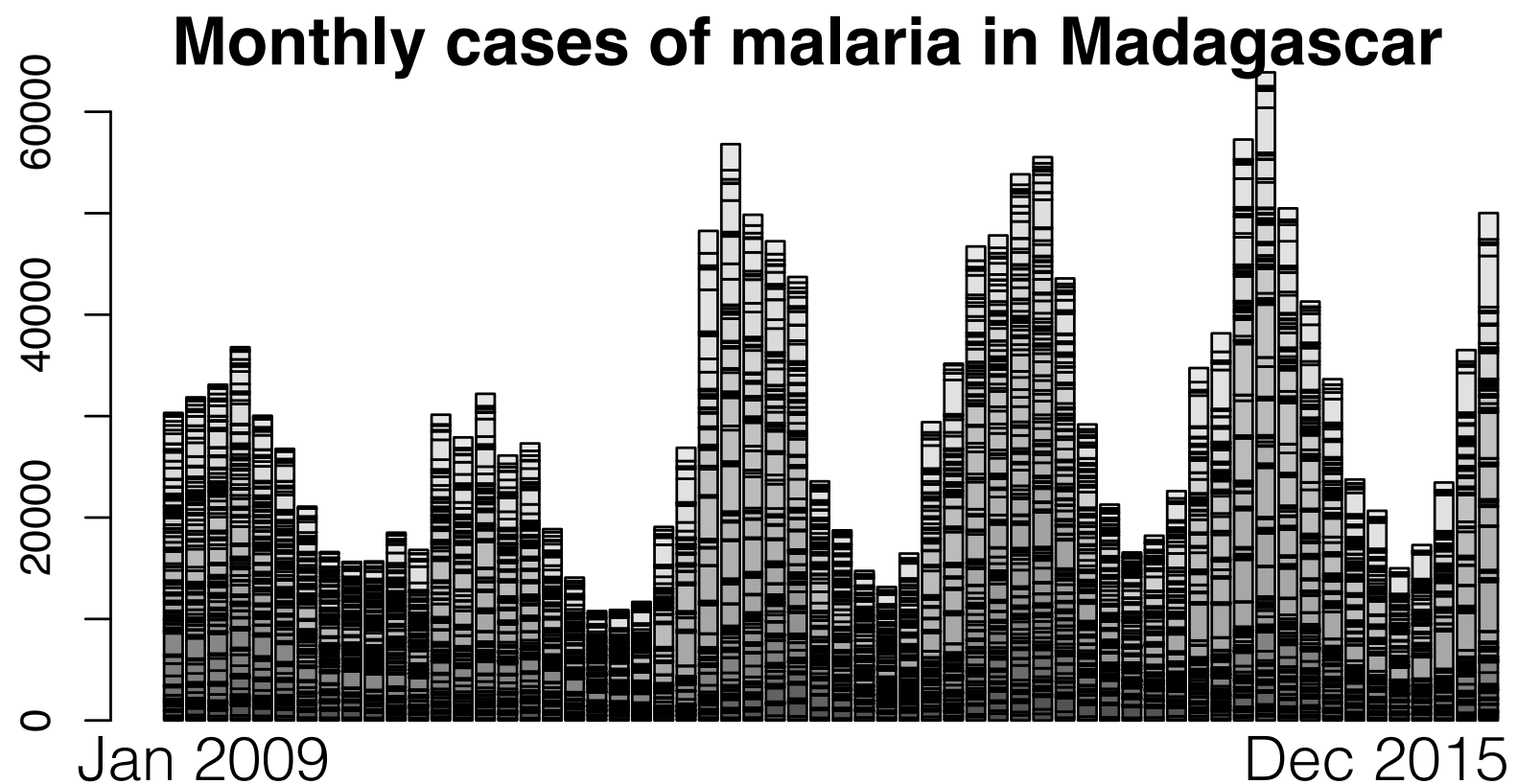
Sources and sinks of malaria parasites

Spatial Wallinga-Teunis Method



Sources and sinks of malaria parasites

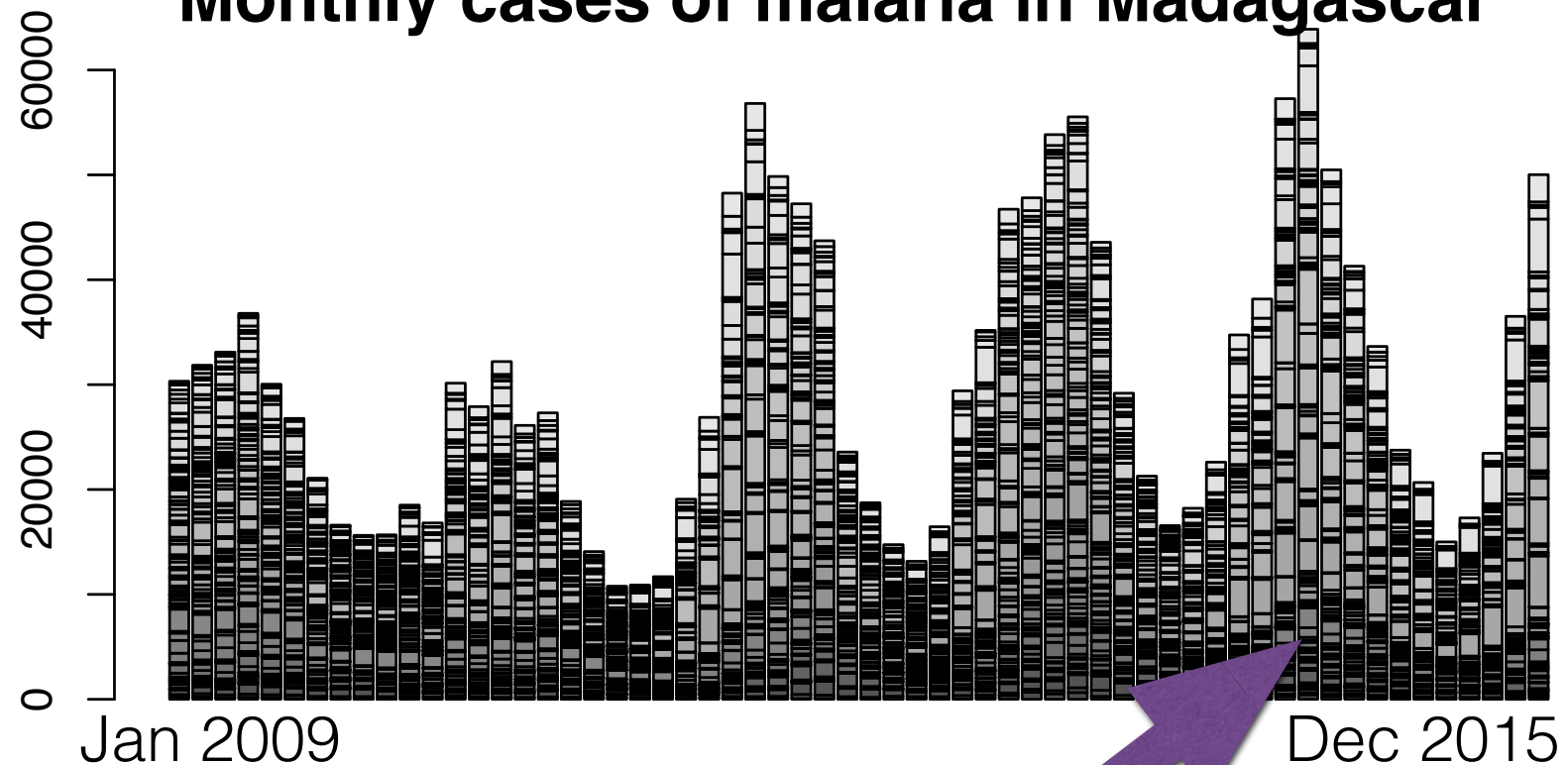
Tana District



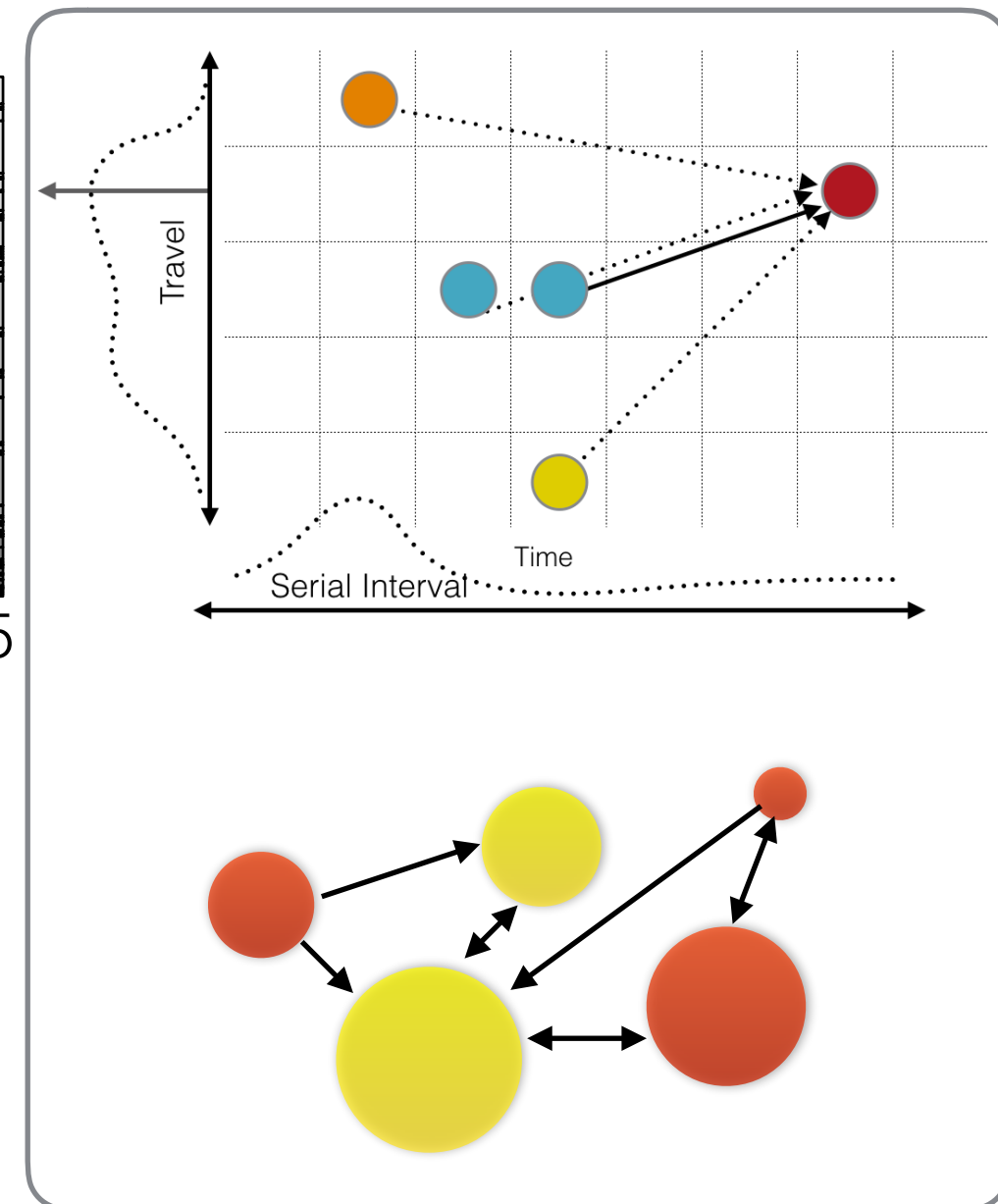
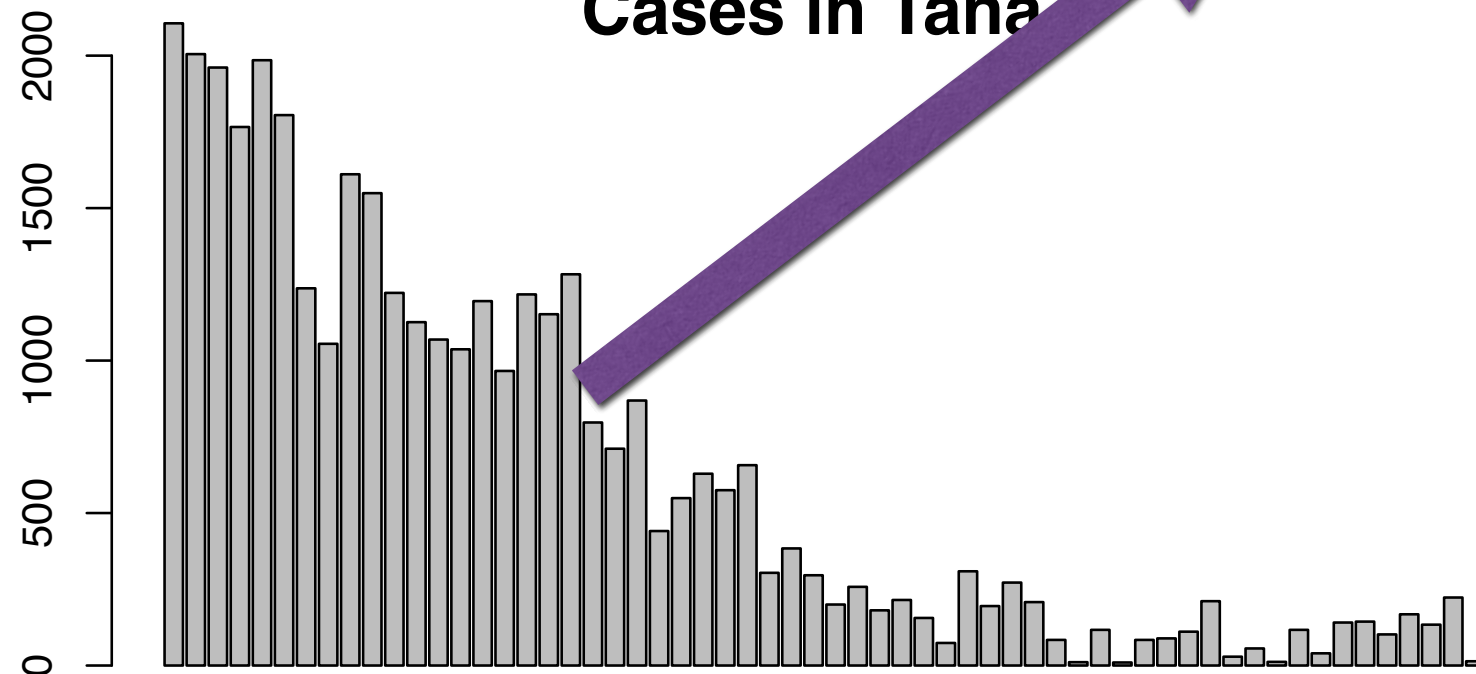
Sources and sinks of malaria parasites

Tana District

Monthly cases of malaria in Madagascar

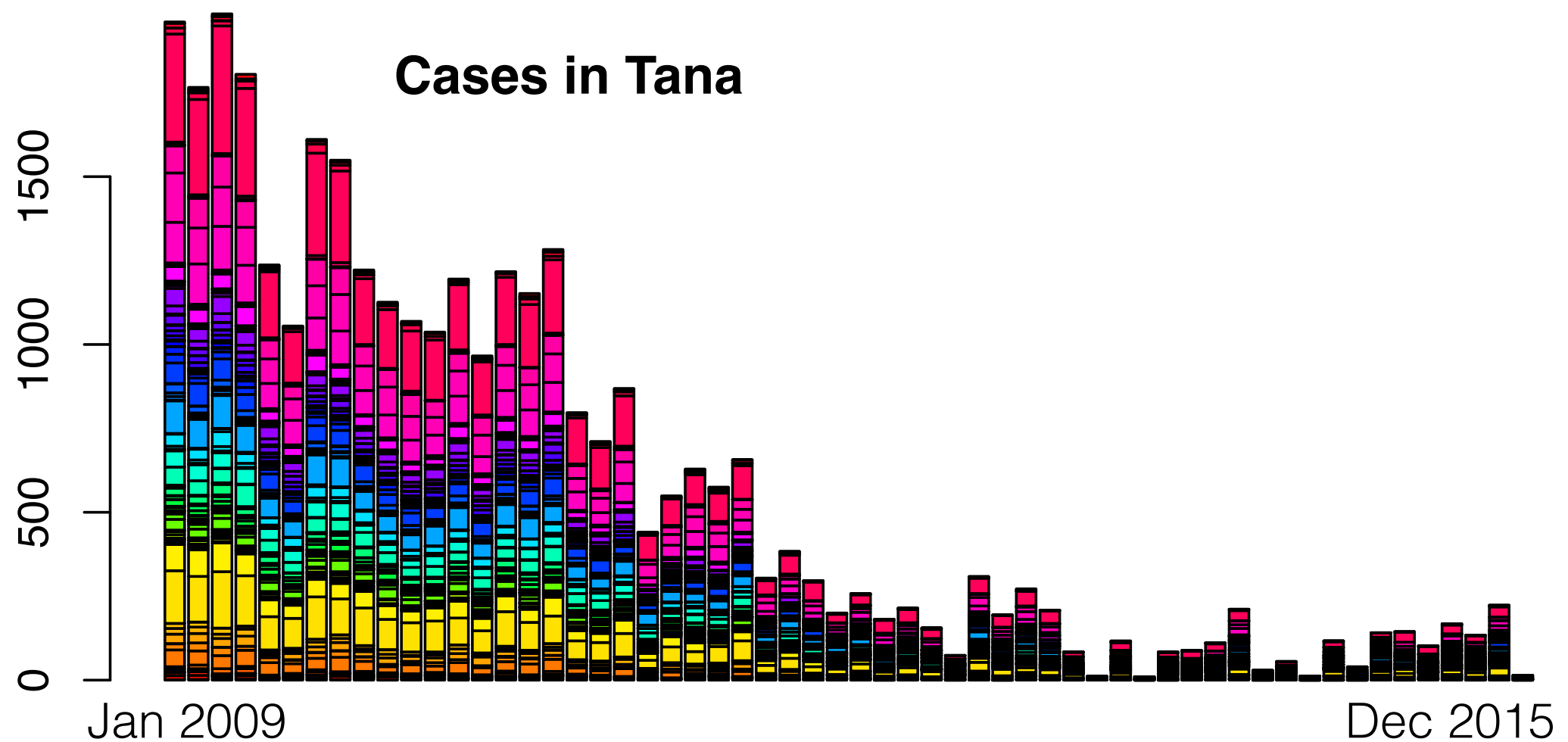


Cases in Tana



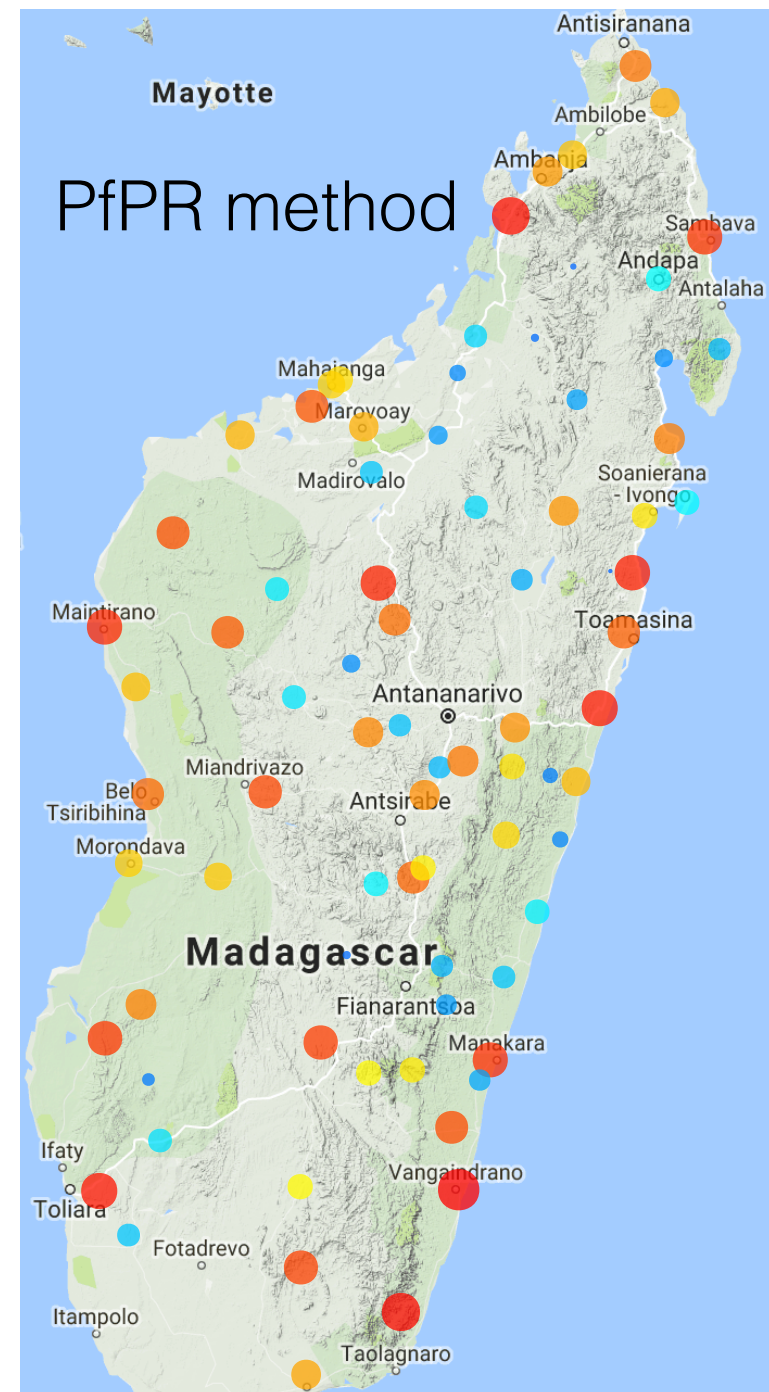
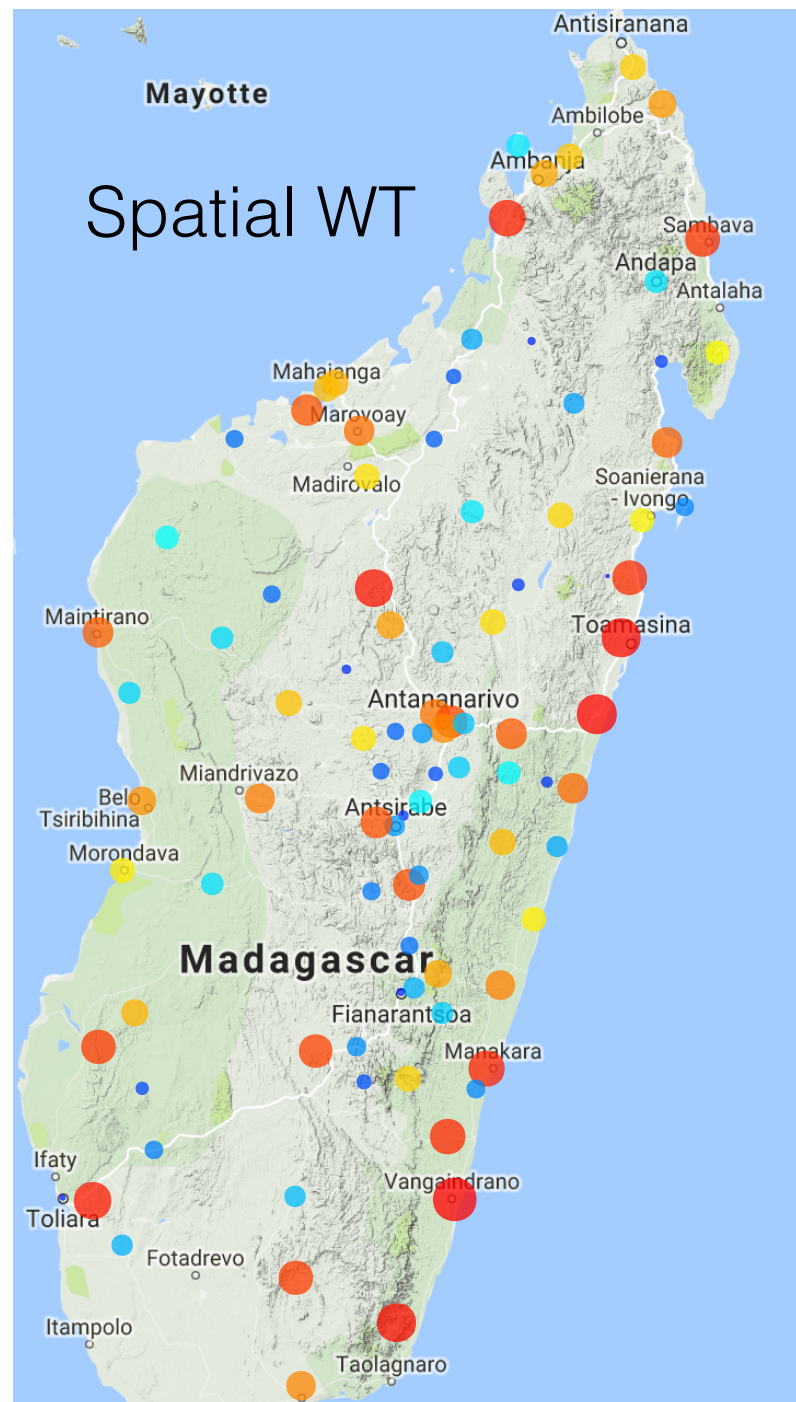
Sources and sinks of malaria parasites

Tana District

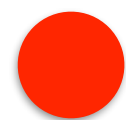


Sources and sinks of malaria parasites

Tana District



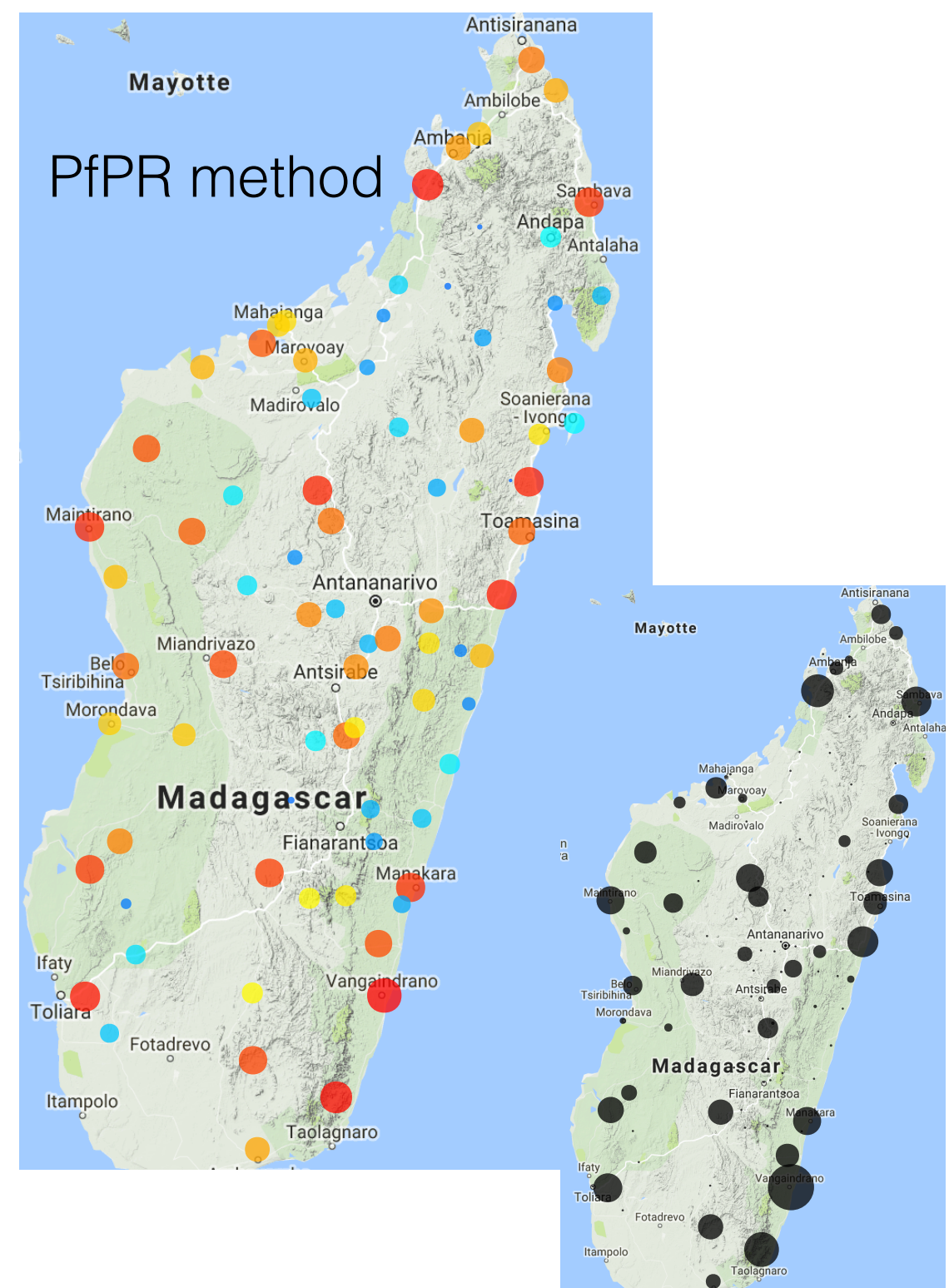
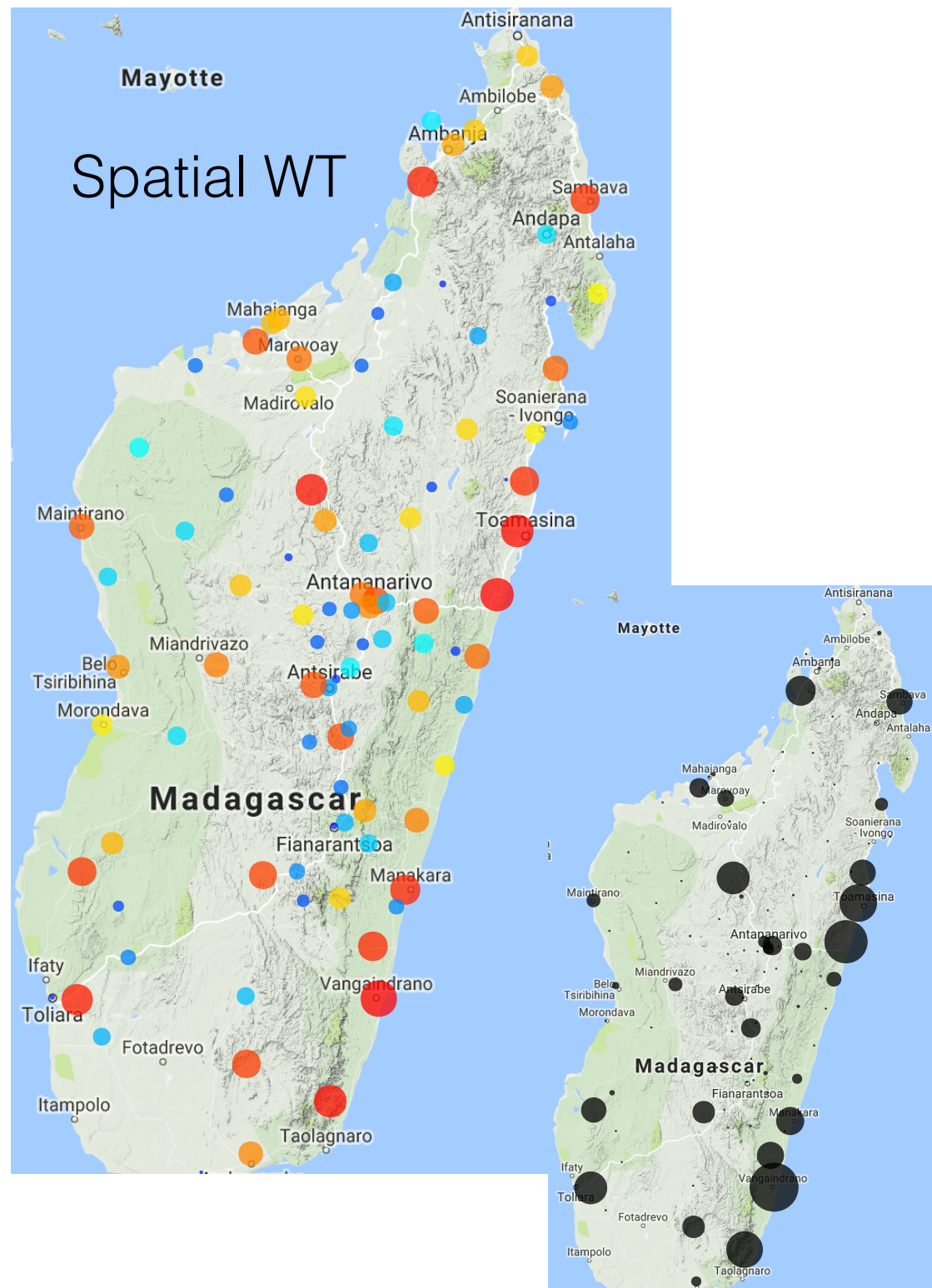
Smallest Source



Largest Source

Sources and sinks of malaria parasites

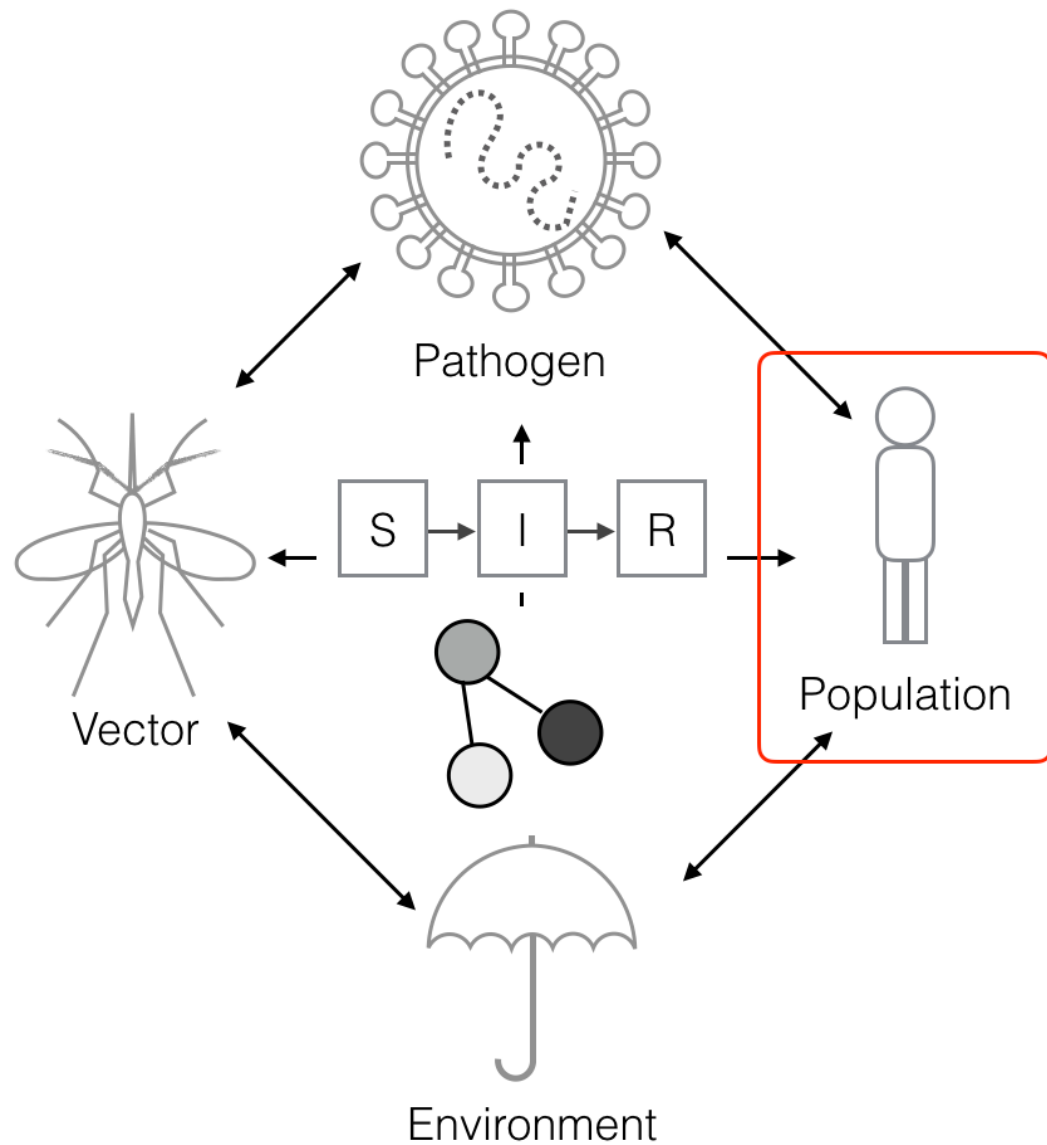
Tana District



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

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Metcalf and Grenfell labs

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Jean-Maurice Rakotondramanga

Jean Michel Heraud

Christophe Rogier

Funders

NIH - MIDAS

Wellcome Trust Sustaining Health

James S McDonnell Foundation

Burroughs-Wellcome Career Award

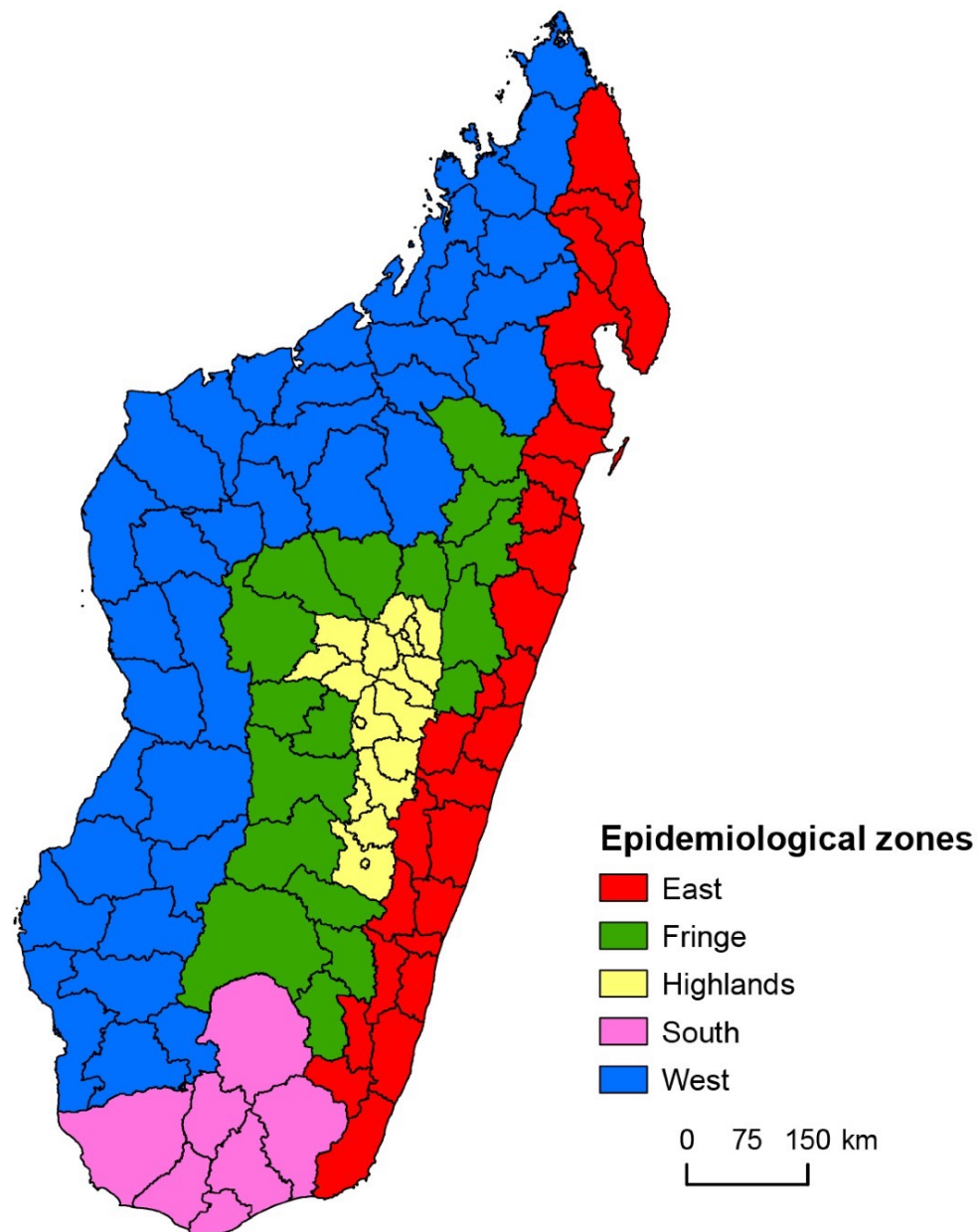
JAMES S.
MCDONNELL
FOUNDATION

BURROUGHS
WELLCOME
FUND 

Thanks!



Malaria in Madagascar



Kesteman et al (2014)

in high transmission >1 case per 1,000

low transmission 0-1 case per 1,000 pop
reported falciparum to vivid
unestus, An. gambiae, An. arabiensis, An.
parensis, An. coustani

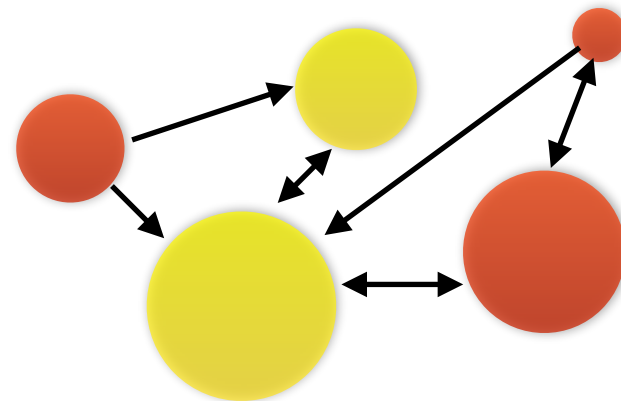
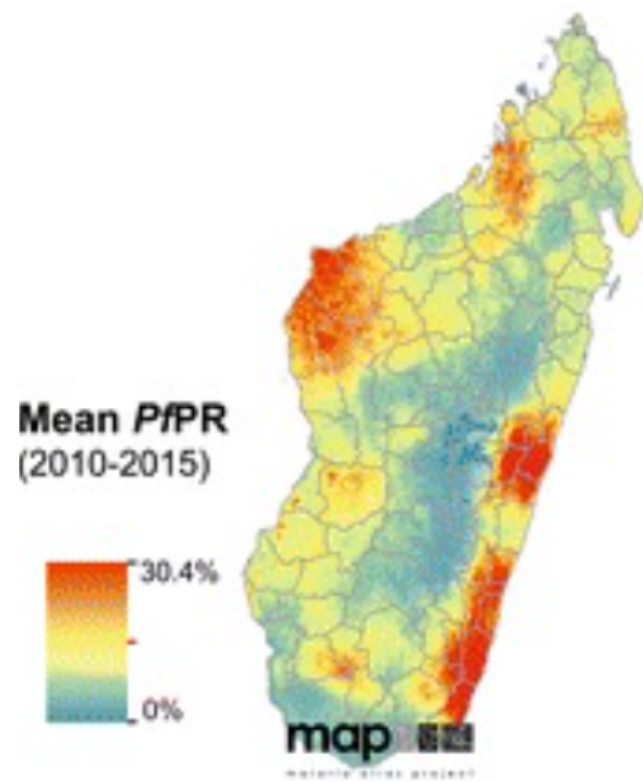
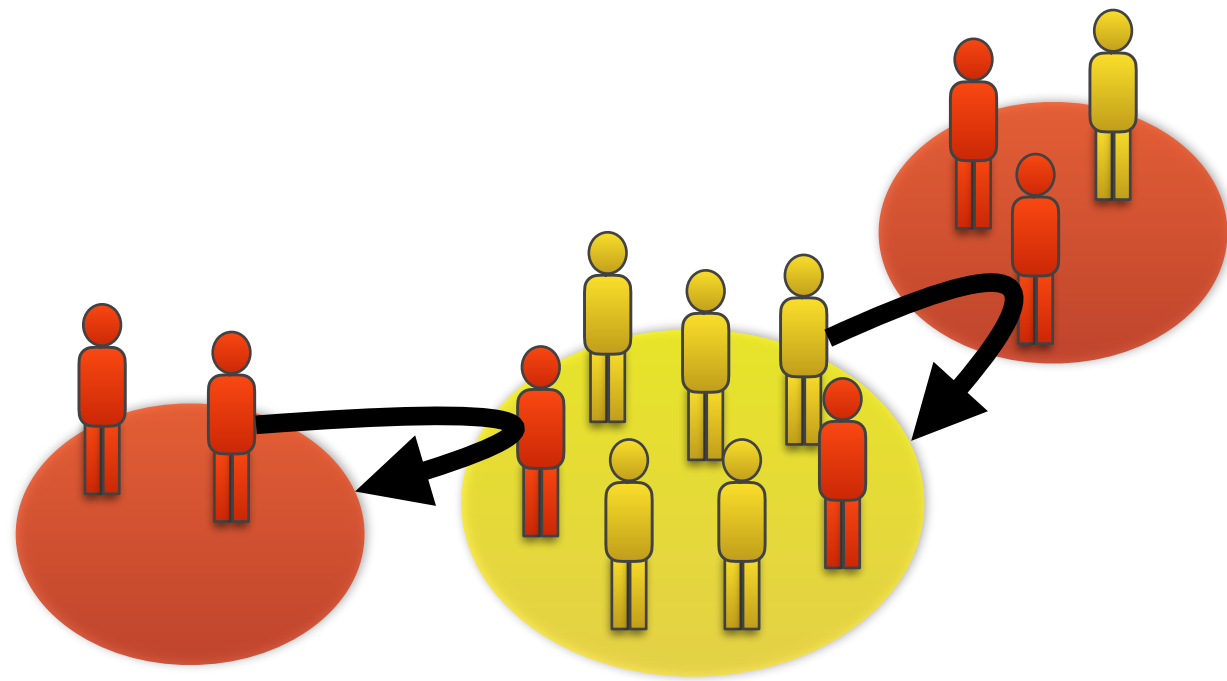
Q - artesunate-amodiaquine

268,597 mi²

226,658 mi² 224,445 mi²

population size madagascar = 23 million

Kesteman et al (2014) texas = 27 million / area slightly bigger

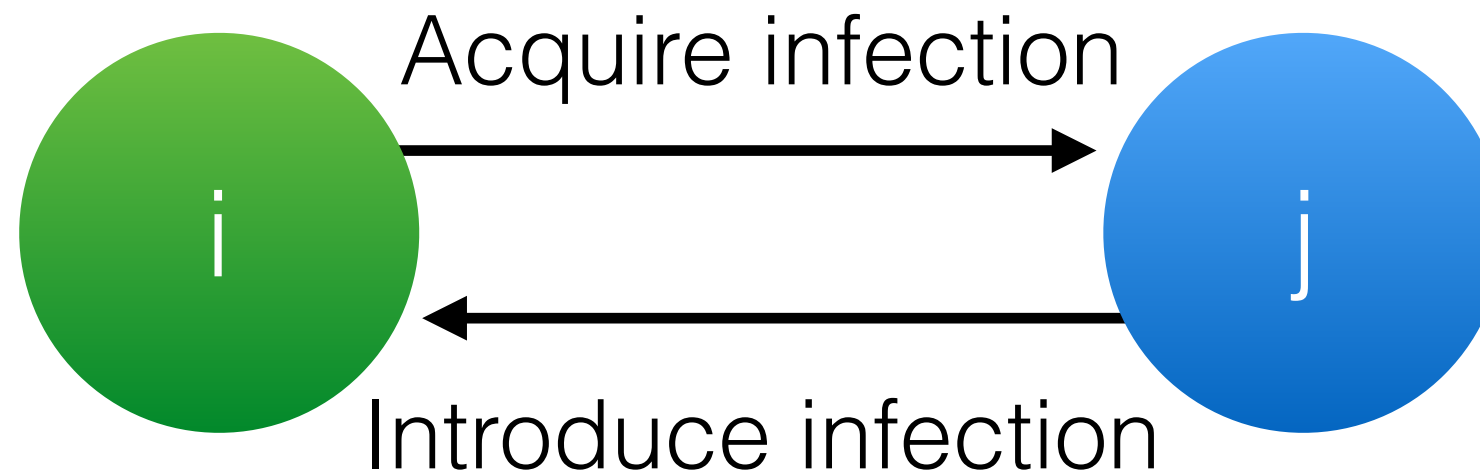


Sources
Sinks

Basic framework

Low transmission

High transmission



Infected individuals from i

$$P(import) = \lambda_j * d * S_i$$

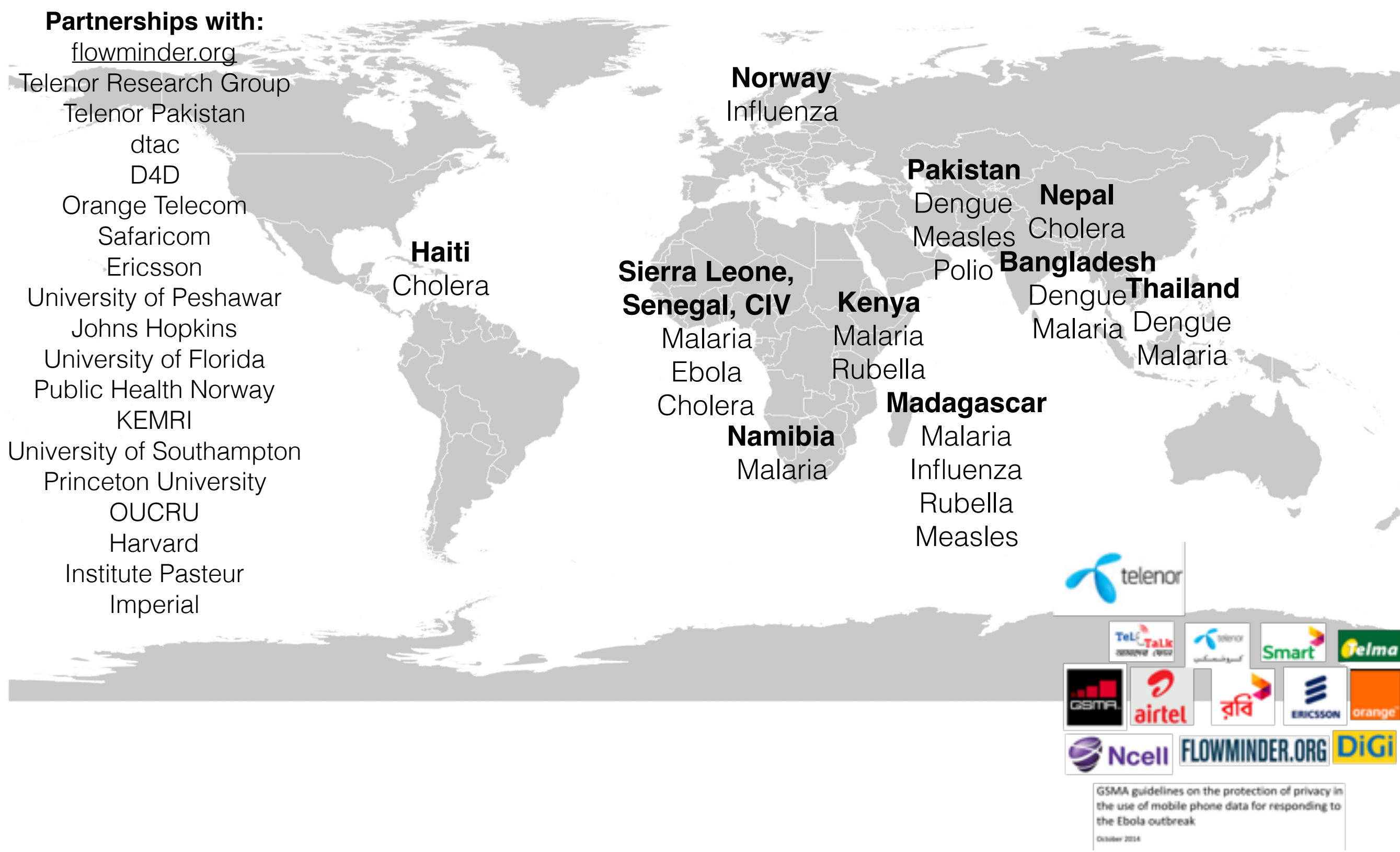
Onward infections?

Susceptible individuals from i

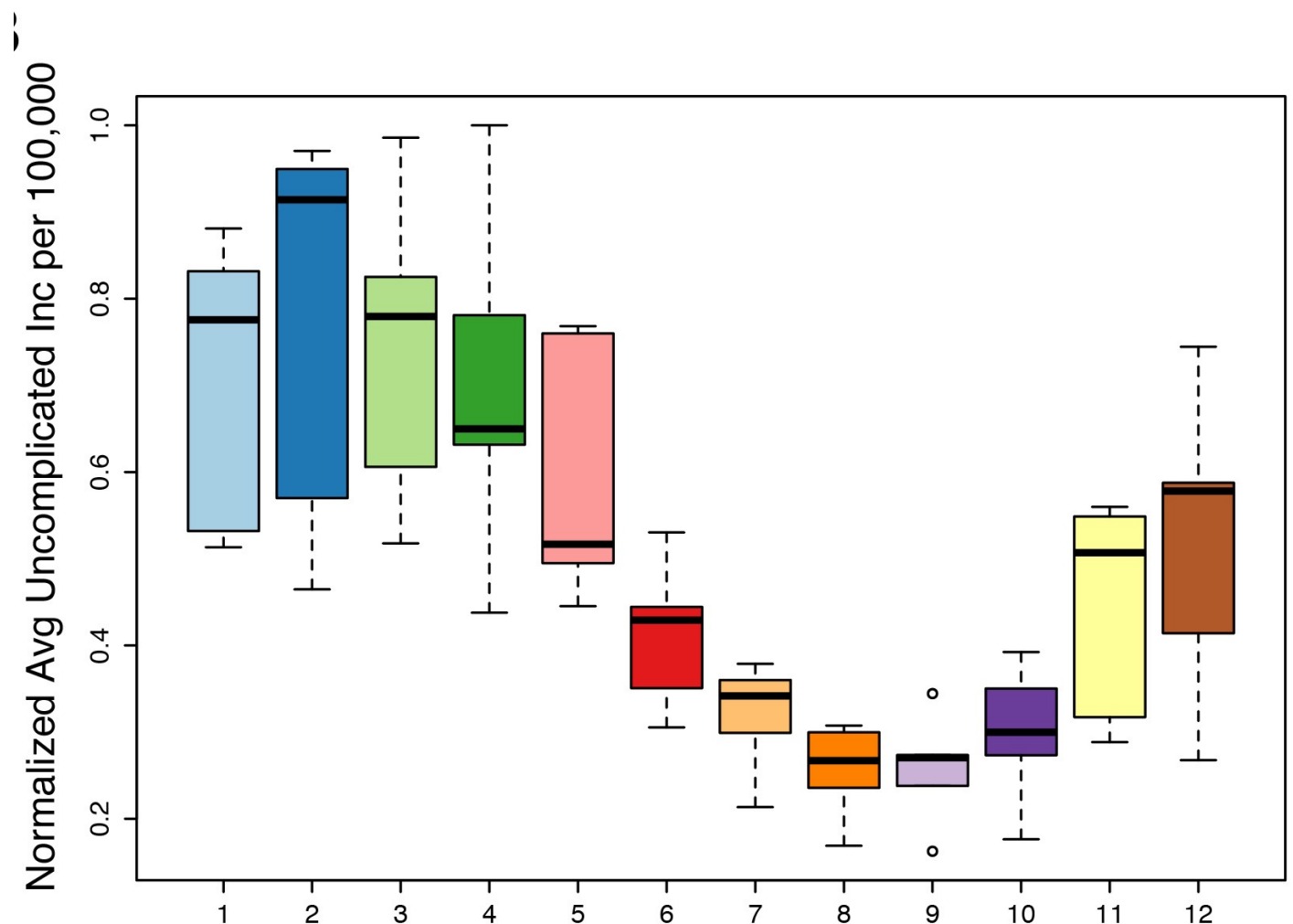
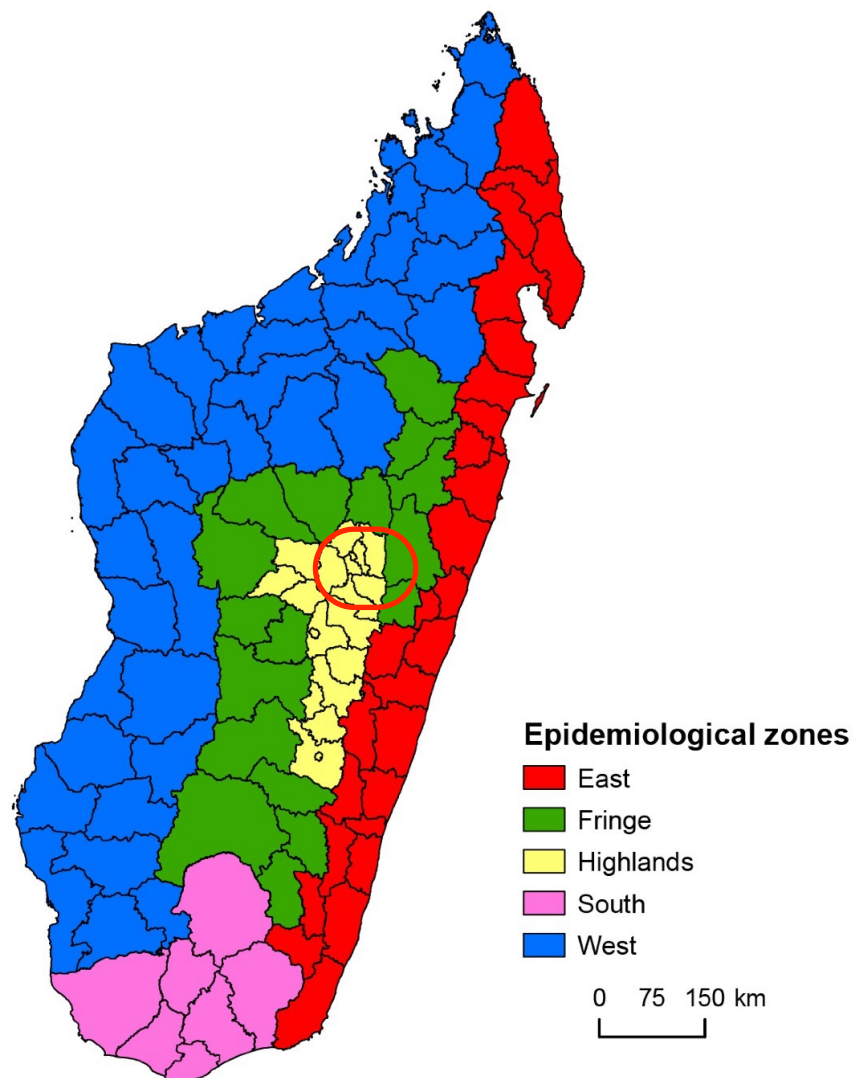
$$P(infect) = \lambda_j * d$$

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



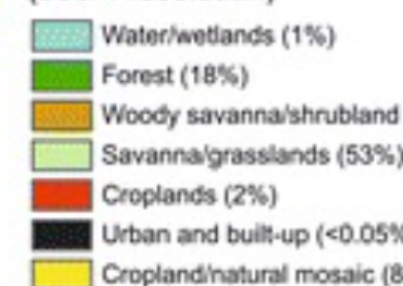
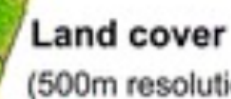
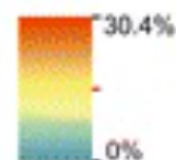
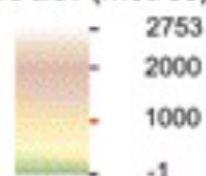
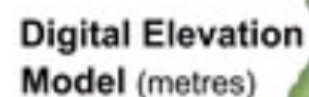
Since the French occupation much attention has been rightly devoted to the making of roads and railway, but the natives engaged in this labour have suffered enormously, owing to their contracting malaria in the unhealthy districts in which from time to time they have worked. Many have died, in spite 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 d prophylaxis. The c a broad level stret west, and south. Through this plain to 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

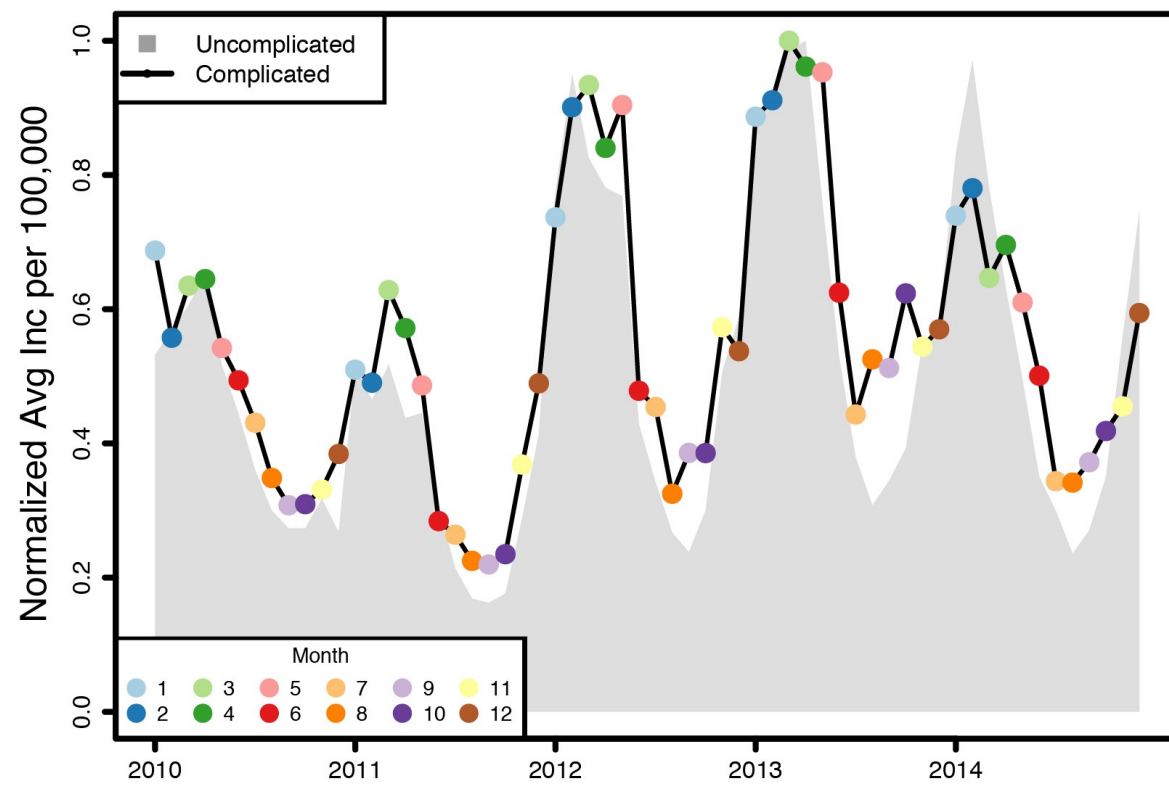
Telecom regulators

Public Health

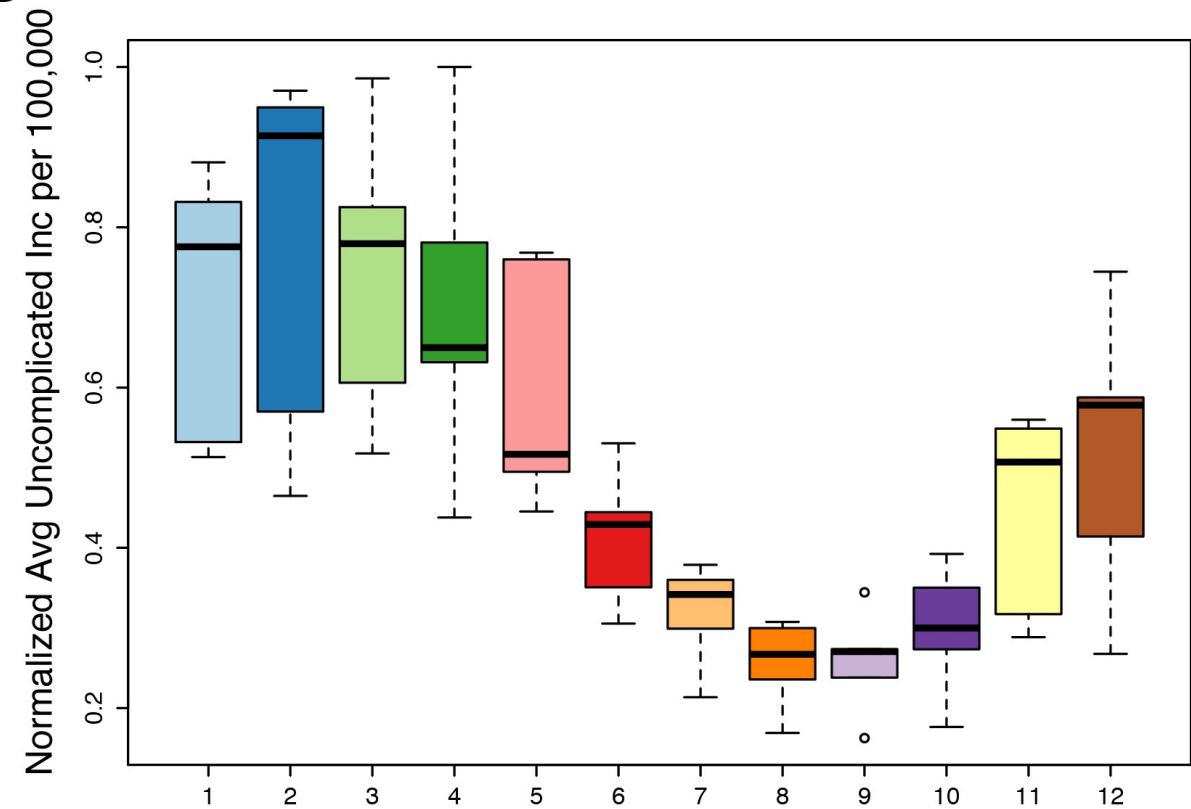
Ministry of health
Epidemiologists

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**?

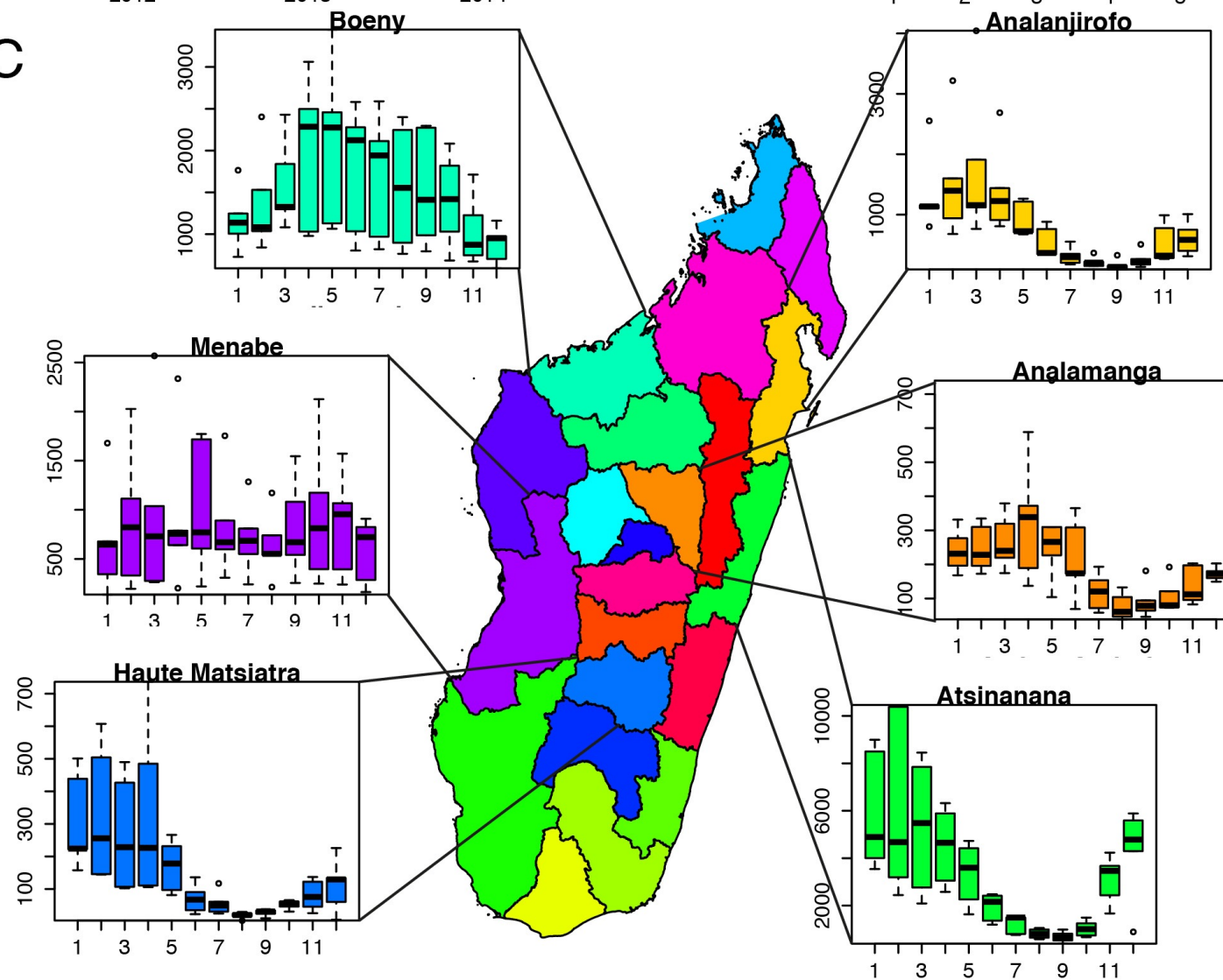
A



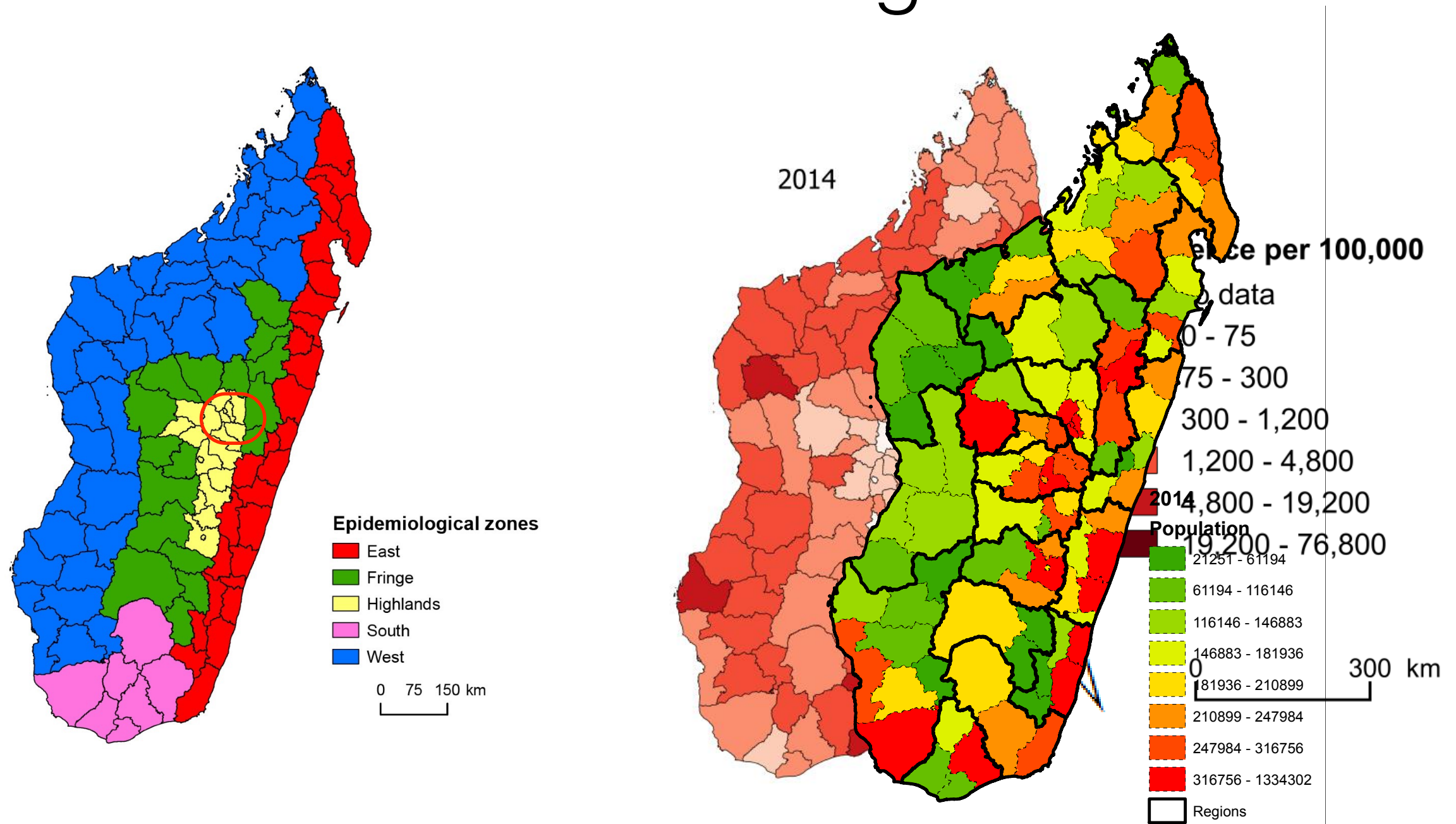
B



C



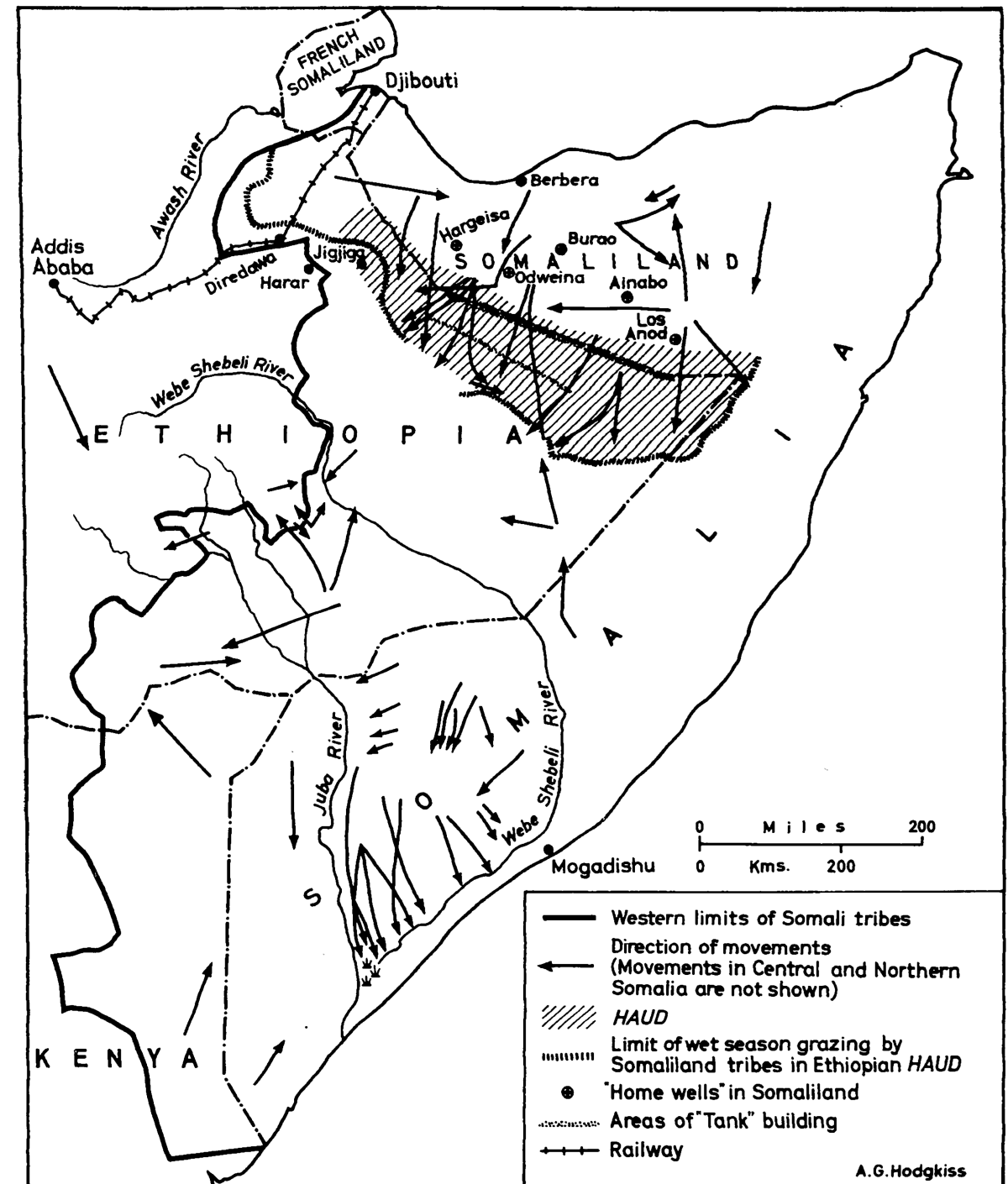
Malaria in Madagascar

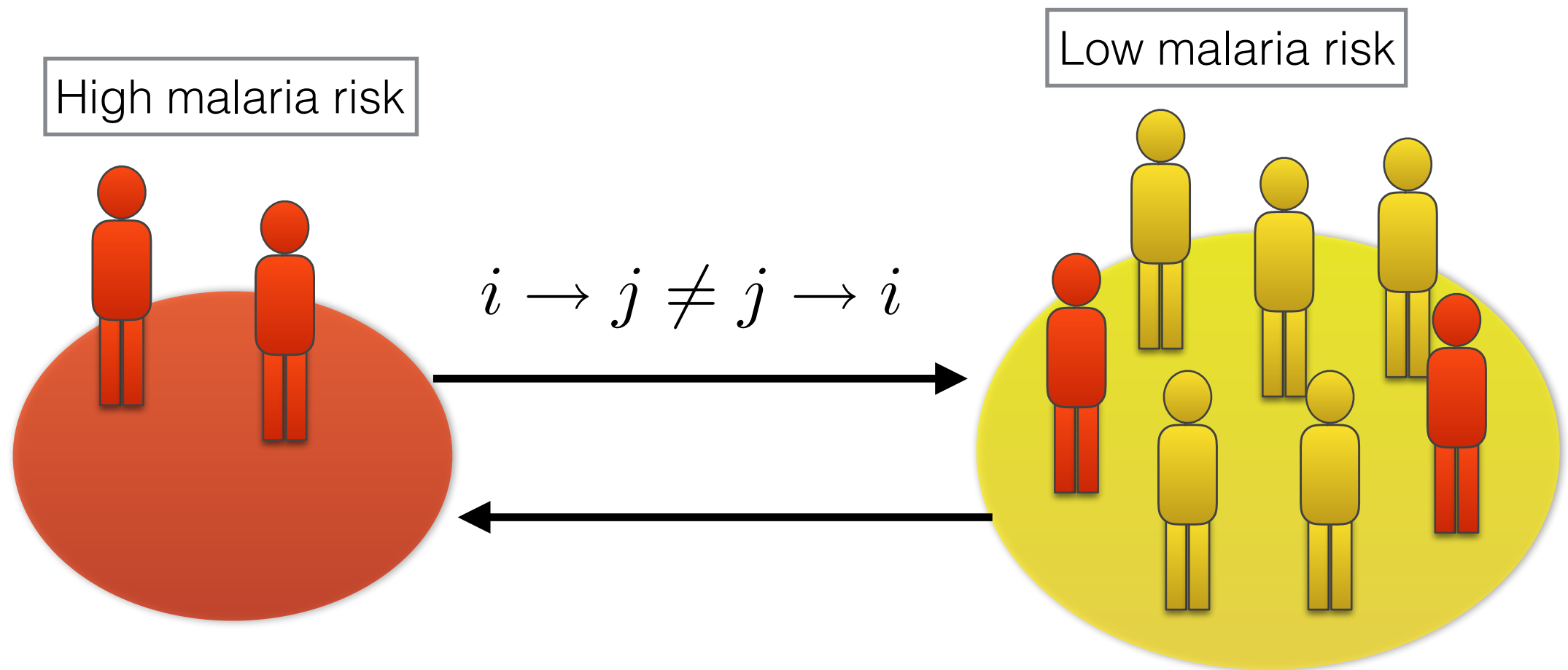


Multiple epidemiological zones
 Year round, endemic transmission on the East and West Coasts
 Central Highlands and South have periodic outbreaks

How can we measure mobility patterns?

"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."





$$P(\text{import}_{i \rightarrow j} | T_d) = 1 - (1 + \alpha b E T_d)^{-1/\alpha}$$

$$P(\text{import}_{i \rightarrow j} | T_d) = \lambda_i T_d / 200$$

$$P(\text{import}_{i \rightarrow j} | T_d) = P f P R_{2-10}(i) T_d / 200$$