Modeling Forest Malaria Using a Time-at-Risk Based Approach

Incorporating Human Movement into the Equation

Alec Georgoff

MMC Meeting, Bangkok, Thailand

November 29, 2018

Background

- What makes forest malaria different?
  - Risk is spread across different “populations” based on time spent in certain locations
  - Forest-going population has different risk than those who stay in village
  - Transmission is occurring away from home
    - People who travel to the same place form a different population

Contrasting Malaria Models

- Ross-Macdonald Model
  - Entire human population exposed to the same mosquito population
  - One transmission location
- Forest Model
  - Transmission occurs at home <u>and</u> away from home
  - Multiple human populations exposed to multiple mosquito populations

Objectives

- Show how reproductive rates and time-at-risk can be used together to model malaria prevalence in a forest system
- Show why time-at-risk and forest reproductive rates have an impact on elimination in villages

Reproductive Rate

Reproductive Rate

$$R = \frac{Ma^2bce^{-gn}}{Hgr}$$

Mosquitoes Per Human

Higher values increase R

Reproductive Rate

$$R = \frac{M\boxed{a^2}bce^{-gn}}{Hgr}$$

Mosquito Biting Rate

Higher values <u>increase</u> R

Reproductive Rate

$$R = \frac{Ma^2 bc e^{-gn}}{Hgr}$$

Proportion of Bites That
Cause Infection

Higher values <u>increase</u> R

Reproductive Rate

$$R = \frac{Ma^2bce^{-gn}}{Hgr}$$

Time for Sporogonic Cycle

Higher values decrease R

Reproductive Rate

$$R = \frac{Ma^2bce^{-\boxed{g}n}}{H\boxed{g}r}$$

Mosquito Death Rate

Higher values <u>decrease</u> R

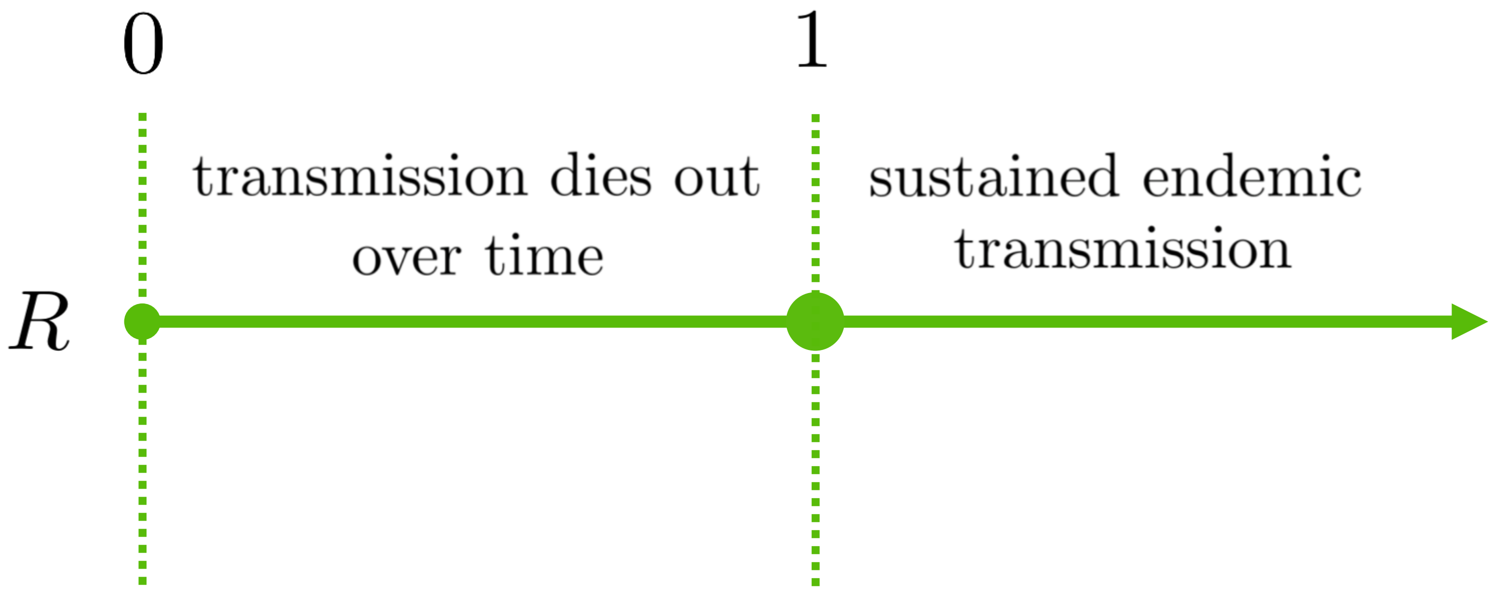
Reproductive Rate

$$R = \frac{M a^2 b c e^{-gn}}{H g \boxed{r}}$$

Human Disease
Recovery

Higher values decrease R

Reproductive Rate



Time-at-Risk

Time-at-Risk (TaR)

$$\mathbf{\Psi} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \end{bmatrix}$$

Rows Sum to 1

Time-at-Risk (TaR)

$$
\mathbf{\Psi} = \begin{array}{cc} & \begin{array}{cccc} \text{loc } 1 & \text{loc } 2 & \dots & \text{loc } n \end{array} \\ \begin{array}{c} \text{population } 1 \\ \text{population } 2 \\ \vdots \\ \text{population } m \end{array} & \begin{bmatrix} p_{11} & p_{12} & \dots & p_{1n} \\ p_{21} & p_{22} & \dots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \dots & p_{mn} \end{bmatrix} \end{array}
$$

Rows Sum to 1

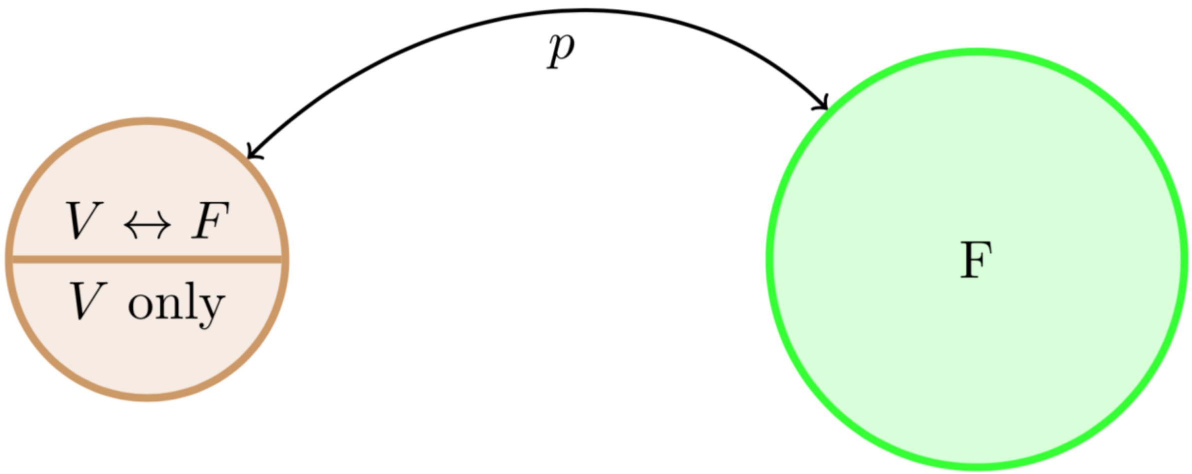
Time-at-Risk (TaR)

$$\boldsymbol{\Psi} = \begin{array}{r c} & \begin{array}{cccc} \text{loc } 1 & \text{loc } 2 & \cdots & \text{loc } n \end{array} \\ \begin{array}{r} \text{population } 1 \\ \text{population } 2 \\ \vdots \\ \text{population } m \end{array} & \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \end{bmatrix} \end{array}$$

Proportion of time spent by population 1 in location 2

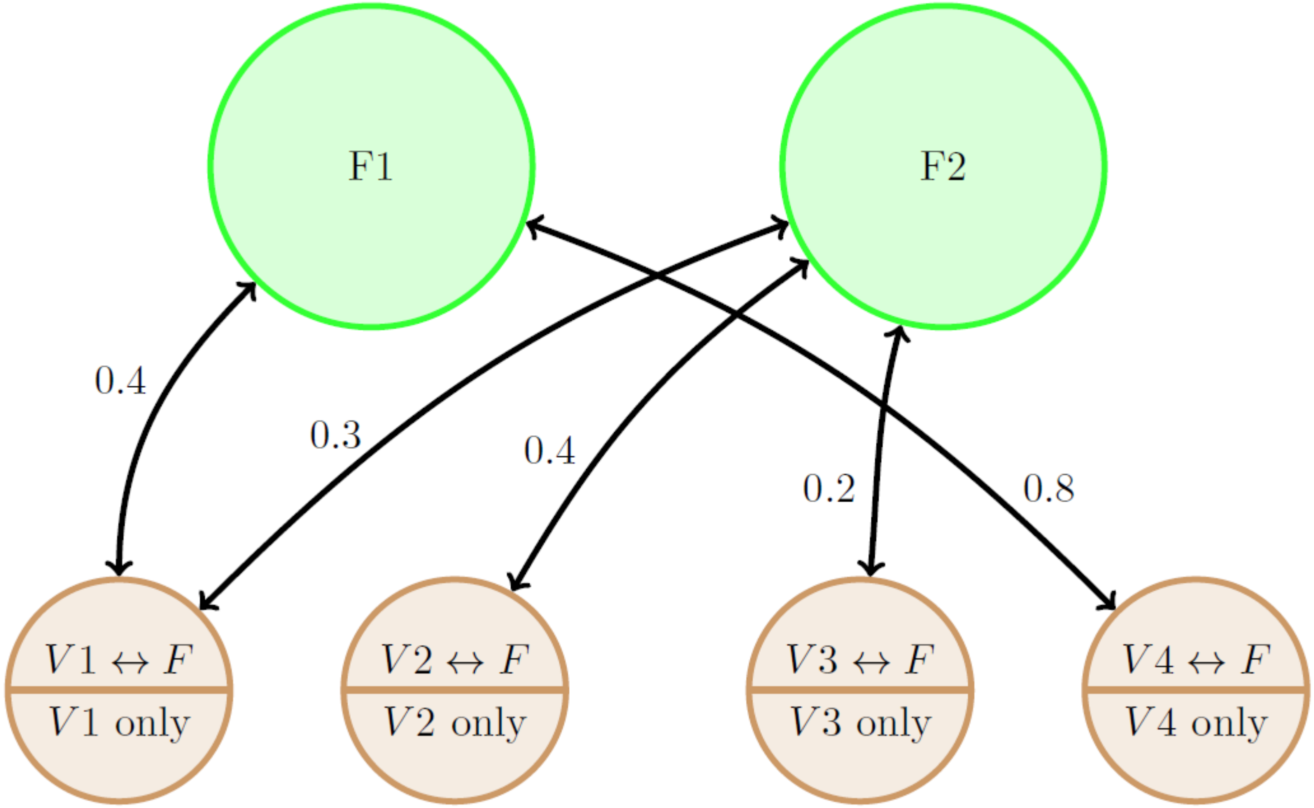
Rows Sum to 1

Time-at-Risk (TaR)

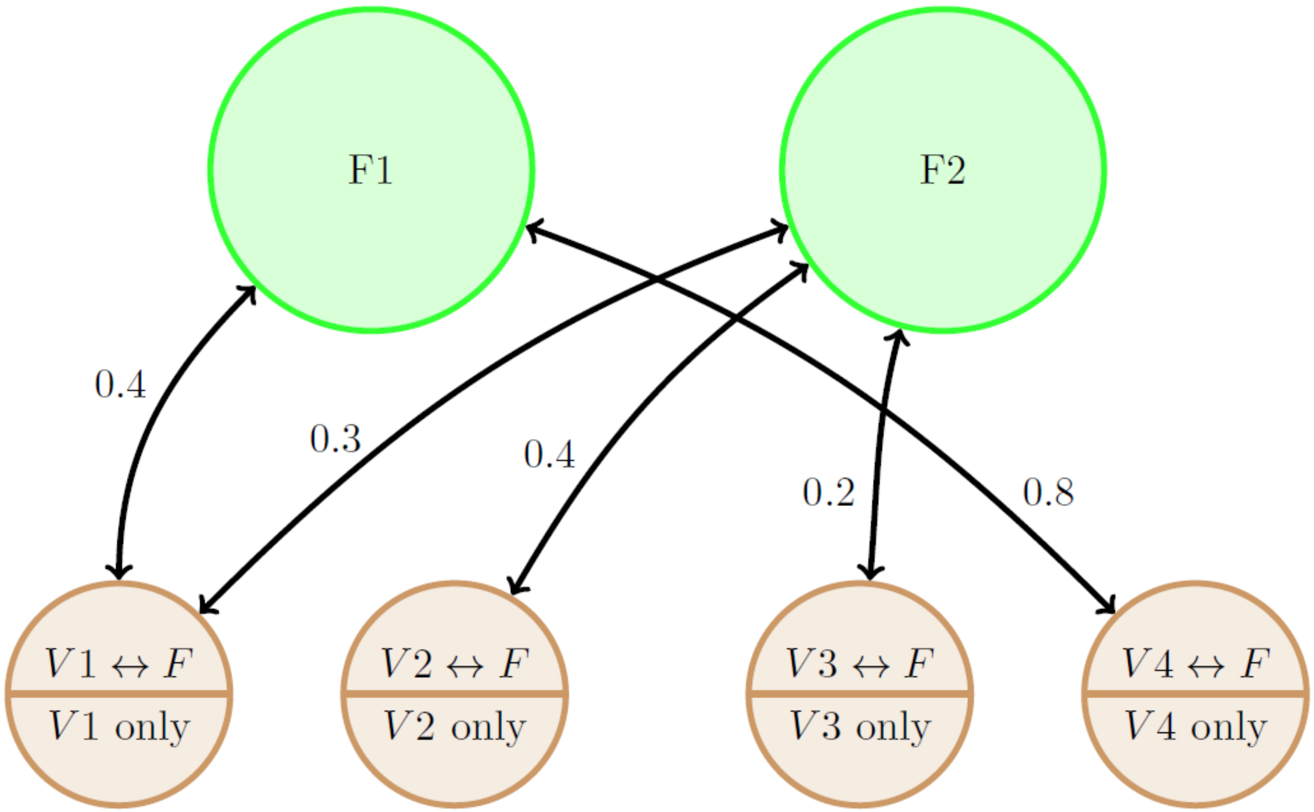


$$
\begin{array}{cc}
 & \begin{array}{cc} \text{V} & \text{F} \end{array} \\
\mathbf{\Psi} = \begin{array}{c} V_{only} \\ V \leftrightarrow F \end{array} & \begin{bmatrix} 1 & 0 \\ 1-p & p \end{bmatrix}
\end{array}
$$

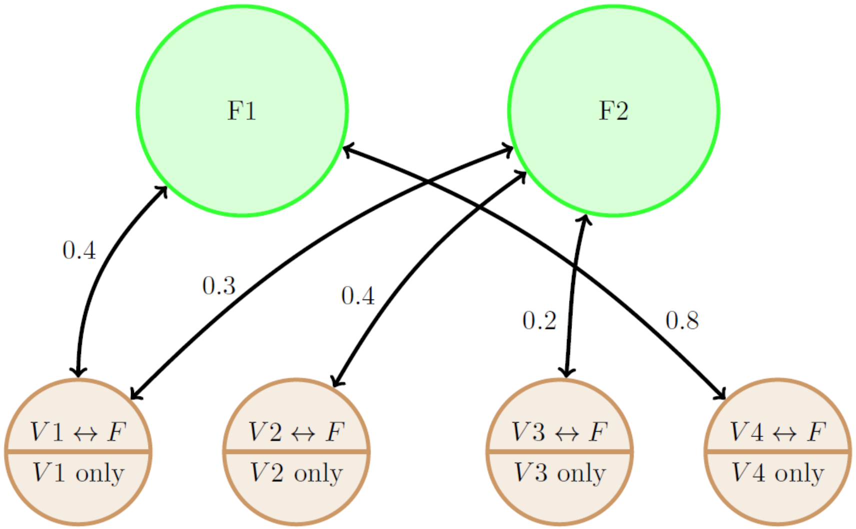
Time-at-Risk (TaR)



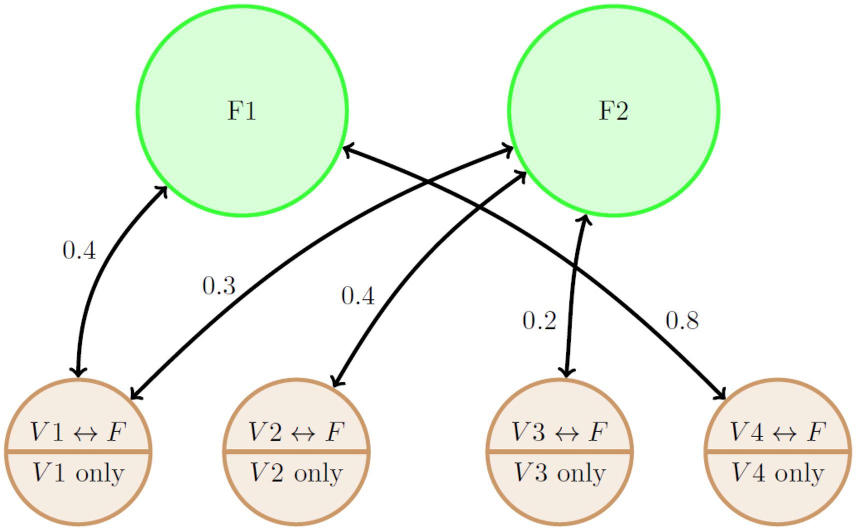
Time-at-Risk (TaR)



Time-at-Risk (TaR)



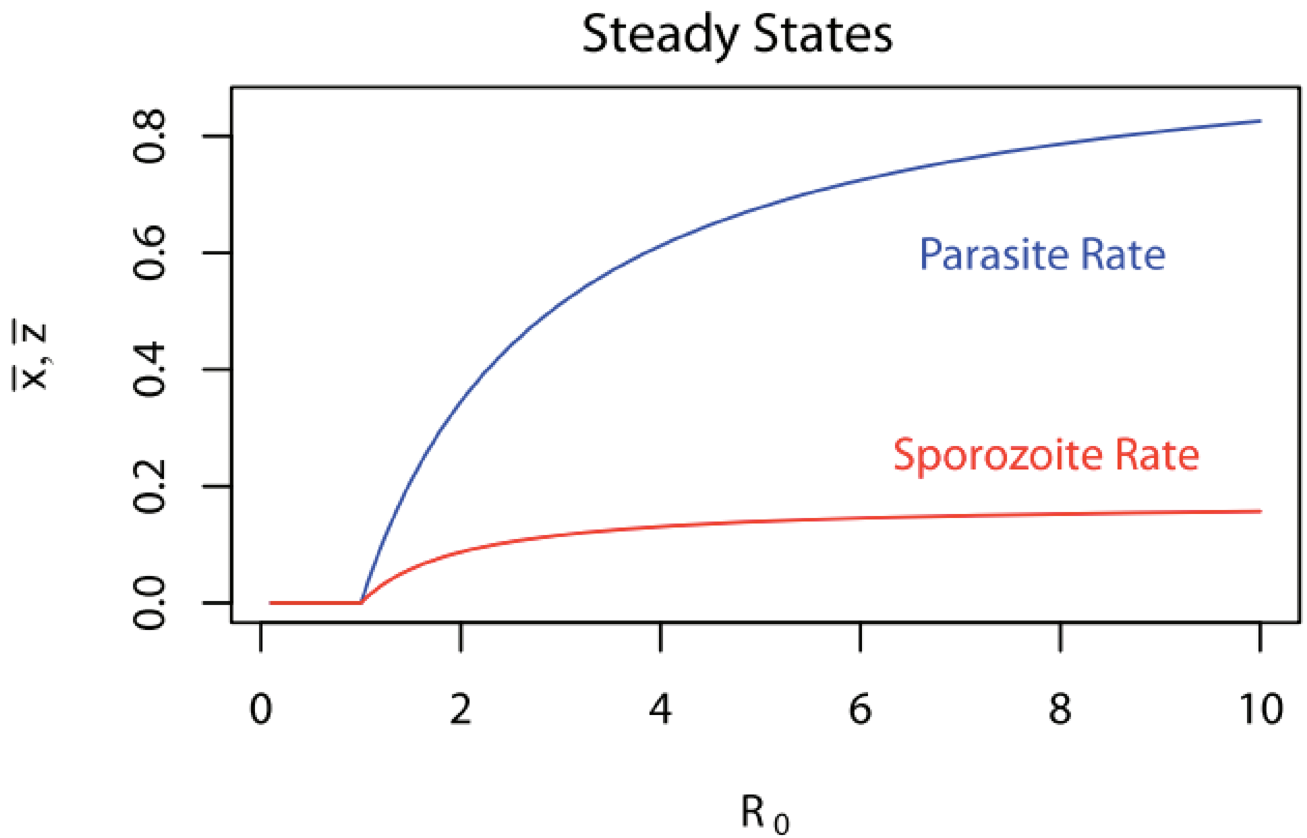
Time-at-Risk (TaR)



$$
\boldsymbol{\Psi} = \begin{array}{c} \\ \mathrm{V1} \leftrightarrow \mathrm{F} \\ \mathrm{V1\ only} \\ \mathrm{V2} \leftrightarrow \mathrm{F} \\ \mathrm{V2\ only} \\ \mathrm{V3} \leftrightarrow \mathrm{F} \\ \mathrm{V3\ only} \\ \mathrm{V4} \leftrightarrow \mathrm{F} \\ \mathrm{V4\ only} \end{array}
\begin{array}{c}
\begin{array}{cccccc} \mathrm{V1} & \mathrm{V2} & \mathrm{V3} & \mathrm{V4} & \mathrm{F1} & \mathrm{F2} \end{array} \\
\begin{bmatrix}
0.3 & 0 & 0 & 0 & 0.4 & 0.3 \\
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.6 & 0 & 0 & 0 & 0.4 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.8 & 0 & 0 & 0.2 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.2 & 0.8 & 0 \\
0 & 0 & 0 & 1 & 0 & 0
\end{bmatrix}
\end{array}
$$

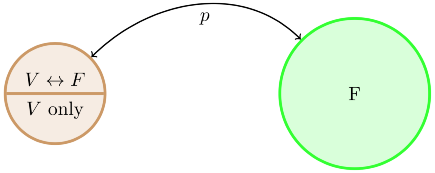
How Forest R and Time-at-Risk Affect Village Transmission

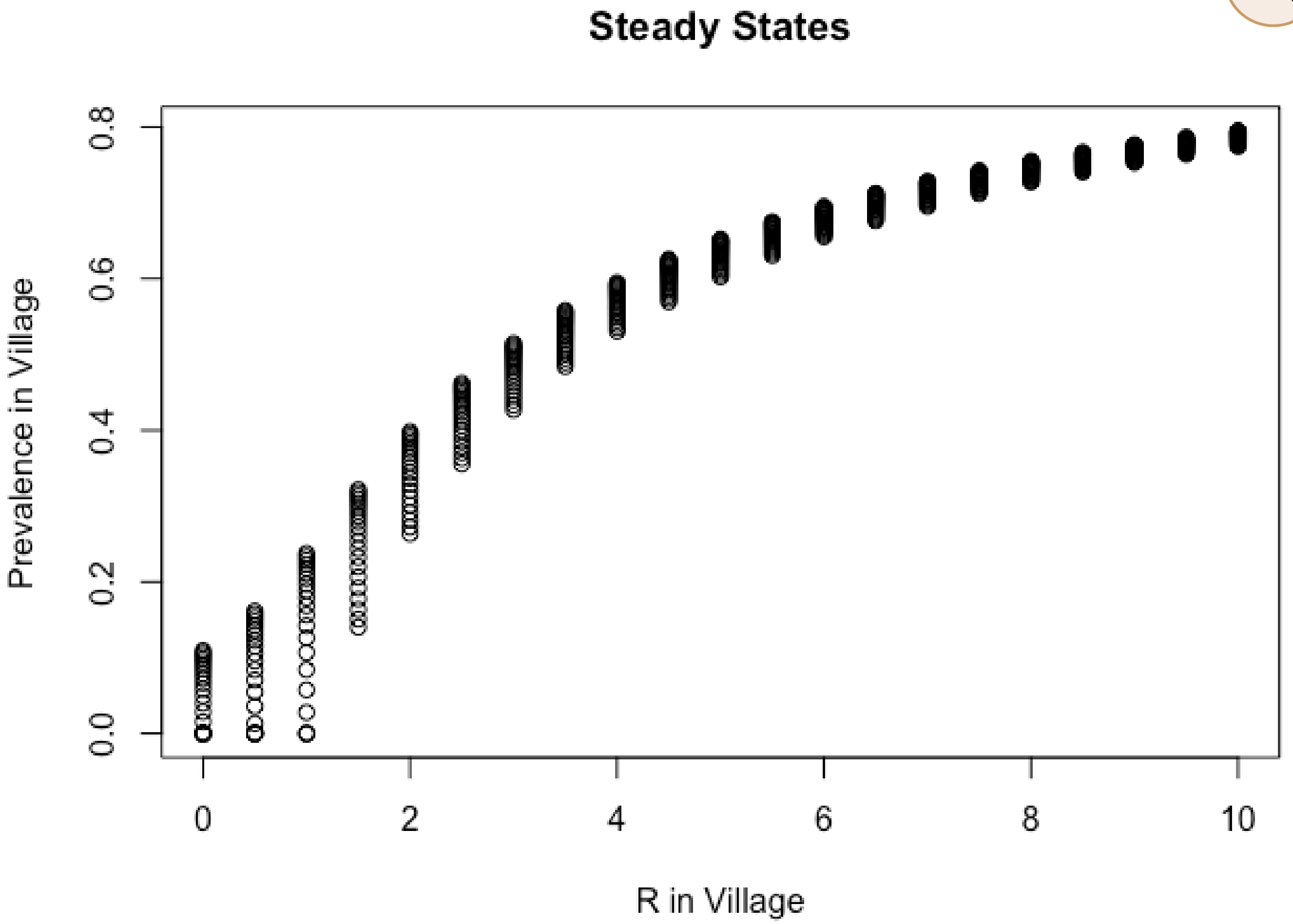
Traditional Model



Every R value has an associated steady state prevalence
(derived from parasite rate)

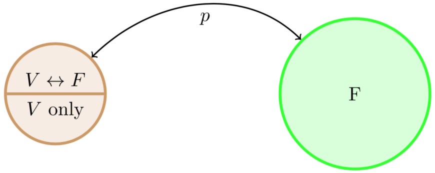
Forest Model – Effect of Forest R

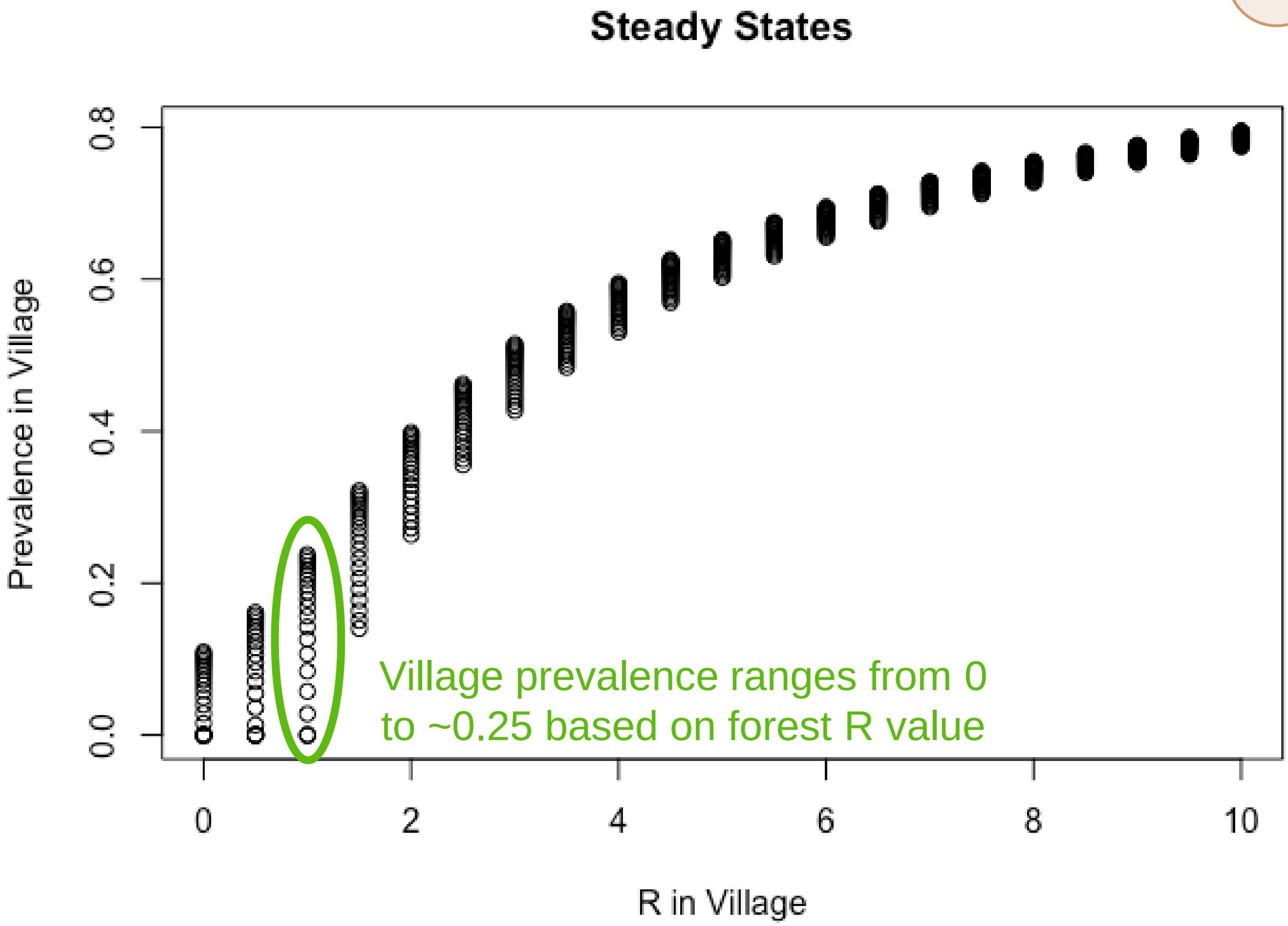




Village prevalence at given R value <u>depends on R value in the forest</u>

Forest Model – Effect of Forest R

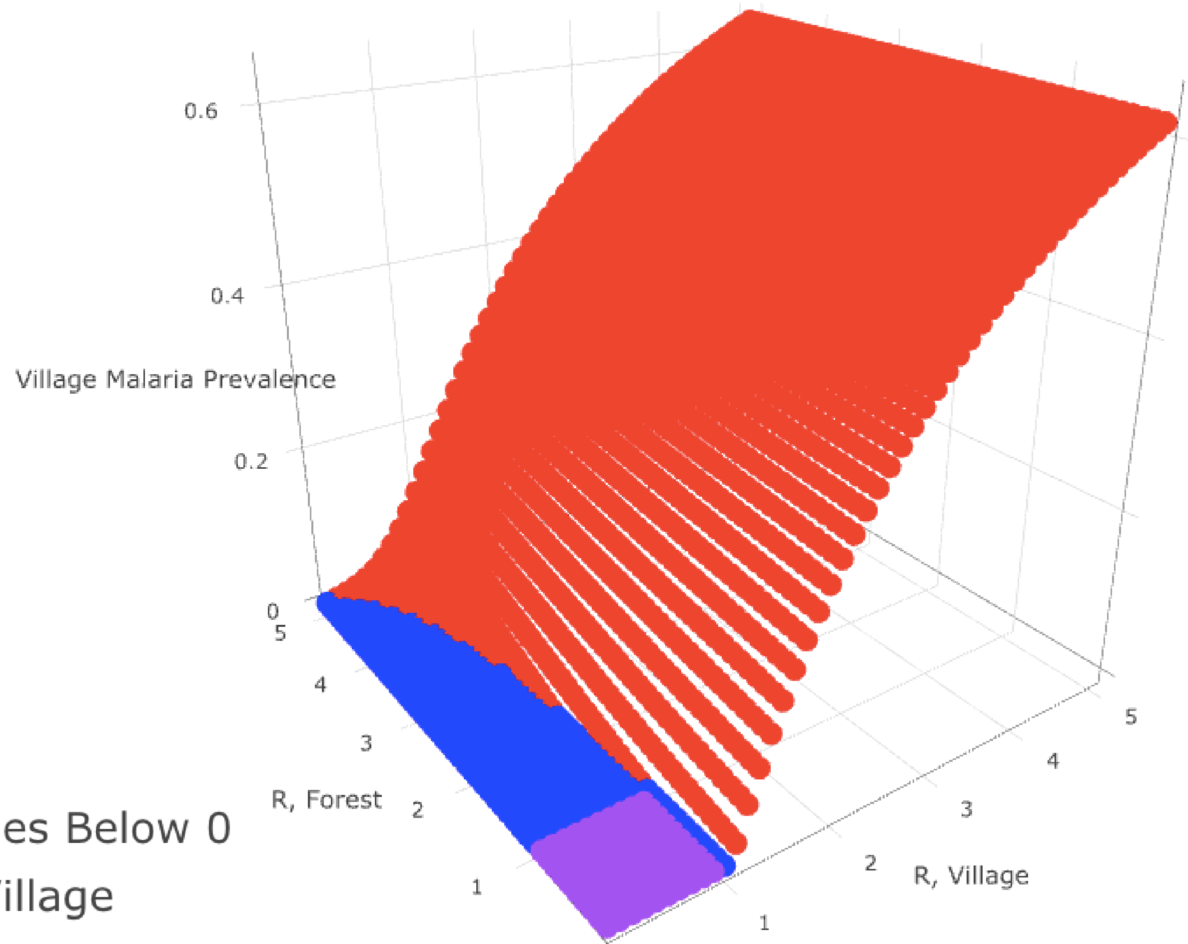




Village prevalence at given R value depends on R value in the forest

Forest Model – Effect of Time-at-Risk

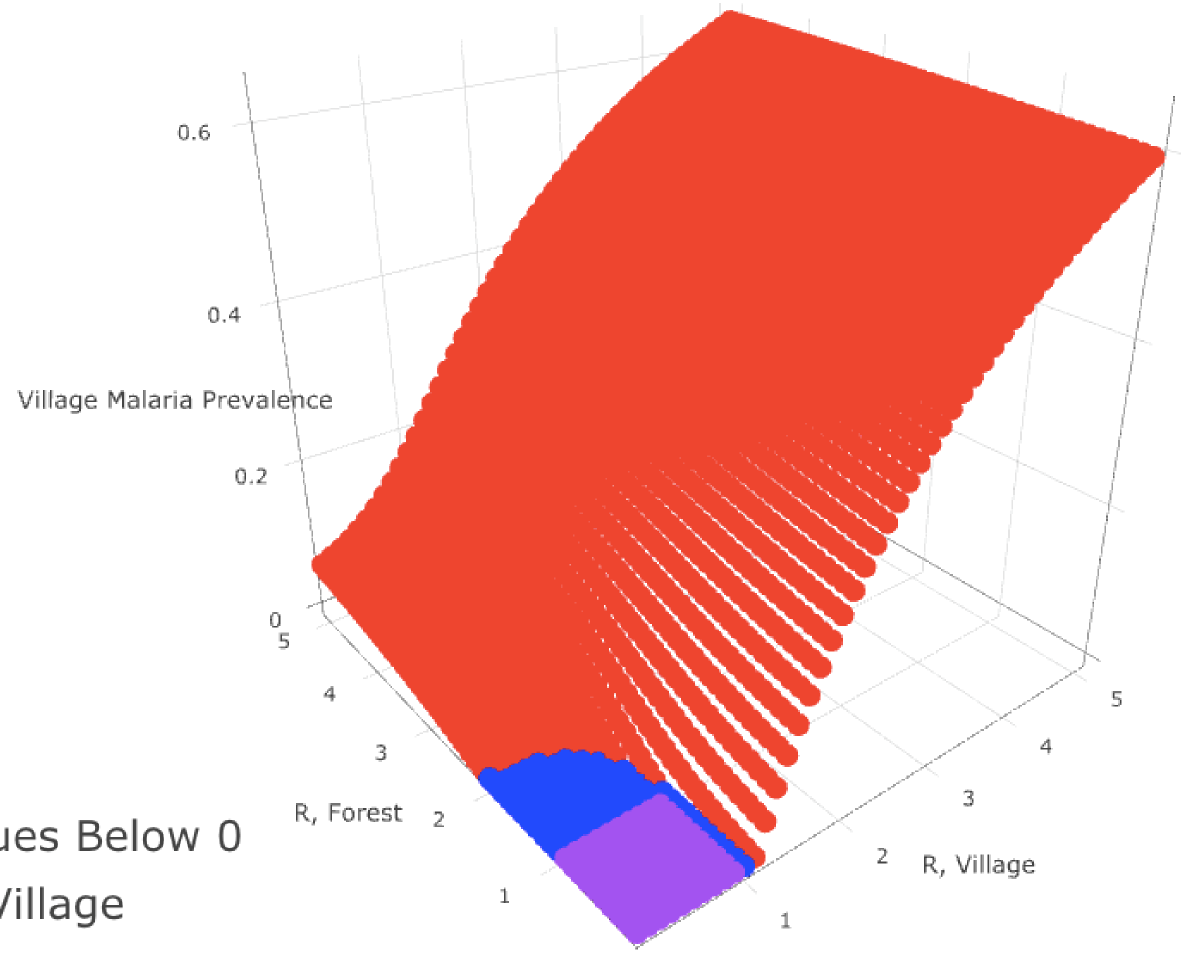
p = 0.2



- Both R Values Below 0
- Malaria in Village
- No Malaria in Village

Forest Model – Effect of Time-at-Risk

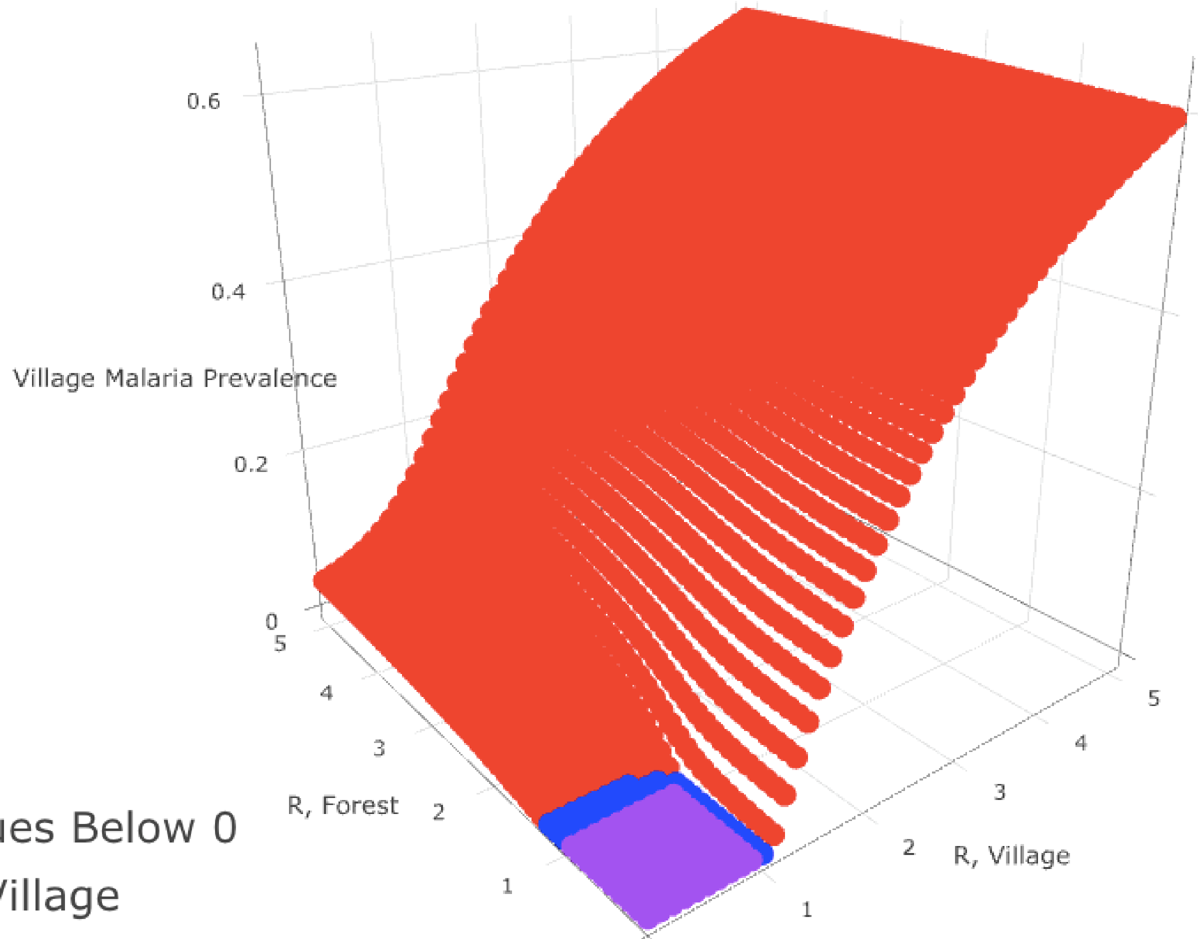
p = 0.5



- Both R Values Below 0
- Malaria in Village
- No Malaria in Village

Forest Model – Effect of Time-at-Risk

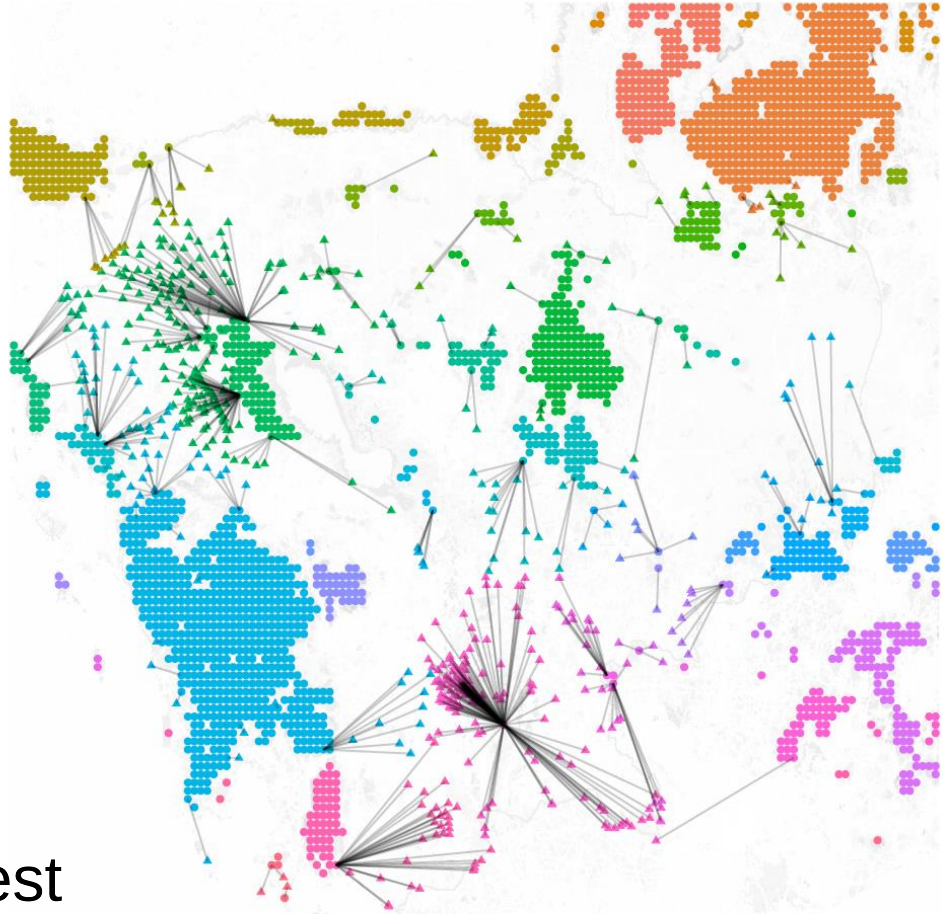
p = 0.8



- Both R Values Below 0
- Malaria in Village
- No Malaria in Village

Next Steps

Data, Data, Data



Connecting villages to closest forest by travel time

Sources:
Satellite landcover data,
OSM village locations,
Friction travel surface

Data, Data, Data

Table 1.4: Details of travellers, risk zones 1-4

	Total		Domain 1		Domain 2	
	N	% [95% CI]	N	% [95% CI]	N	% [95% CI]
	3,906	**100**	**2,013**	**100**	**1,893**	**100**
Last travelled away from home						
Last night	110	3.1 [2.1, 4.6]	47	2.6 [1.4,4.6]	63	3.8 [2.3, 6.2]
<1 week	836	20.3 [17.6, 23.4]	400	18.8 [15.2, 23.1]	436	22.0 [18.1, 26.5]
1-<4 weeks	1,040	25.5 [22.6, 28.6]	582	27.3 [23.4, 31.7]	458	23.4 [19.3, 28.0]
≥4 weeks	1,831	48.6 [44.5, 52.8]	943	49.3 [43.9, 54.8]	888	47.9 [41.6, 54.2]
Not specified	89	2.4 [1.6, 3.6]	41	1.9 [1.1, 3.5]	48	3.0 [1.7, 5.0]
Reasons for travel						
Work in forest	342	8.9 [6.9, 11.4]	130	6.3 [3.8, 10.3]	212	11.7 [8.8, 15.5]
Work on ***chamkar***/plantation	918	22.8 [17.7, 29.0]	291	14.3 [8.8, 22.4]	627	32.4 [24.5, 41.5]
Visit relatives	552	13.1 [10.8, 15.8]	325	14.1 [10.7, 18.4]	227	12.0 [9.3, 15.3]
Other	1,512	40.0 [34.1, 46.2]	805	42.4 [32.8, 52.7]	707	37.3 [31.7, 43.2]
Trips away from home past 3 months						
1-2	2,689	69.5 [66.1, 72.8]	1,500	74.8 [70.5, 78.6]	1,189	63.7 [58.1, 69.0]
3-5	669	17.2 [14.6, 20.0]	267	13.8 [10.4, 18.1]	402	20.9 [17.4, 25.0]
6-10	221	5.2 [4.0, 6.8]	95	4.2 [3.0, 5.9]	126	6.3 [4.3, 9.3]
>10	95	2.4 [1.9, 3.1]	30	1.4 [0.9, 2.2]	65	3.5 [2.5, 4.8]
Not specified	232	5.7 [4.5, 7.0]	121	5.8 [4.4, 7.6]	111	5.6 [3.9, 7.8]
Countries visited in 2013						
Laos, Thailand, Vietnam	811	21.4 [15.7, 28.5]	594	30.2 [19.9, 42.9]	217	11.6 [8.3,15.9]

Travel surveys

Source:
Cambodia Malaria Survey 2013

Data, Data, Data

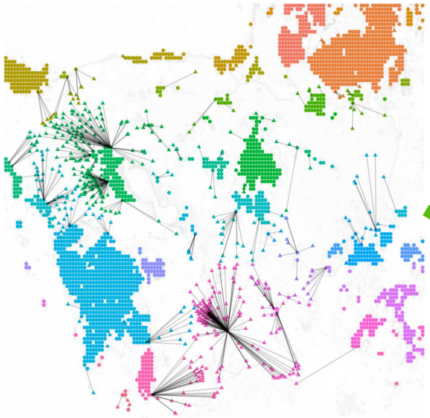


Table 1.4: Details of travellers, risk zones 1-4

	Total		Domain 1		Domain 2	
	N	% [95% CI]	N	% [95% CI]	N	% [95% CI]
	3,906	100	2,013	100	1,893	100
Last travelled away from home						
Last night	110	3.1 [2.1, 4.6]	47	2.6 [1.4,4.6]	63	3.8 [2.3, 6.2]
<1 week	836	20.3 [17.6, 23.4]	400	18.8 [15.2, 23.1]	436	22.0 [18.1, 26.5]
1-<4 weeks	1,040	25.5 [22.6, 28.6]	582	27.3 [23.4, 31.7]	458	23.4 [19.3, 28.0]
≥4 weeks	1,831	48.6 [44.5, 52.8]	943	49.3 [43.9, 54.8]	888	47.9 [41.6, 54.2]
Not specified	89	2.4 [1.6, 3.6]	41	1.9 [1.1, 3.5]	48	3.0 [1.7, 5.0]
Reasons for travel						
Work in forest	342	8.9 [6.9, 11.4]	130	6.3 [3.8, 10.3]	212	11.7 [8.8, 15.5]
Work on *chamkar*/plantation	918	22.8 [17.7, 29.0]	291	14.3 [8.8, 22.4]	627	32.4 [24.5, 41.5]
Visit relatives	552	13.1 [10.8, 15.8]	325	14.1 [10.7, 18.4]	227	12.0 [9.3, 15.3]
Other	1,512	40.0 [34.1, 46.2]	805	42.4 [32.8, 52.7]	707	37.3 [31.7, 43.2]
Trips away from home past 3 months						
1-2	2,689	69.5 [66.1, 72.8]	1,500	74.8 [70.5, 78.6]	1,189	63.7 [58.1, 69.0]
3-5	669	17.2 [14.6, 20.0]	267	13.8 [10.4, 18.1]	402	20.9 [17.4, 25.0]
6-10	221	5.2 [4.0, 6.8]	95	4.2 [3.0, 5.9]	126	6.3 [4.3, 9.3]
>10	95	2.4 [1.9, 3.1]	30	1.4 [0.9, 2.2]	65	3.5 [2.5, 4.8]
Not specified	232	5.7 [4.5, 7.0]	121	5.8 [4.4, 7.6]	111	5.6 [3.9, 7.8]
Countries visited in 2013						
Laos, Thailand, Vietnam	811	21.4 [15.7, 28.5]	594	30.2 [19.9, 42.9]	217	11.6 [8.3,15.9]

$$\Psi = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \end{bmatrix}$$

Use data to build a realistic TaR matrix

Takeaways

- Standard Ross-Macdonald models are not sufficient for modeling forest malaria
- Time-at-Risk accounts for human travel and its impact on population definitions
- Transmission dynamics in the forest can have a large impact on transmission dynamics in the village
- Data from high and low level sources are needed to accurately represent the TaR matrix

Questions?