Early Warning System and Portfolio Decision Model for Infectious Diseases

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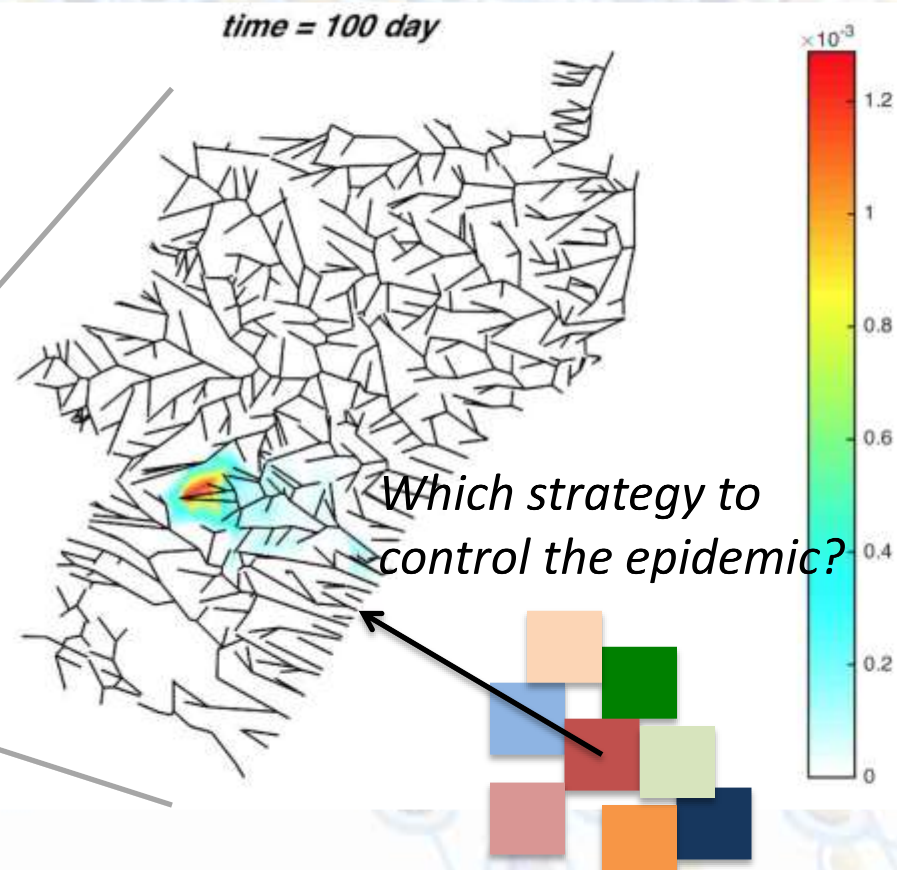
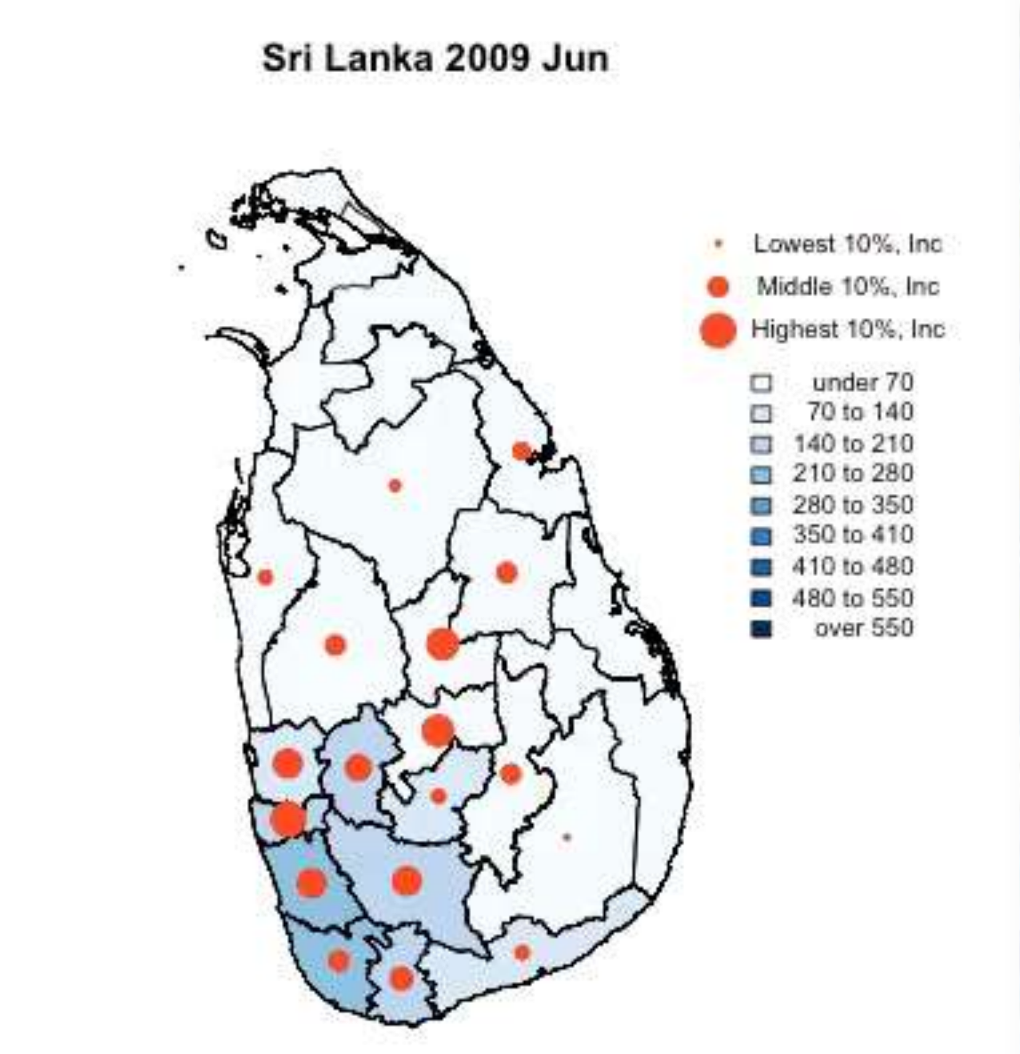
Portfolio Decision Modeling: Kolkata Case Study

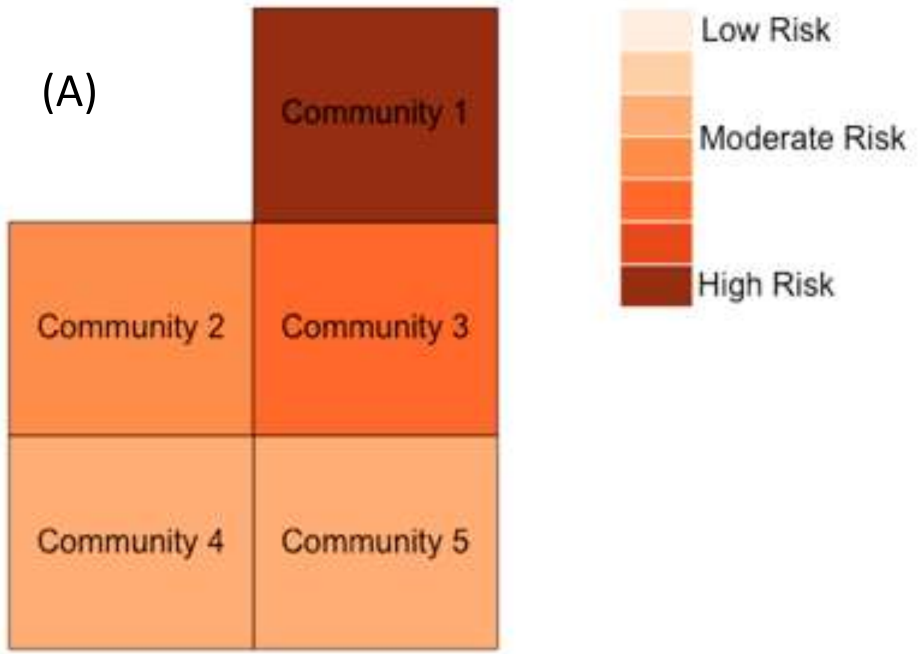


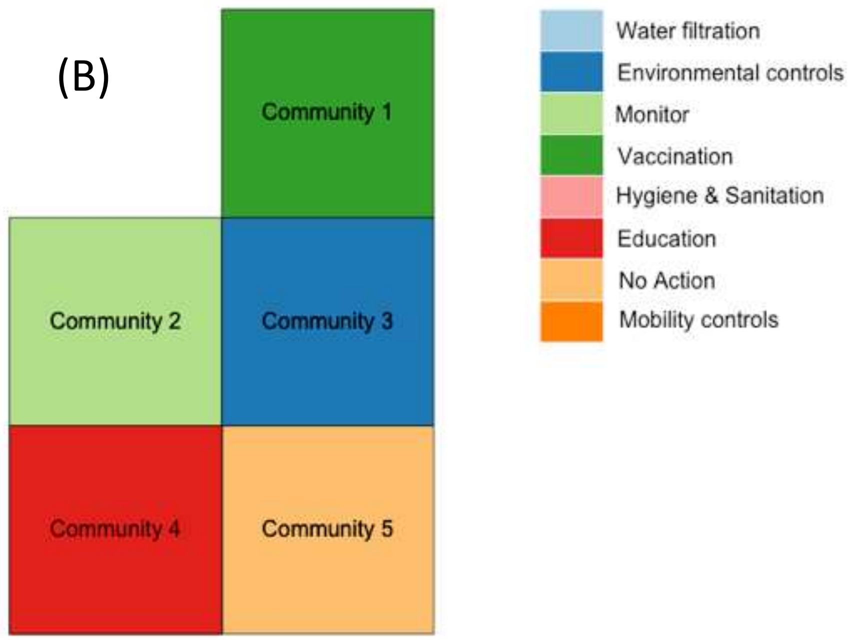
Which strategy to control the epidemic?

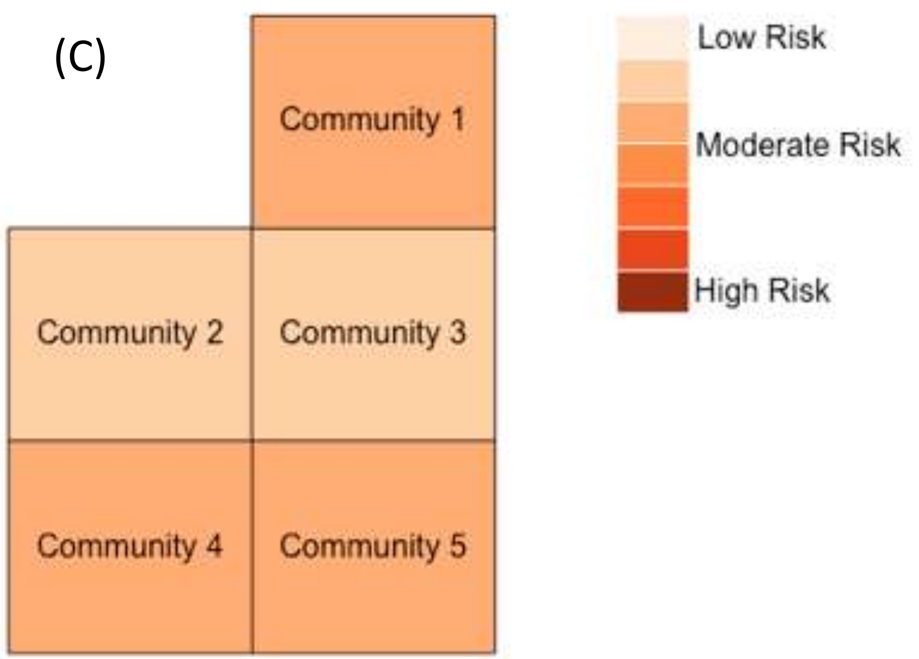
You et al., 2013, PLoS ONE
Convertino and Valverde, 2013, PLoS ONE
Convertino and Nardi, 2015, Nature Clim. C.



Reddy et al., 2015, submitted to PNAS



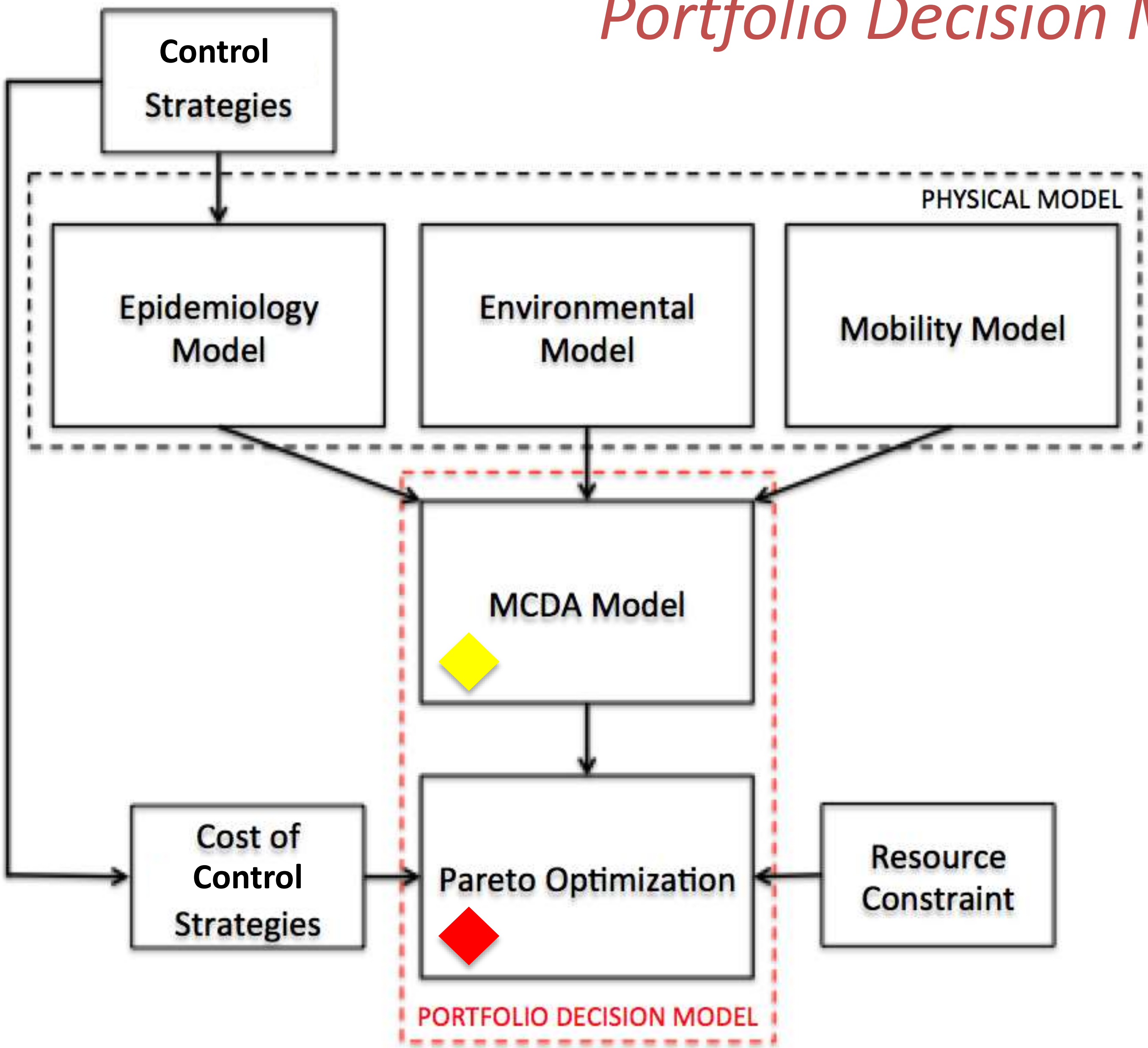




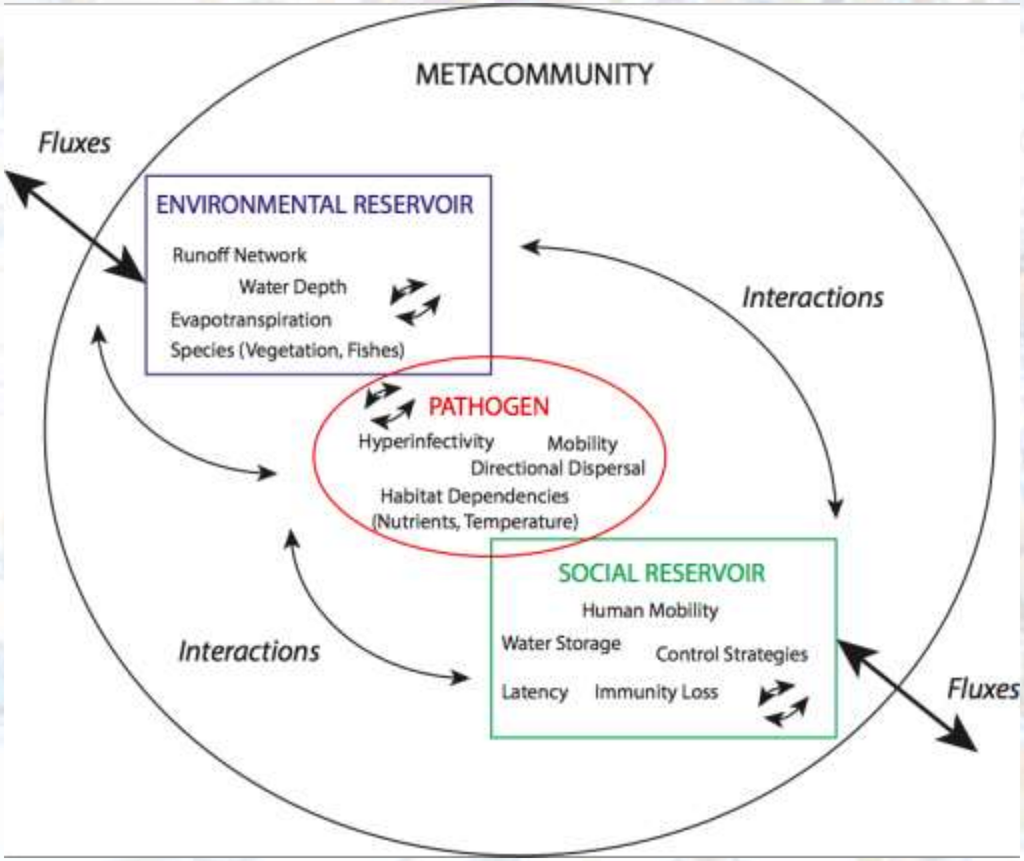
Visualization

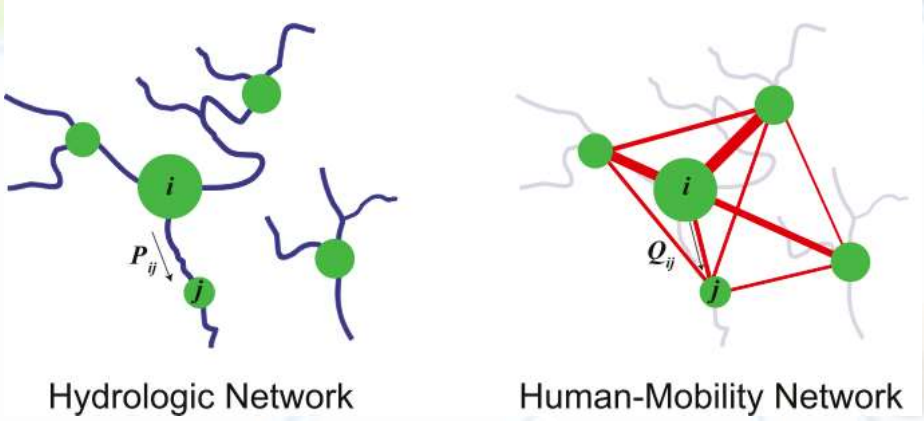
(A) Output of the physical model" expected system risk based on the epidemiology model, environmental and mobility model
(B) Output of the portfolio decision model, selection of the optimal control set at the community scale
(C) Portfolio controlled solution: Lowest systemic risk.

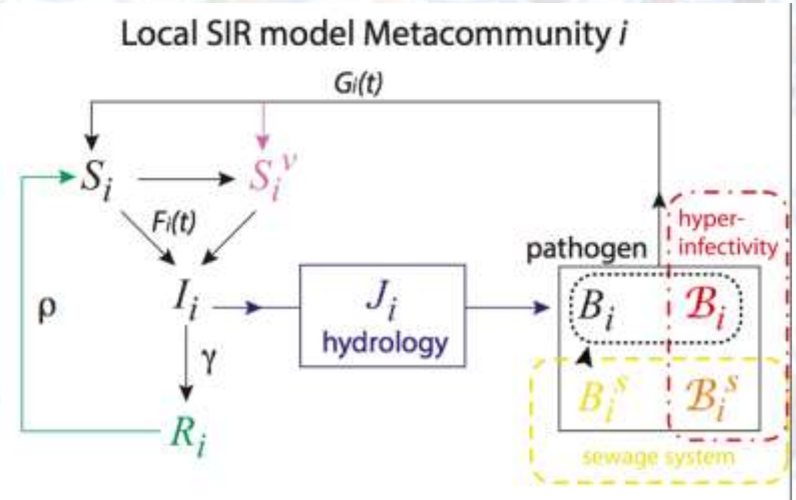
Portfolio Decision Model



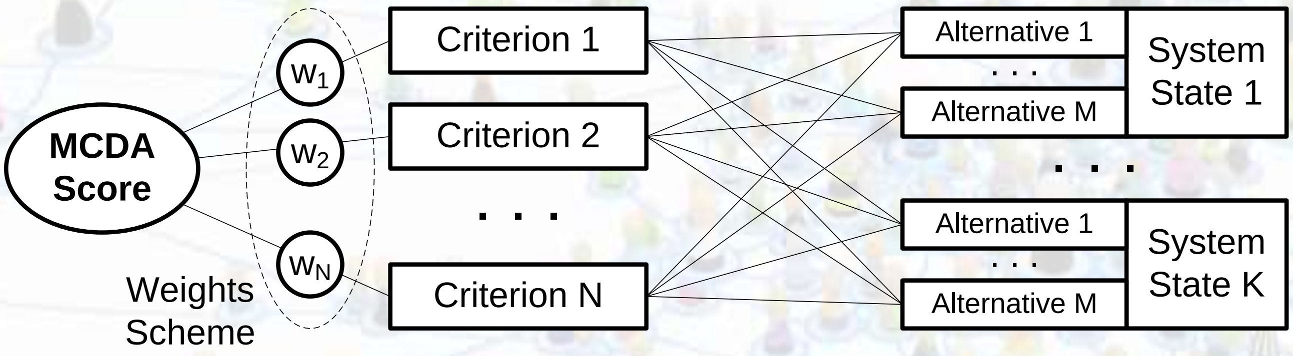
Convertino et al., 2014, WRR







MCDA



Alternatives	Criteria	System States			
		State 1	State 2	. . .	State K
Alternative 1	Criterion 1	$X_{1,1,1}$	$X_{2,1,1}$	. . .	$X_{K,1,1}$
	Criterion 2	$X_{1,1,2}$	$X_{2,1,2}$	. . .	$X_{K,1,2}$
	. . .	. . .	. . .	. . .	. . .
	Criterion N	$X_{1,1,N}$	$X_{2,1,N}$	. . .	$X_{K,1,N}$
. . .	. . .	. . .	. . .	$X_{k,m,n}$	. . .
Alternative M	Criterion 1	$X_{1,M,1}$	$X_{2,M,1}$	. . .	$X_{K,M,1}$
	Criterion 2	$X_{1,M,2}$	$X_{2,M,2}$	. . .	$X_{K,M,2}$
	. . .	. . .	. . .	. . .	. . .
	Criterion N	$X_{1,M,N}$	$X_{2,M,N}$	. . .	$X_{K,M,N}$

Local Population-adjusted Risk

Alternative Effectiveness ~Efficacy

$$V^*_{m,j}(\underline{R}) = (1 - \boxed{v_j(\underline{R})}) \boxed{f_{i(j)}} R_{i(j),m} \, V_{m,j}(\underline{R})$$

Population Vulnerability (if available and meaningful)

~Urgency

Systemic Risk

Stakeholder Preferences

$$V_T(\underline{R}) = \sqrt{\sum_{m=1}^{M} \sum_{j=1}^{J} (V^*_{m,j}(\underline{R}) \boxed{w_j})^2} =$$

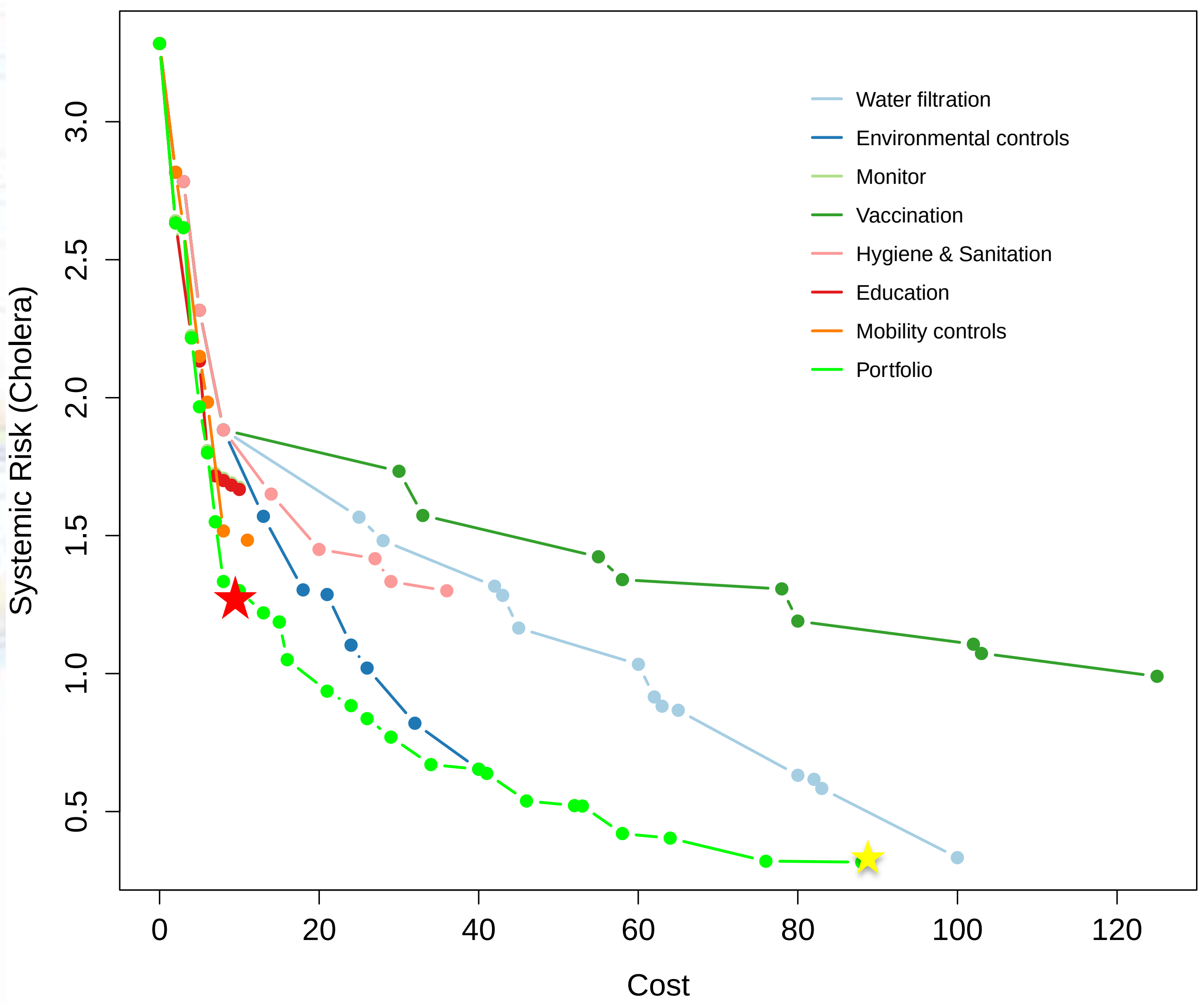
$$= \sqrt{V_N(\underline{R})^2 + V_H(\underline{R})^2}$$

m=disease management alternative
i=site
j=criteria or ecosystem services (e.g., incidence, water quality)

Is there an efficacy/effectiveness of control alternatives?

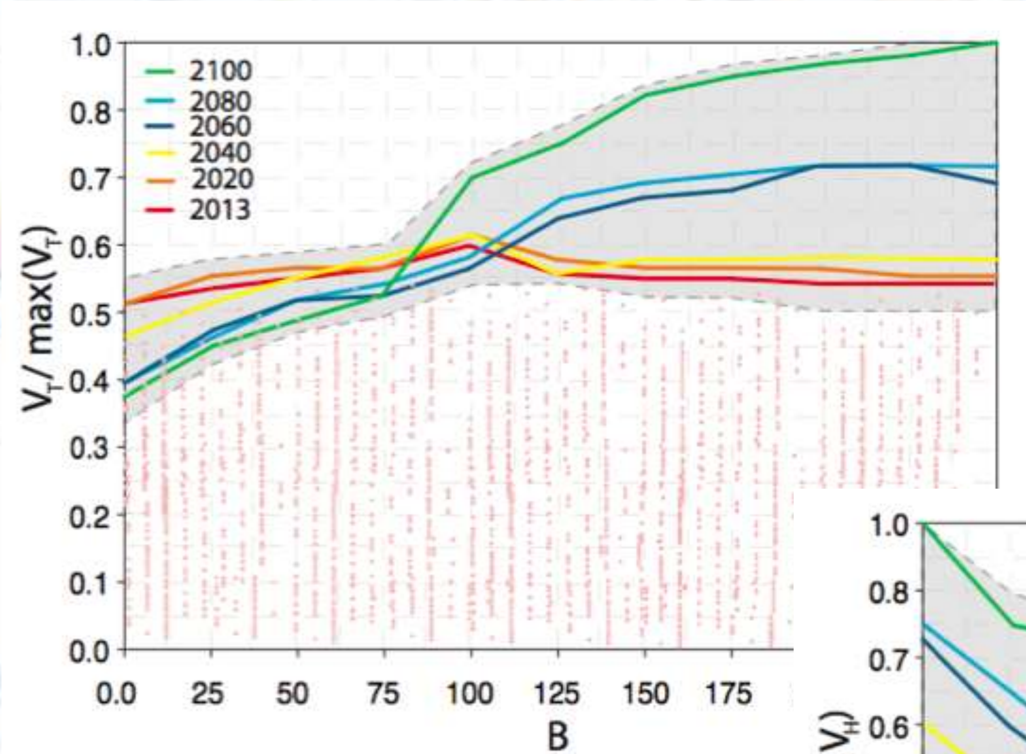
Is there history of disease management strategies?

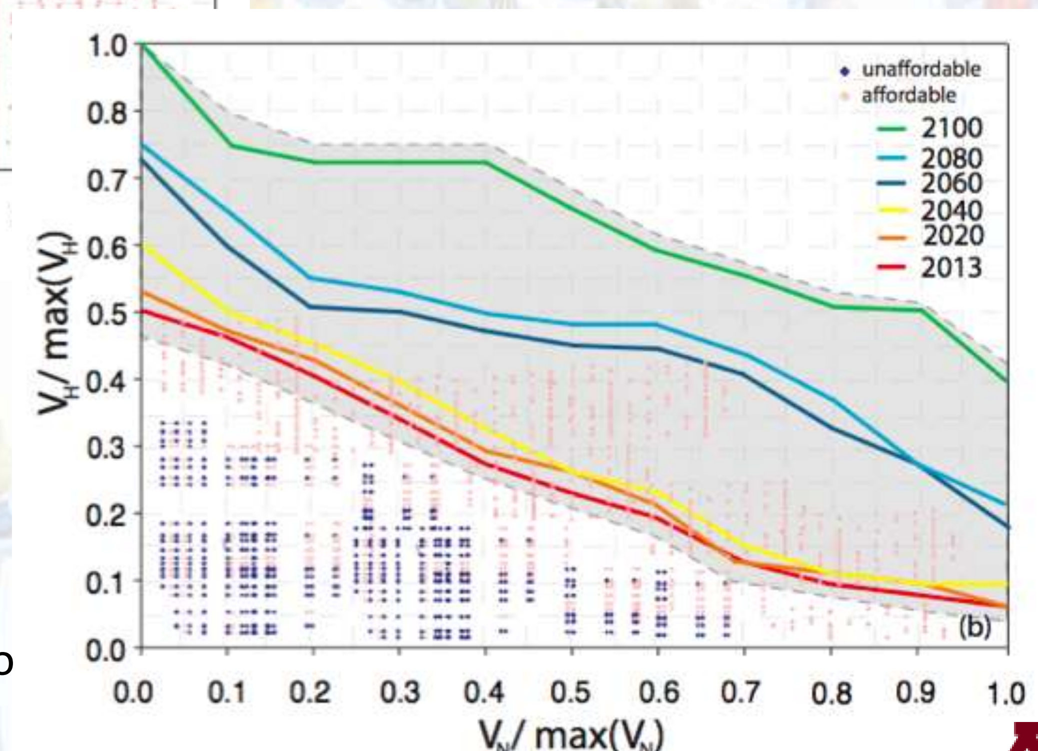
Portfolio Optimality



Yang et al., 2015, in prep

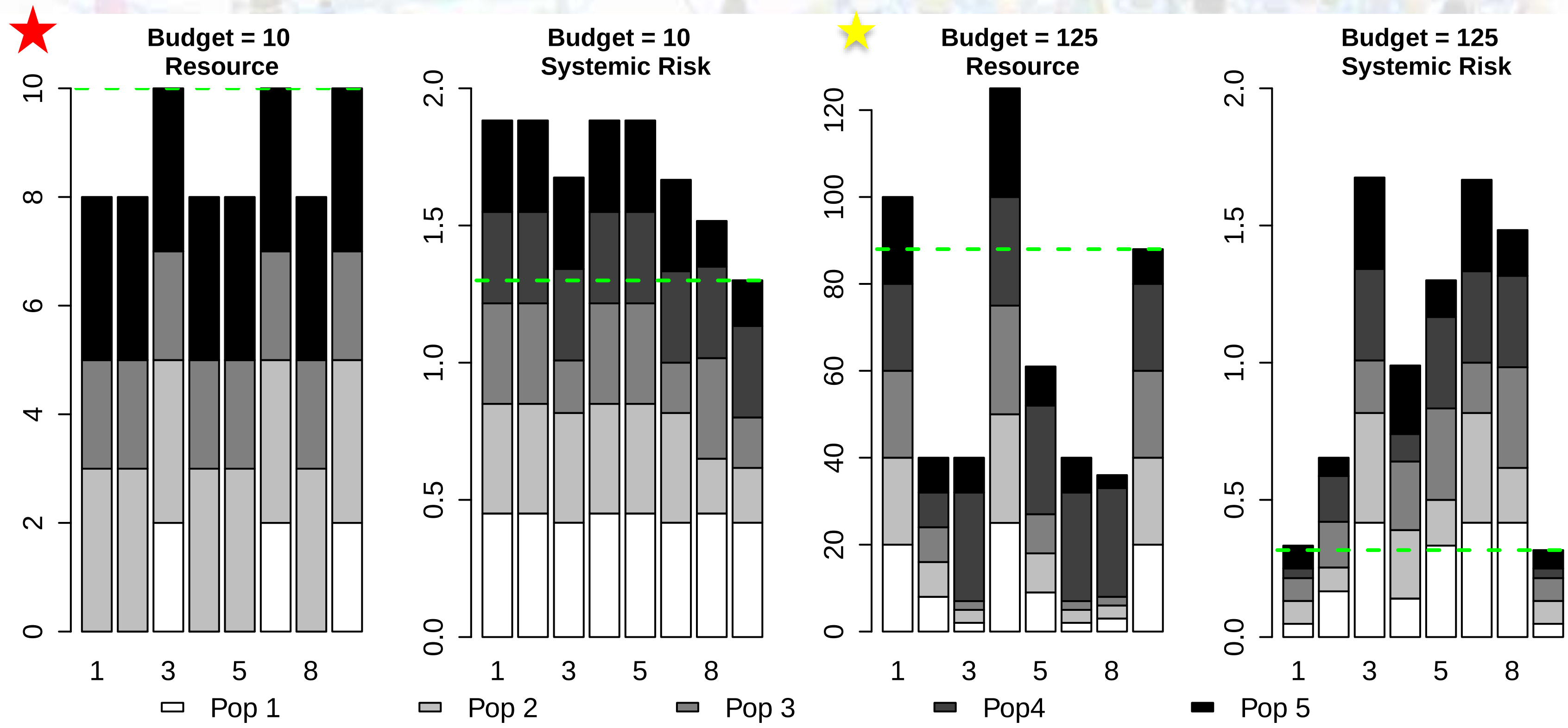
Pareto Frontiers considering urban and rural benefits



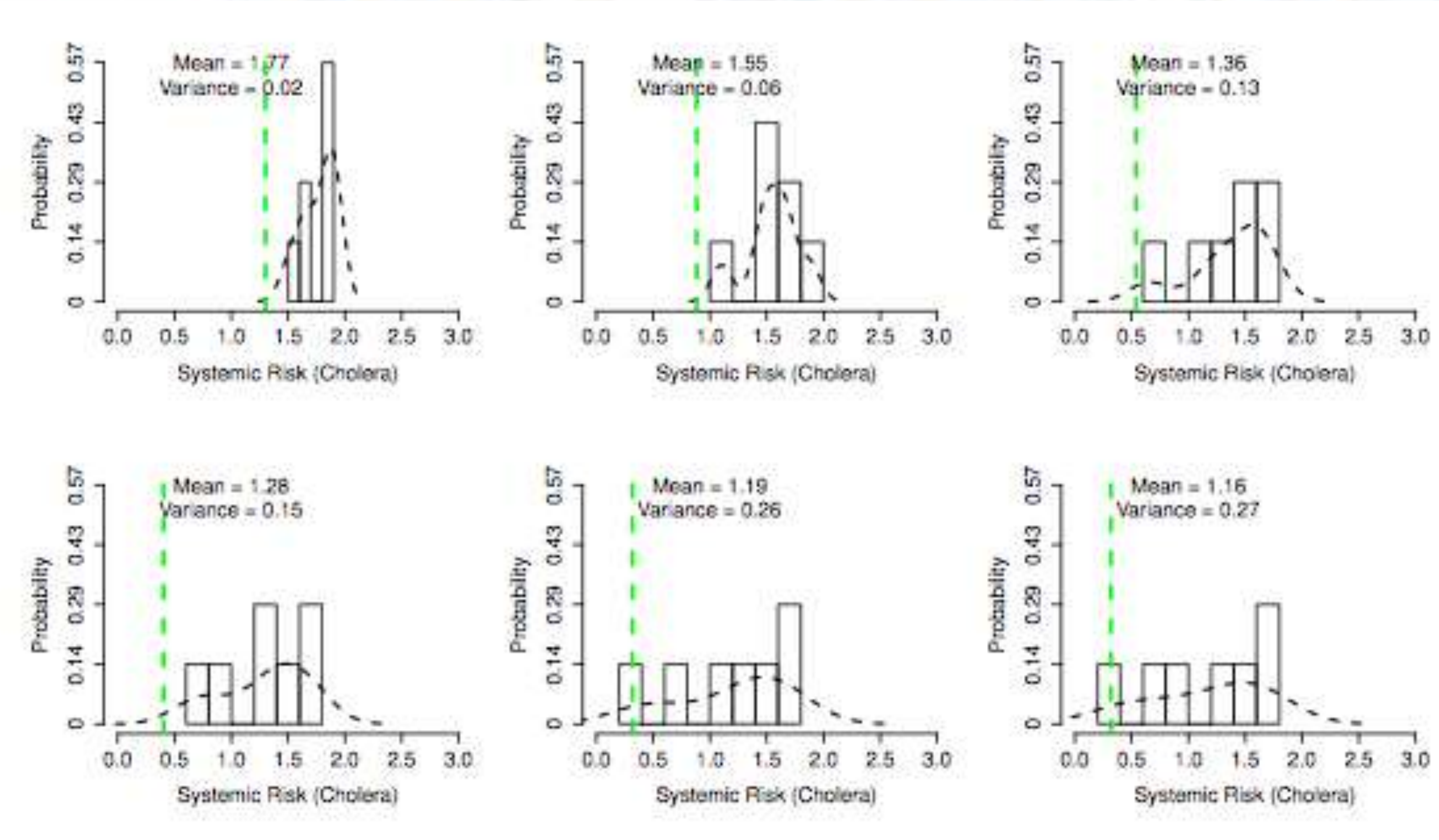


The relative values of urban and rural populations are assessed in the portfolio considering stakeholder preferences

Budget and Risk Diversification

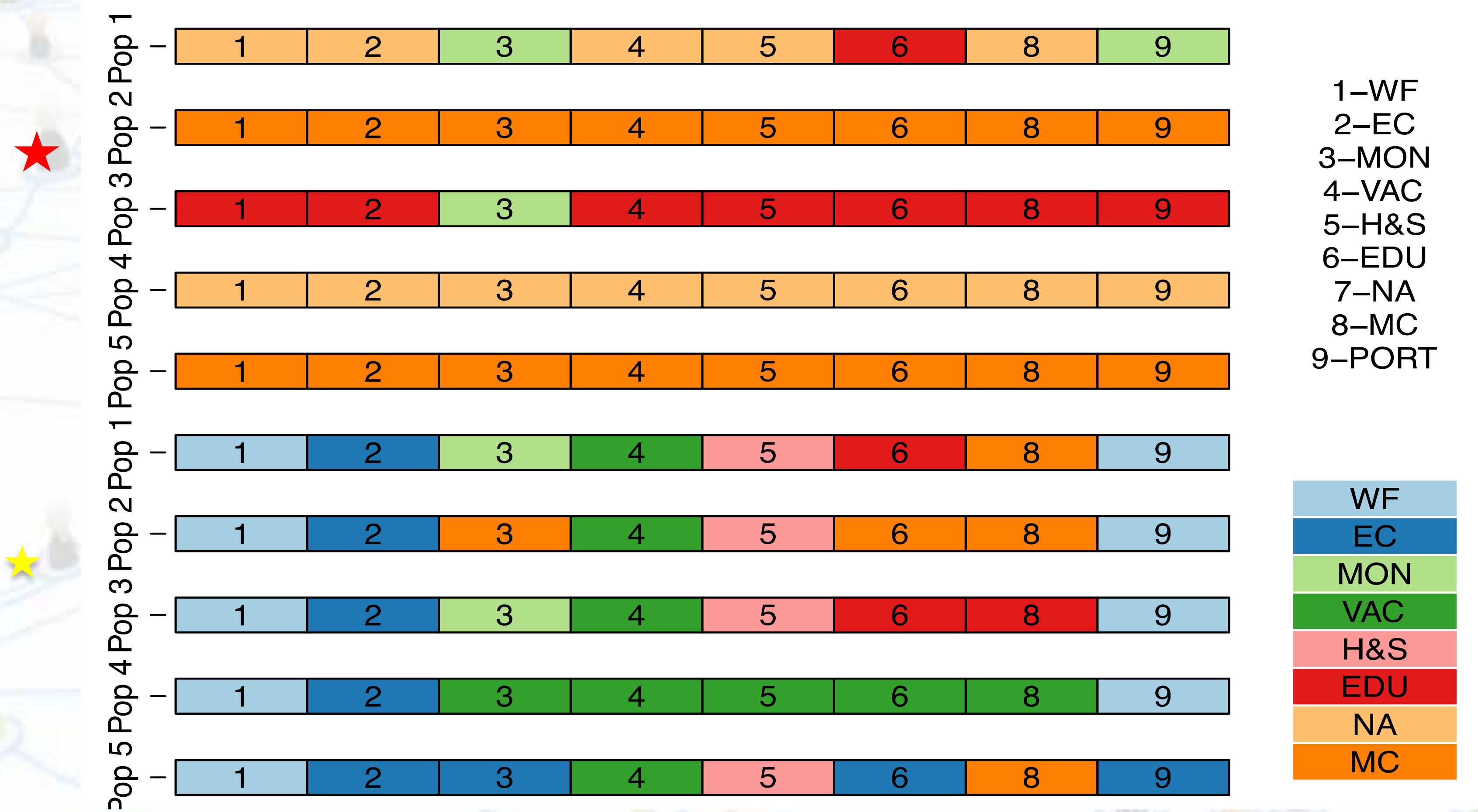


The lower the budget the lower the expense of the portfolio and the higher the risk



Green=portfolio solution

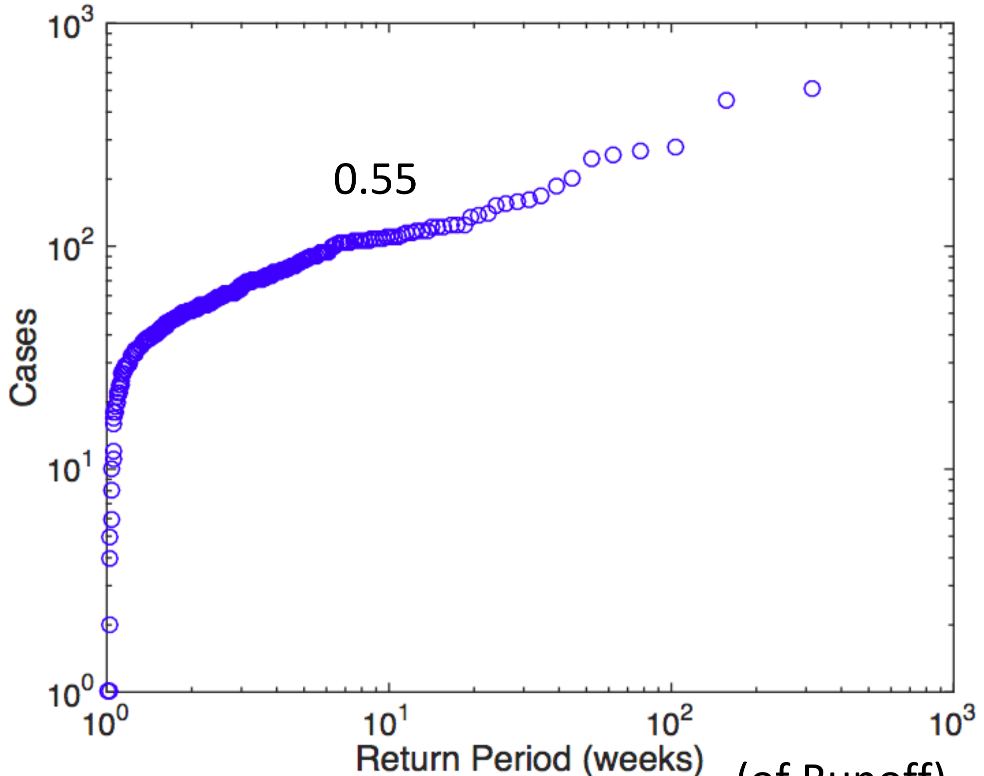
Pareto Optimal Strategies



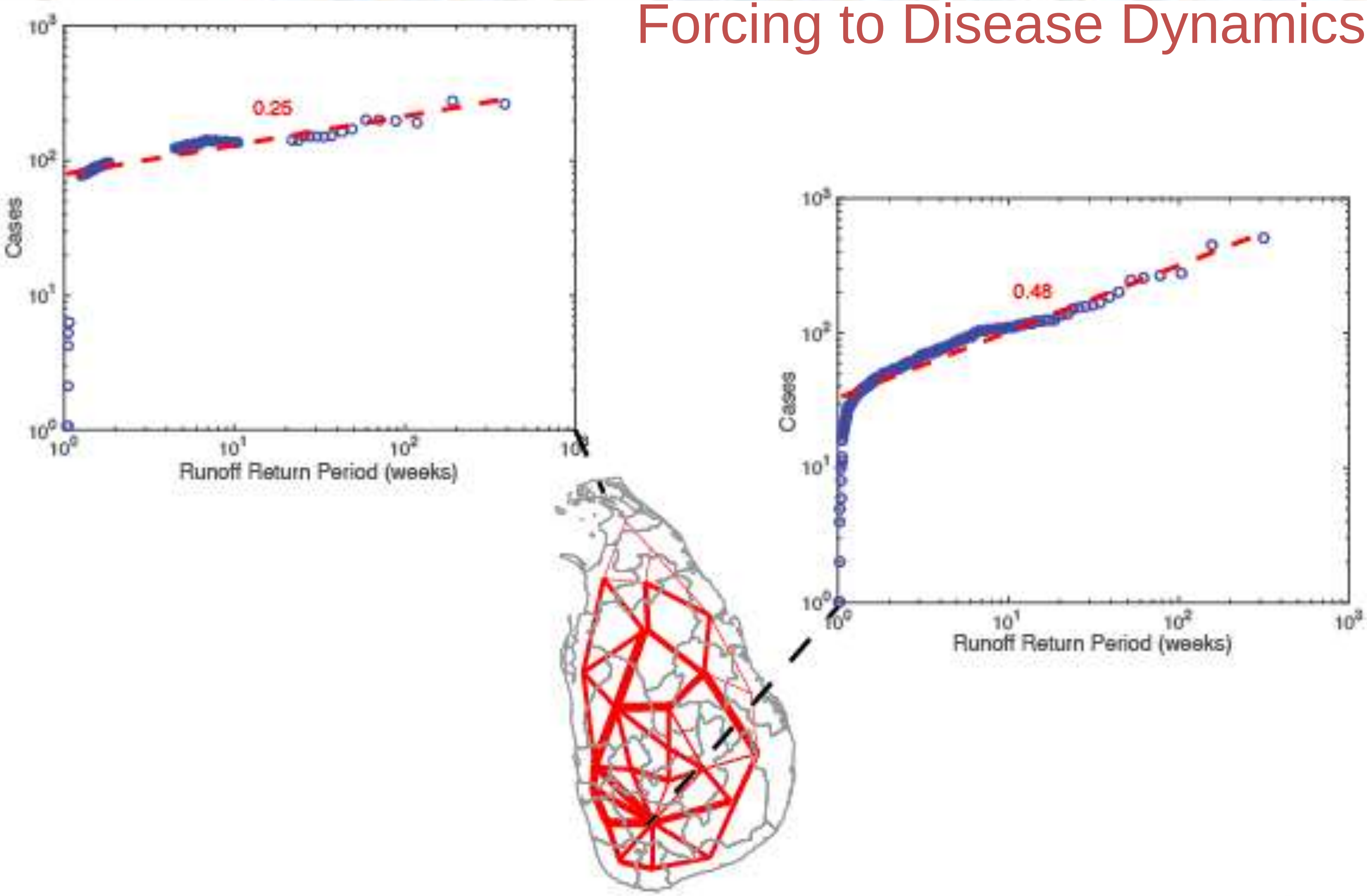
Monocontrol is not selecting one alternative a priori vs. a priori selected alternatives (in the latter scenario budget constraint may not allow to select the imposed alternative)

Portfolio does allow multiple alternatives

Scaling Epidemiology

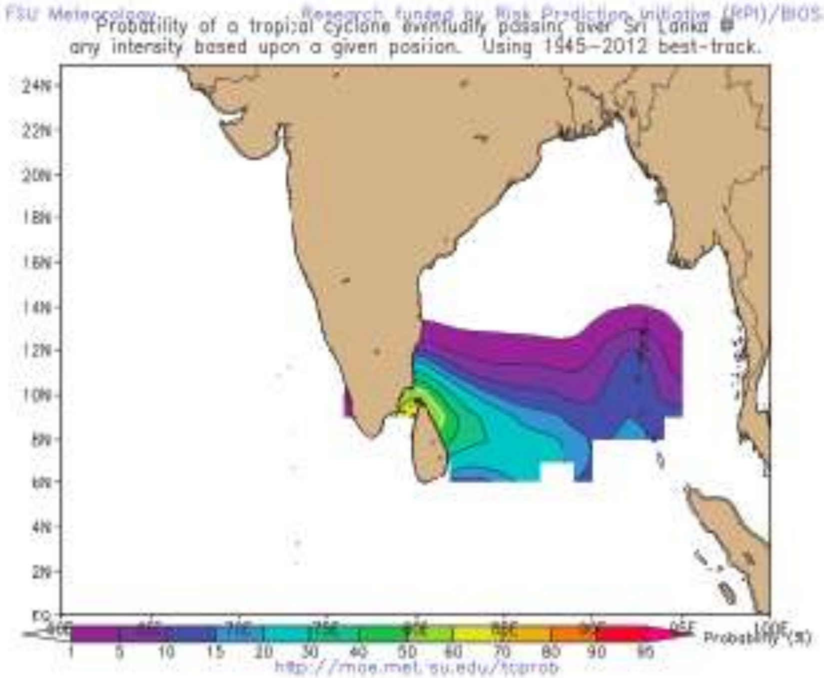


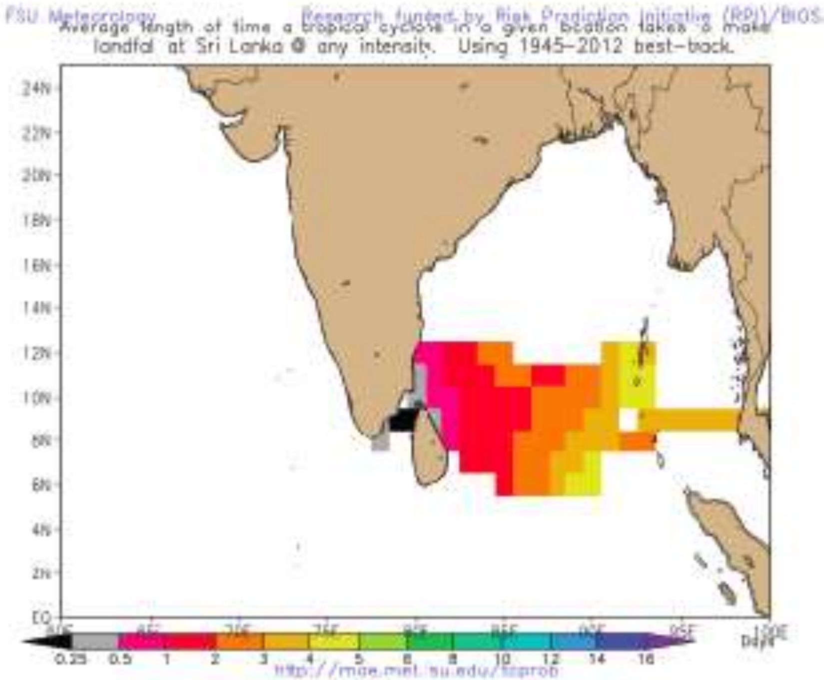
From Large Scale Forcing to Disease Dynamics

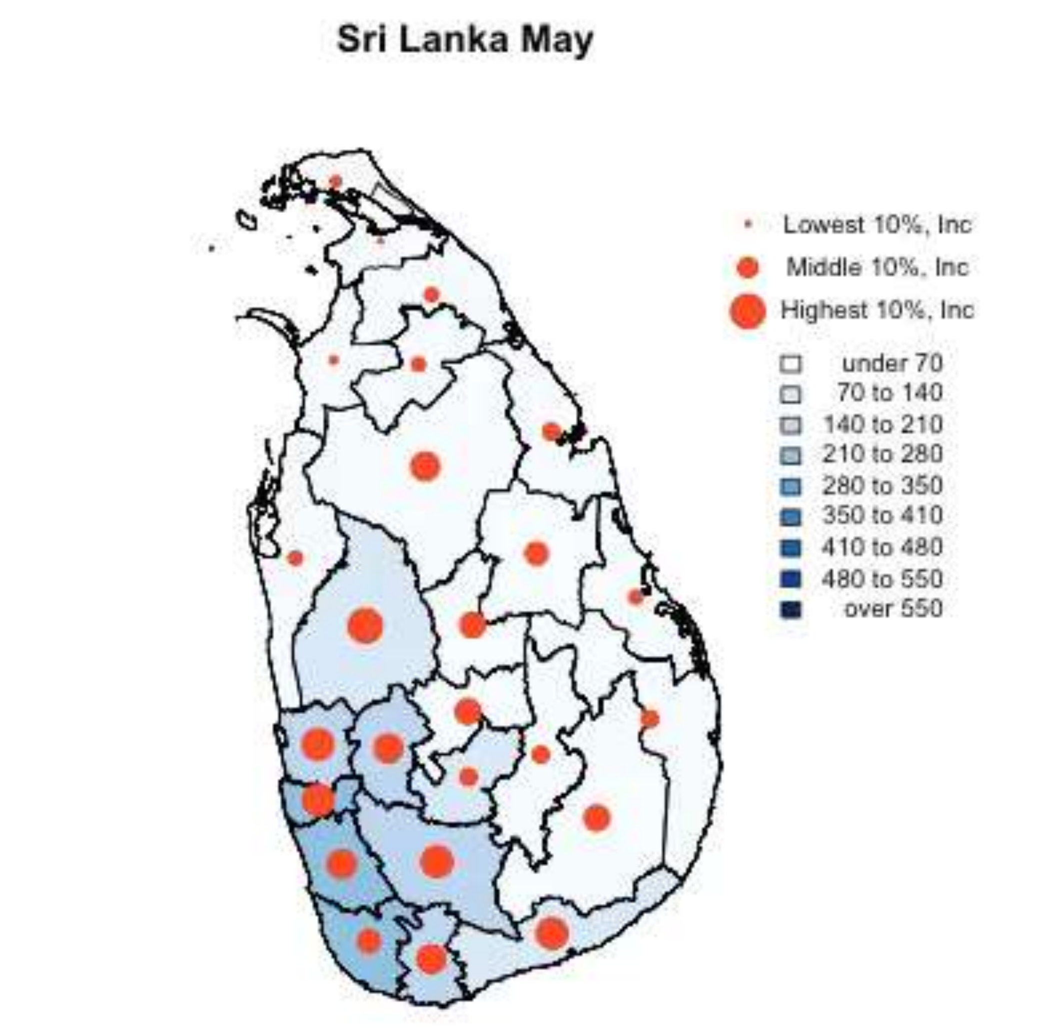


From Large Scale

Forcing to Disease Dynamics

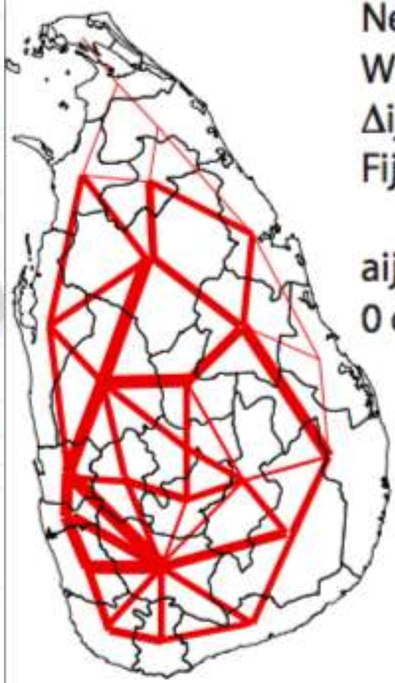






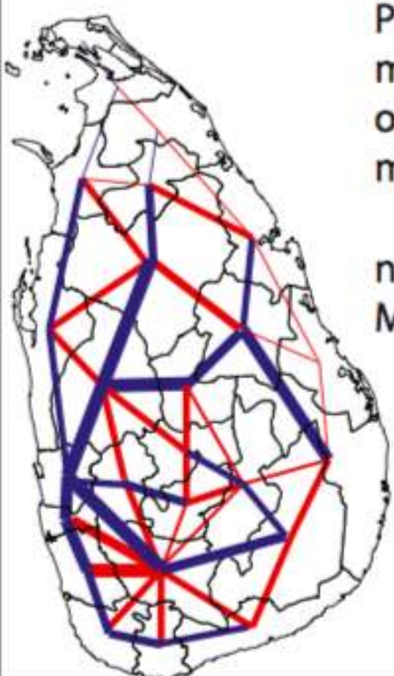
Reddy et al., 2015, submitted to PNAS

Optimal Transmission Networks (OTN)



Nearest Neighborhood Model
Wij ~ 1/Δij (width)
Δij=|Ci-Cj| (gradient of cases)
Fij=1/Δij (fluxes)

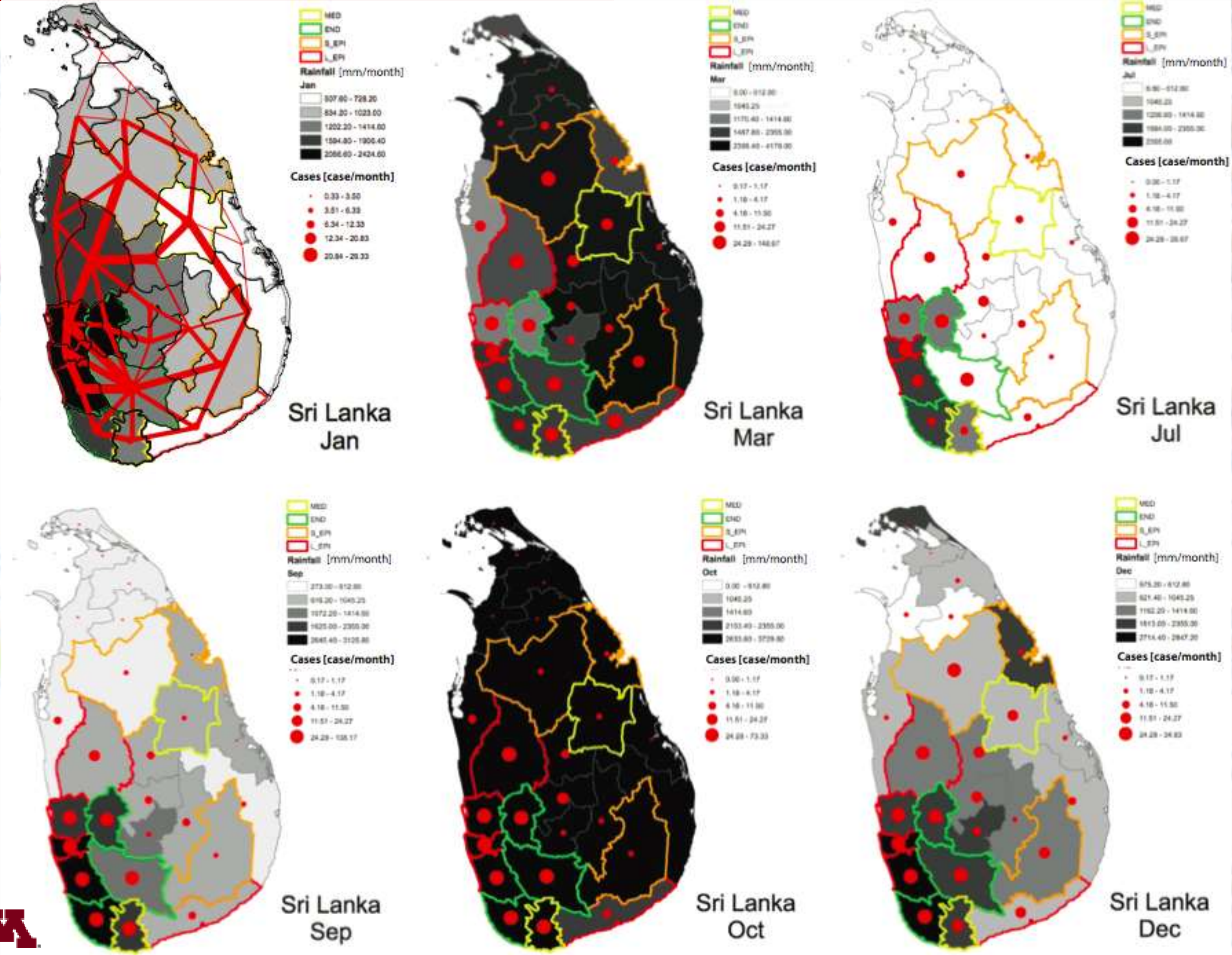
aij=1 if j adjacent to j
0 otherwise



Preferential Case Pathways (at a closure point)
max Wij ~ 1/Δij
or min Δij=|Ci-Cj|
max(Fij)=1/min(Δij)

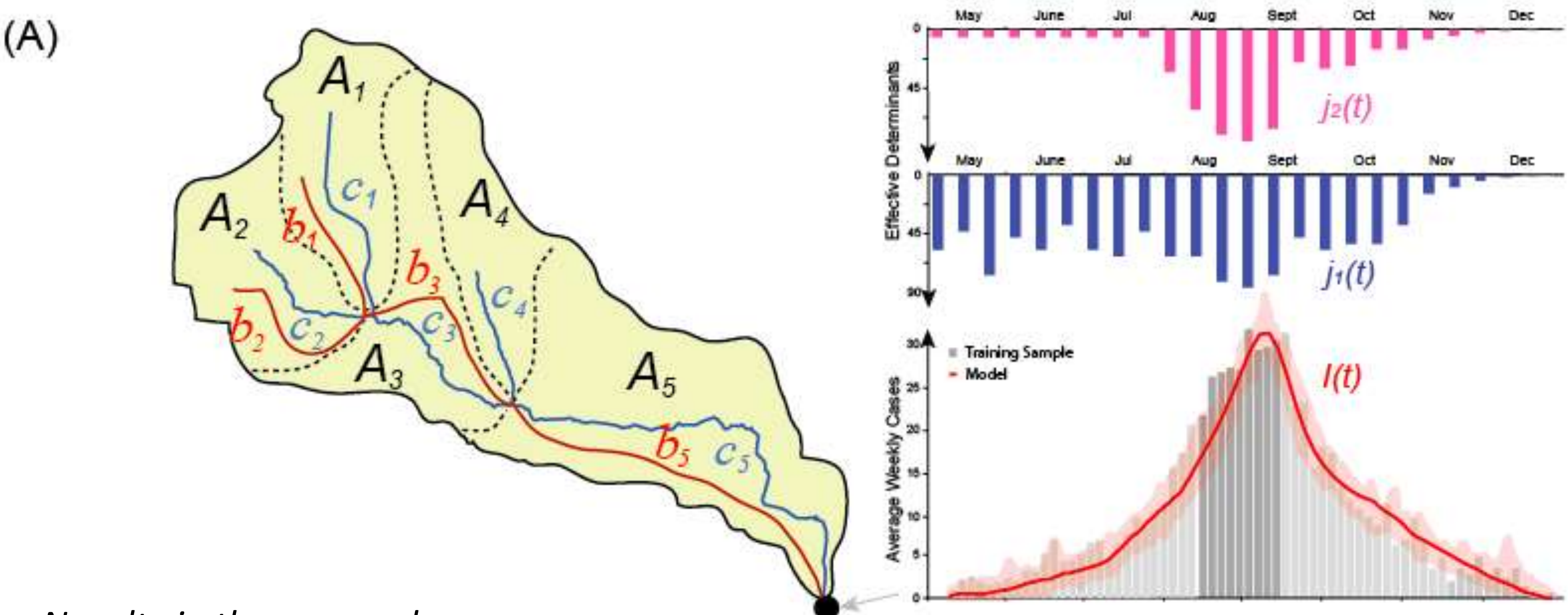
non looping network
Minimum Spanning Tree

Here OTN is an optimal recurrence network of cases.
The resolution is too coarse to map this functional network back to a structural network of transmission.



MED
END
S_EPI
L_EPI
Rainfall [mm/month]
Cases [case/month]
Sri Lanka Jan
Sri Lanka Mar
Sri Lanka Jul
Sri Lanka Sep
Sri Lanka Oct
Sri Lanka Dec

On the Morphological Effective Systemic EpiGraph (MESE)



Novelty in the approach:

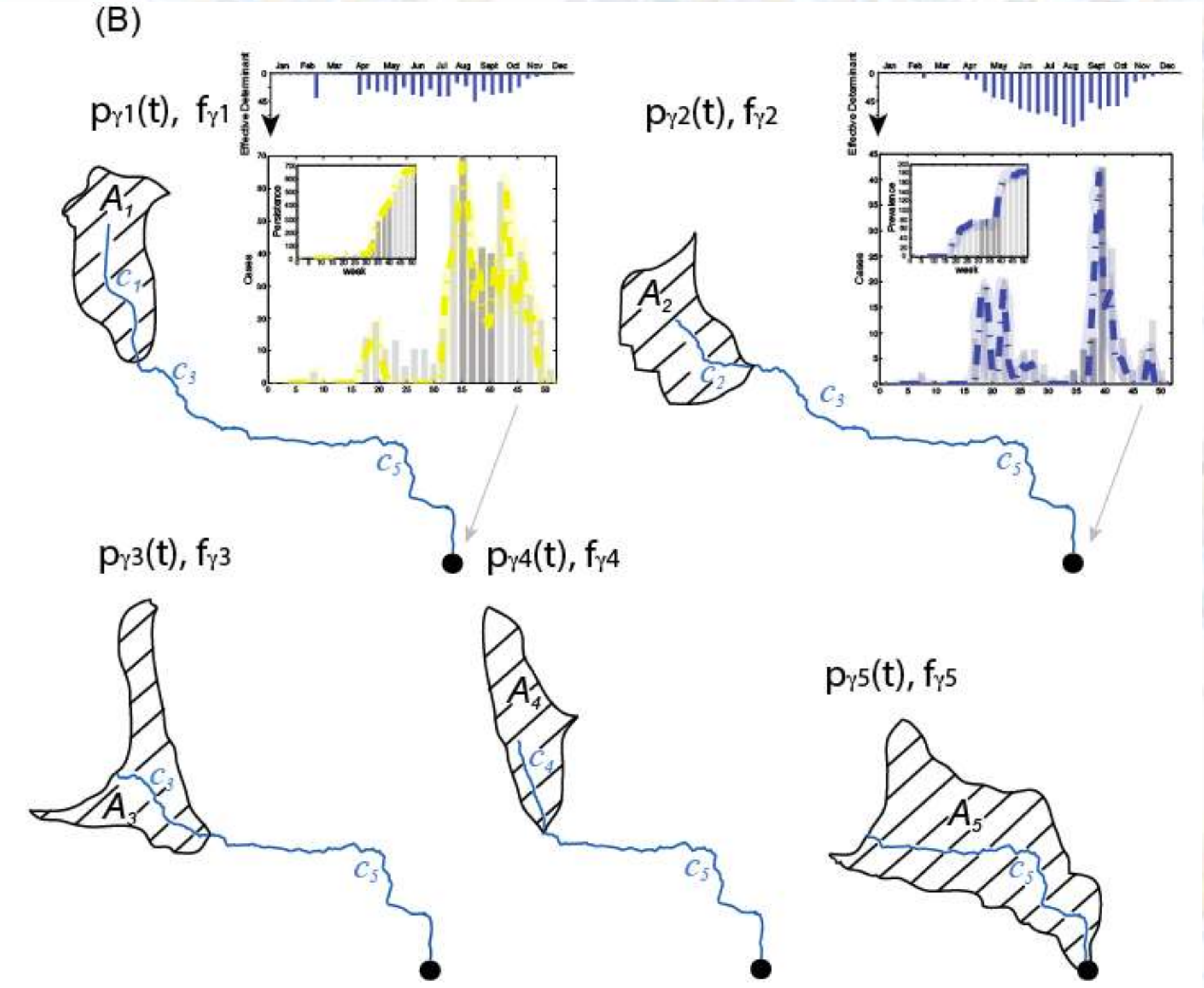
- Uncertainty and multiplicity in transmission routes and disease determinants
- Bidirectional fluxes on transmissions
- Effective distances (related to effective velocities)

Novelty in the Epi:

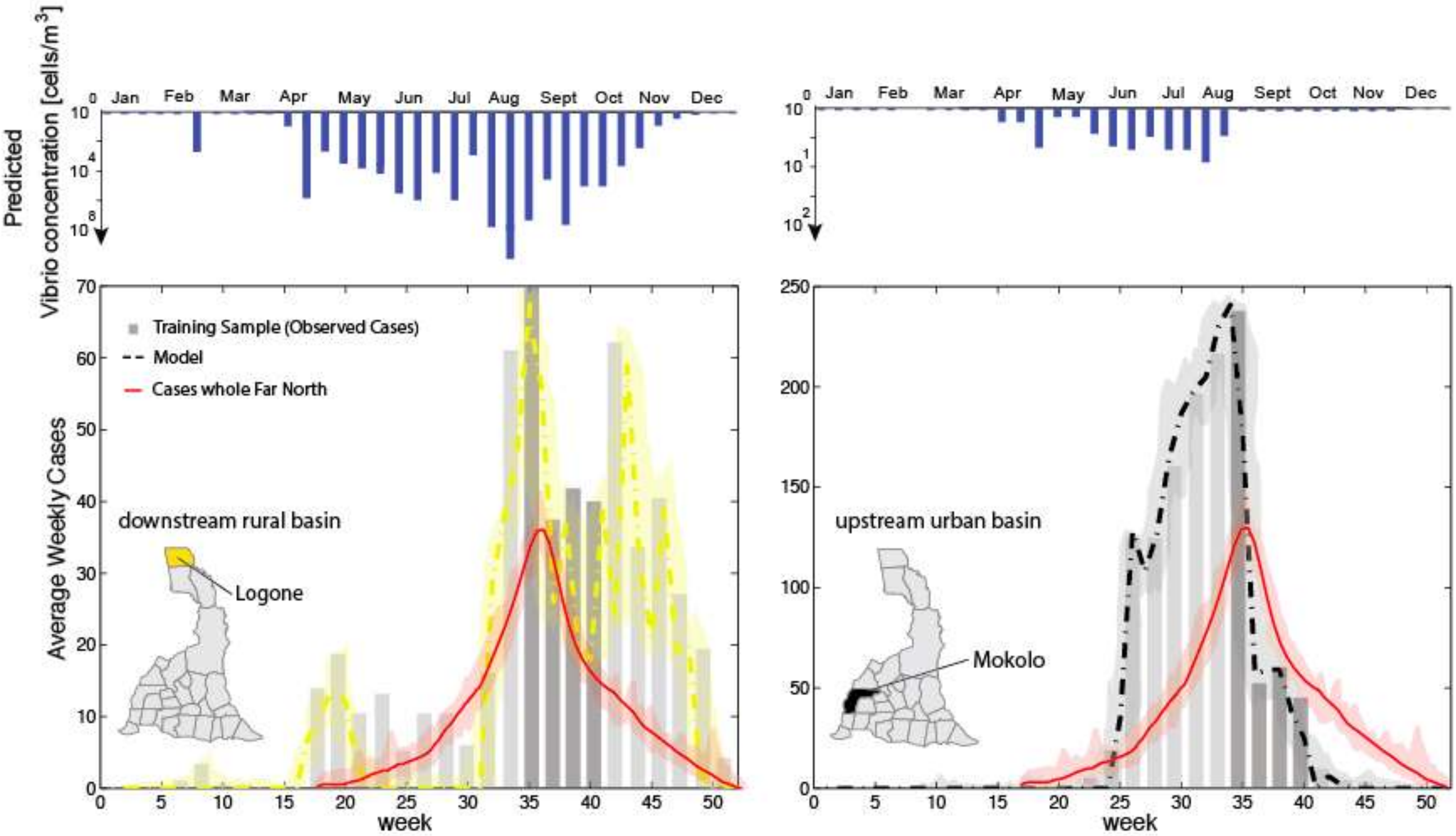
- Morphology contribution of disease production
- Time delay
- Factor interactions

Convertino, Huang, Liu, 2014, WRR, submitted

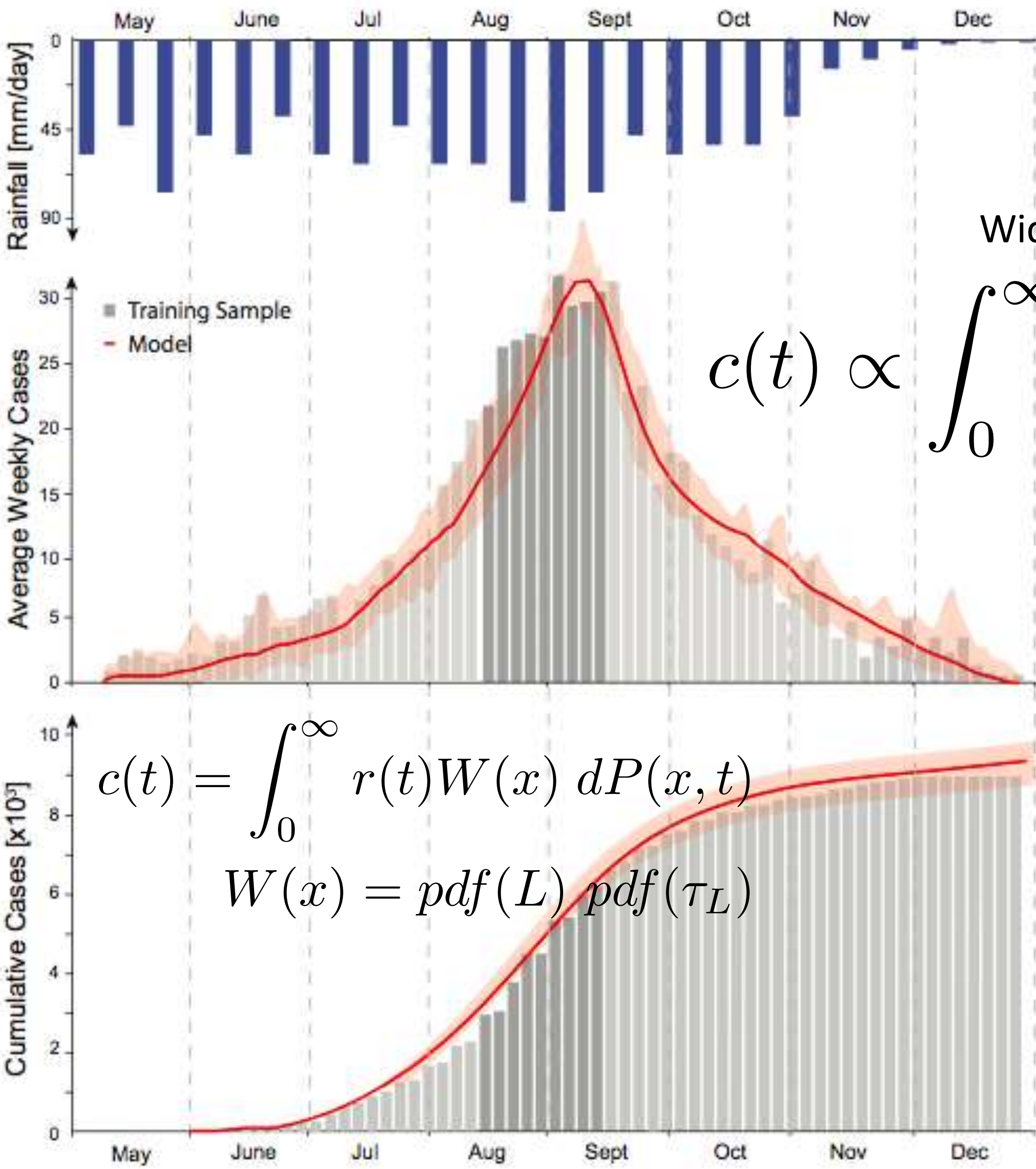
On the Morphological Effective Systemic EpiGraph (MESE)



Traveling Waves in Multislice Networks (G_0 vs R_0)



W(x) only dependent on Network Topology (travel time distribution)

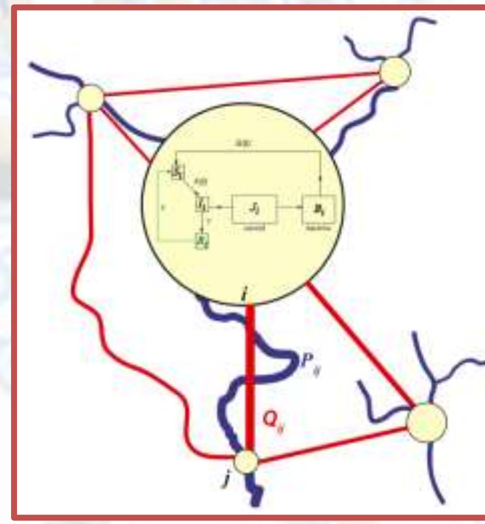


Width Function

$$c(t) \propto \int_0^\infty \boxed{W(x)}\, dP(x,t)$$

$$c(t) = \int_0^\infty r(t) W(x)\, dP(x,t)$$

$$W(x) = pdf(L)\, pdf(\tau_L)$$



Multislice Network

Connectopathies, Factorgenicity and Population Outcomes: A Morphological Effective Systemic EpiGraph model (MESE)

EPI (STATIC; RISK) TRANSPORT (DYNAMICS; OUTCOME)

$$I(\tau) = A \int \boxed{j_e(\tau)} \boxed{[p_\gamma(f_{\gamma_1} * f_{\gamma_n})]_{t-\tau}} d\tau$$

$$I(\tau) = A \int j_e(\tau) W(t-\tau) d\tau$$

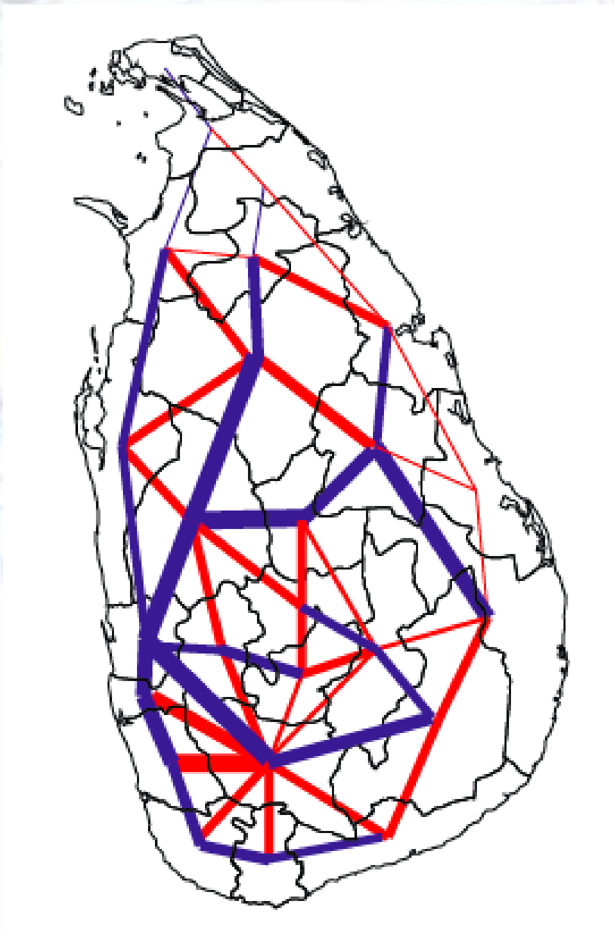
$$f_\gamma = pdf(L_\gamma) pdf(T_{L_\gamma})$$

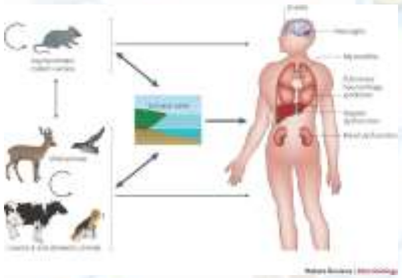
L=network length

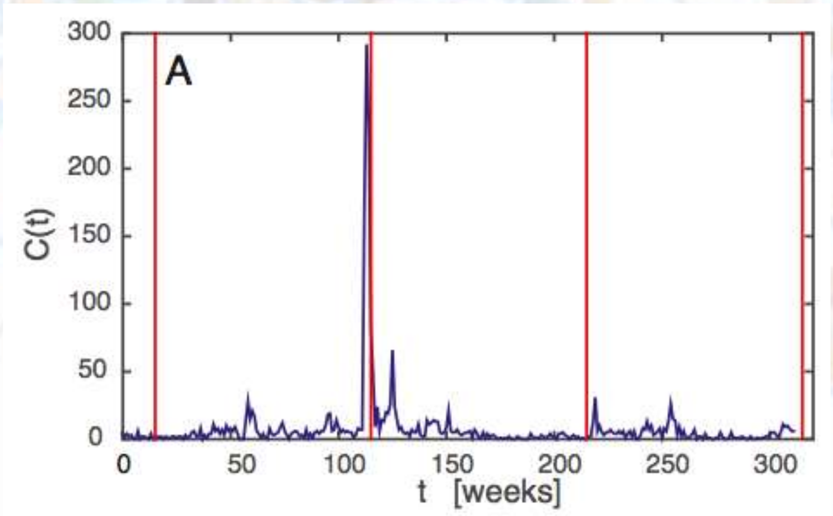
Travel Time distribution ~ Arrival Time distribution (of Cases) ~ $(\text{Residence Time})^{-1}$

Convertino, Huang, Liu, 2014, WRR, submitted
… GIUH from Rodriguez-Iturbe and Valdes, 1979

Scaling and Early Warning Models: Application to Leptospirosis in Sri Lanka



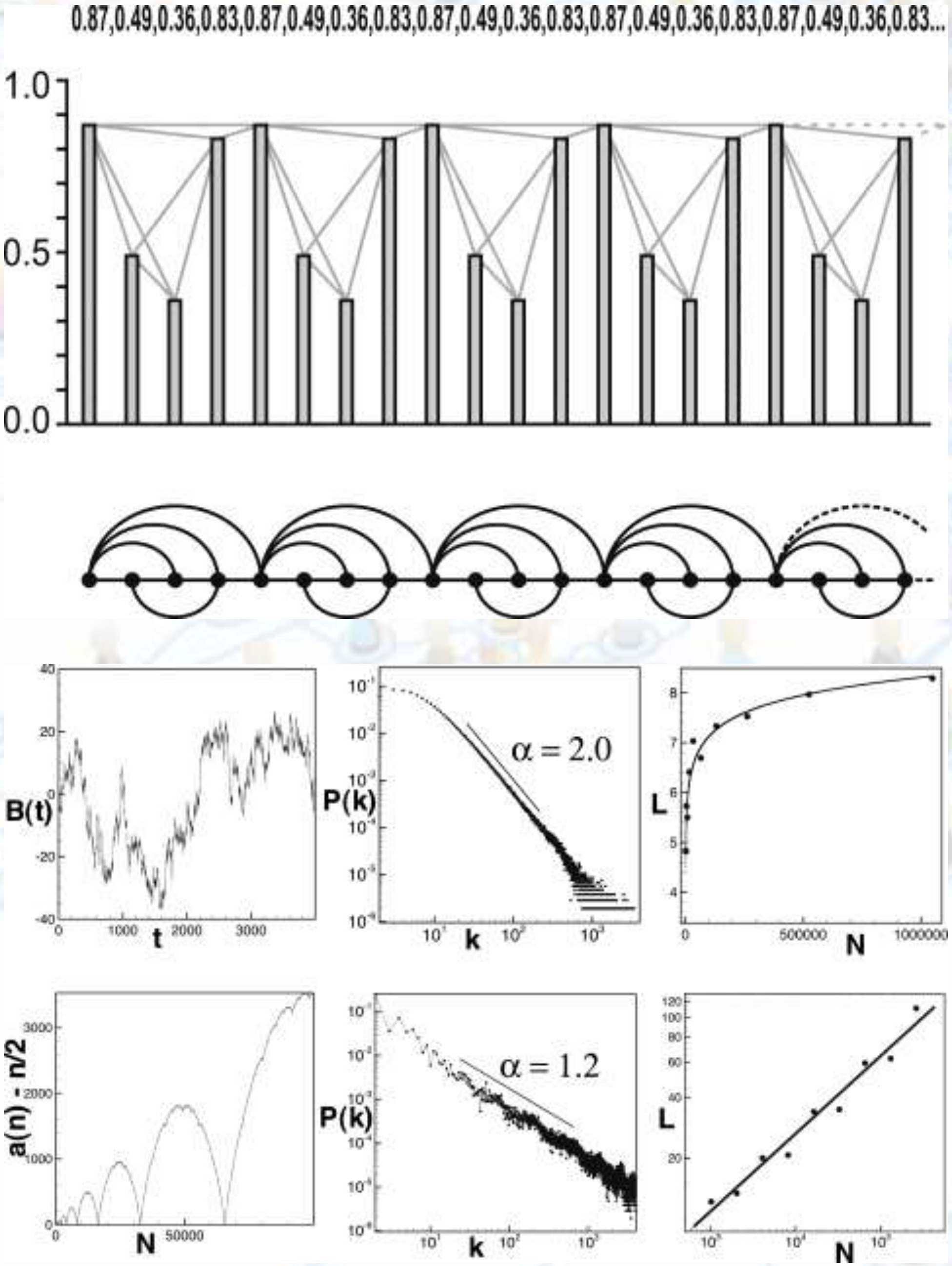




Reddy et al., 2015, submitted to PNAS


Paris
Fête de la Musique / mouvements des mobiles
12 :06 21/06/2008

Visibility Networks: from Time Series to Complex Networks

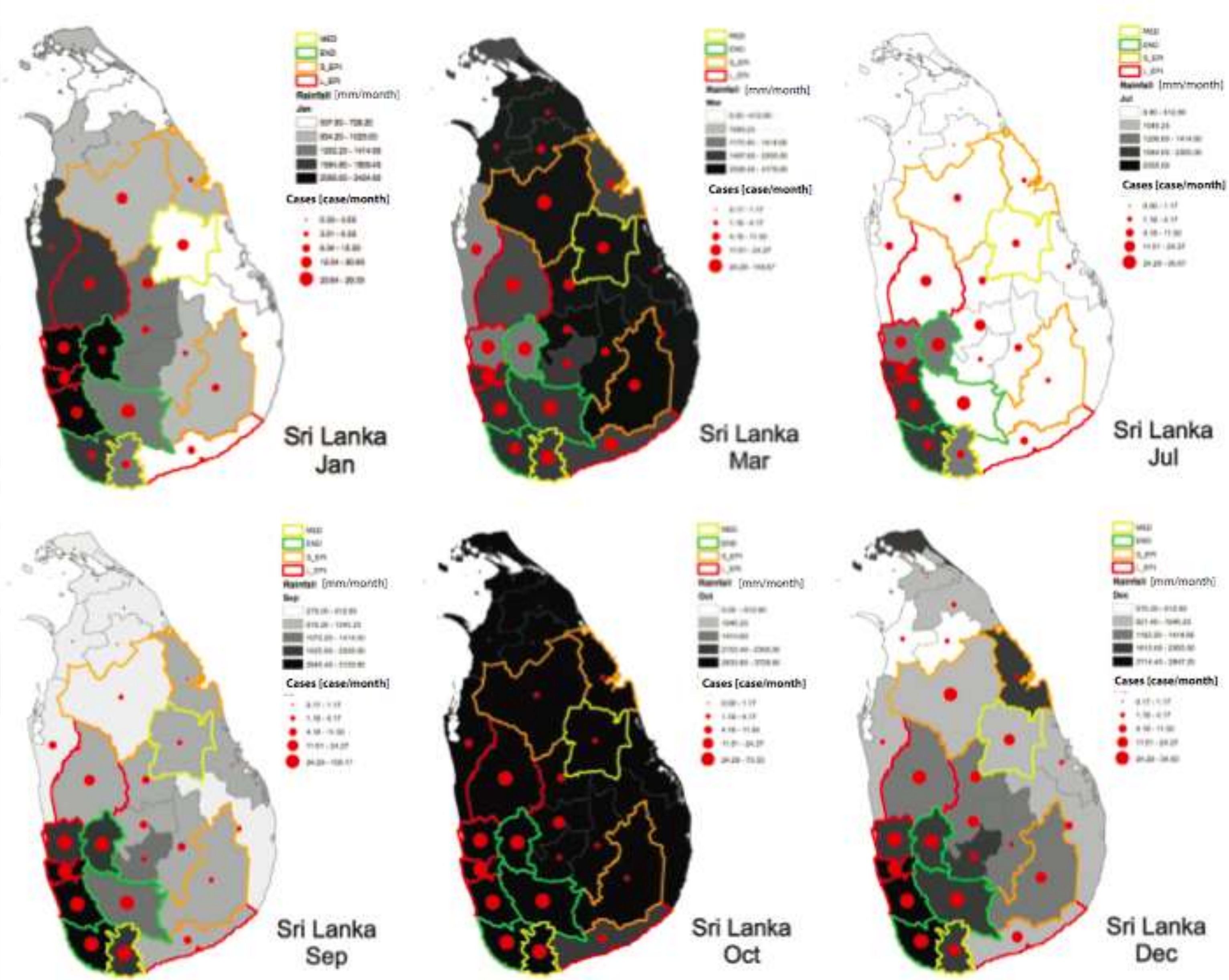


Lacasa et al., 2008, PNAS

Disease Description

- Zoonotic Water-based Disease
- 250 serovars
- Significant endemicity in developing countries
- Animal-Human transmission via environment
- Contracted from contact with contaminated water

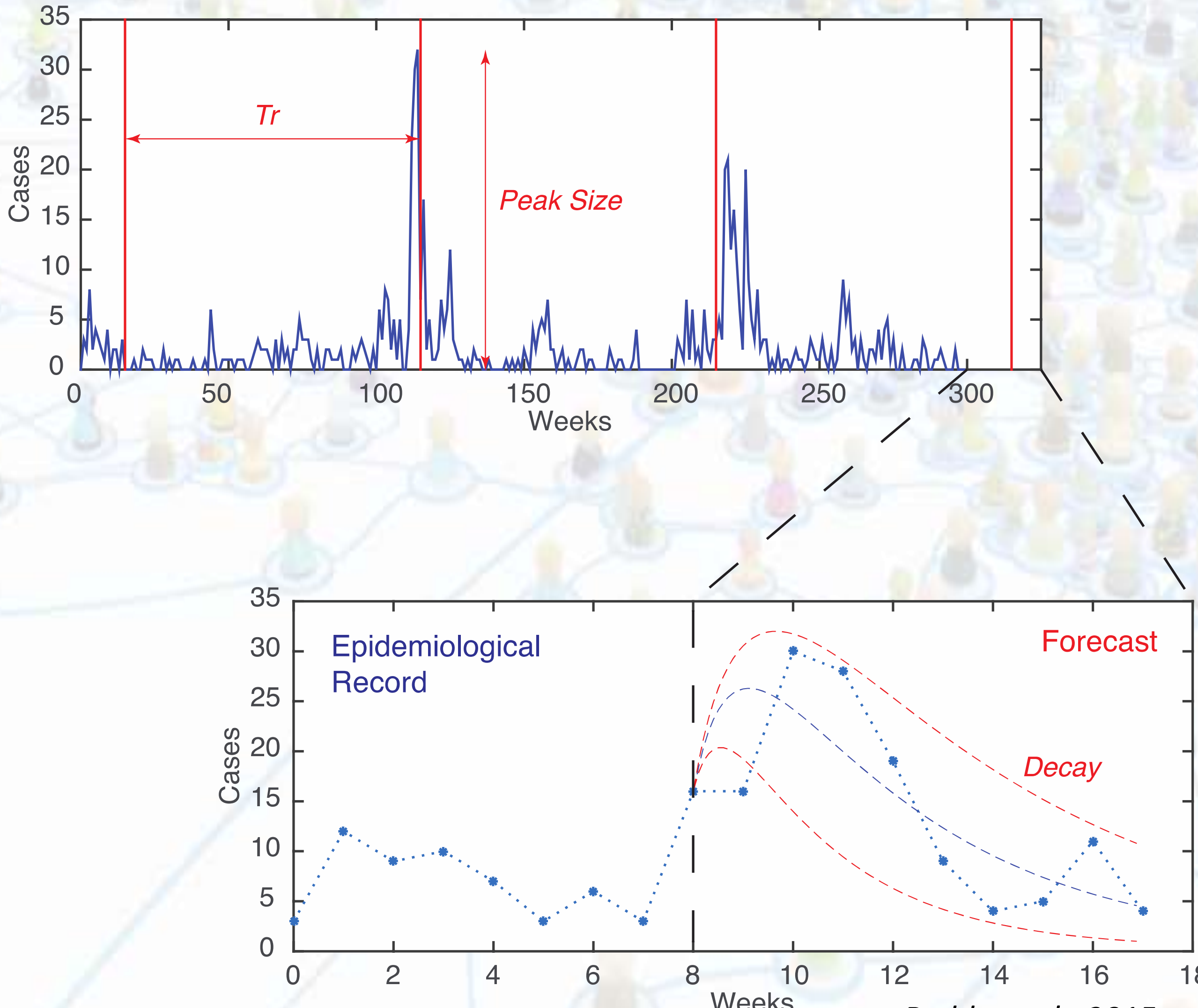
Disease Incidence in Sri Lanka



Disease Dynamics Classification

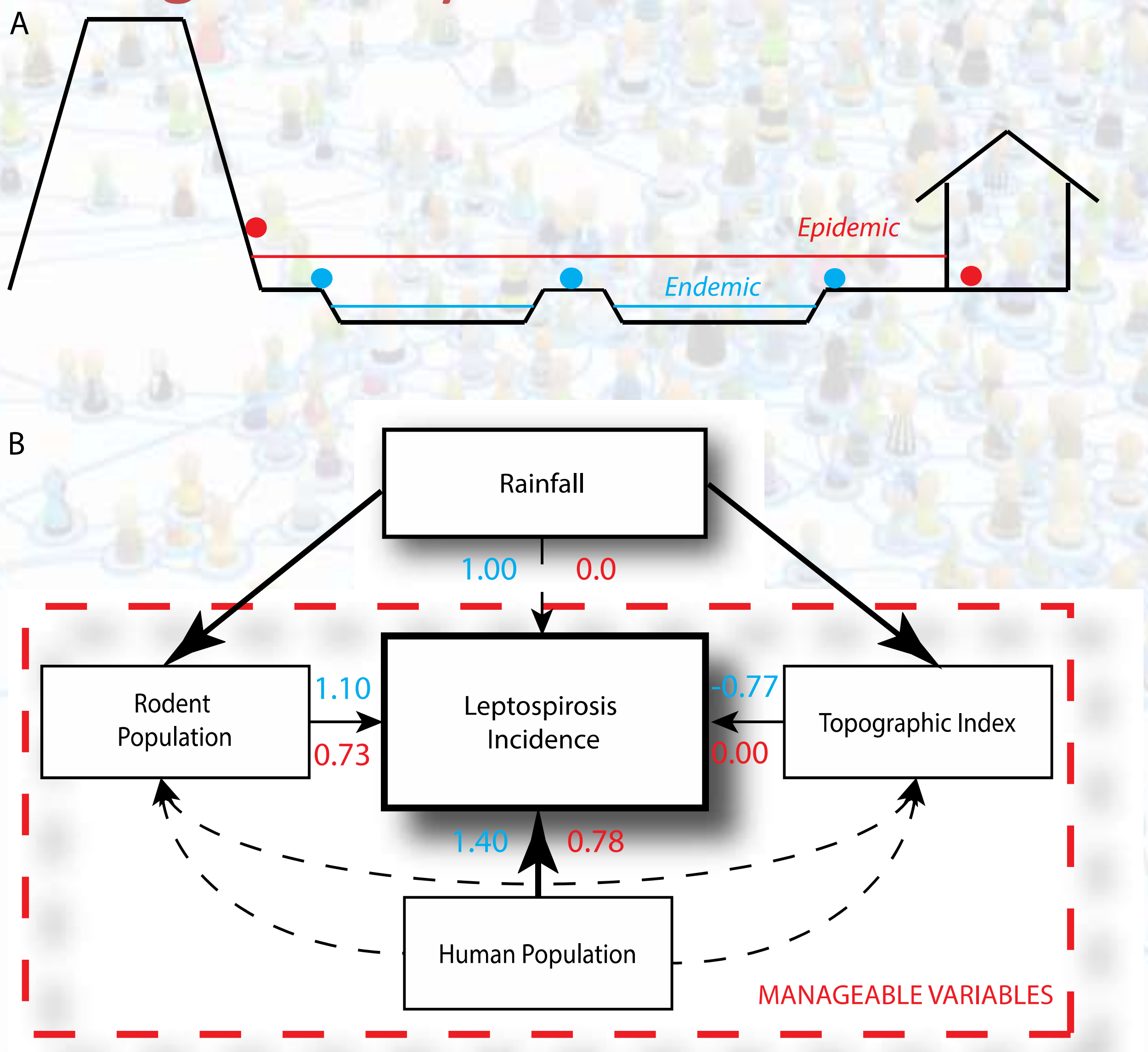
- Extreme events are often described via Pareto or power law distribution using what’s know as the 80-20 rule or Pareto principle
- “80/20 rule” - 80% of outcomes(cases) come from top 20% of causes(events)

Stochastic EWS Model



Reddy et al., 2015, submitted to PNAS

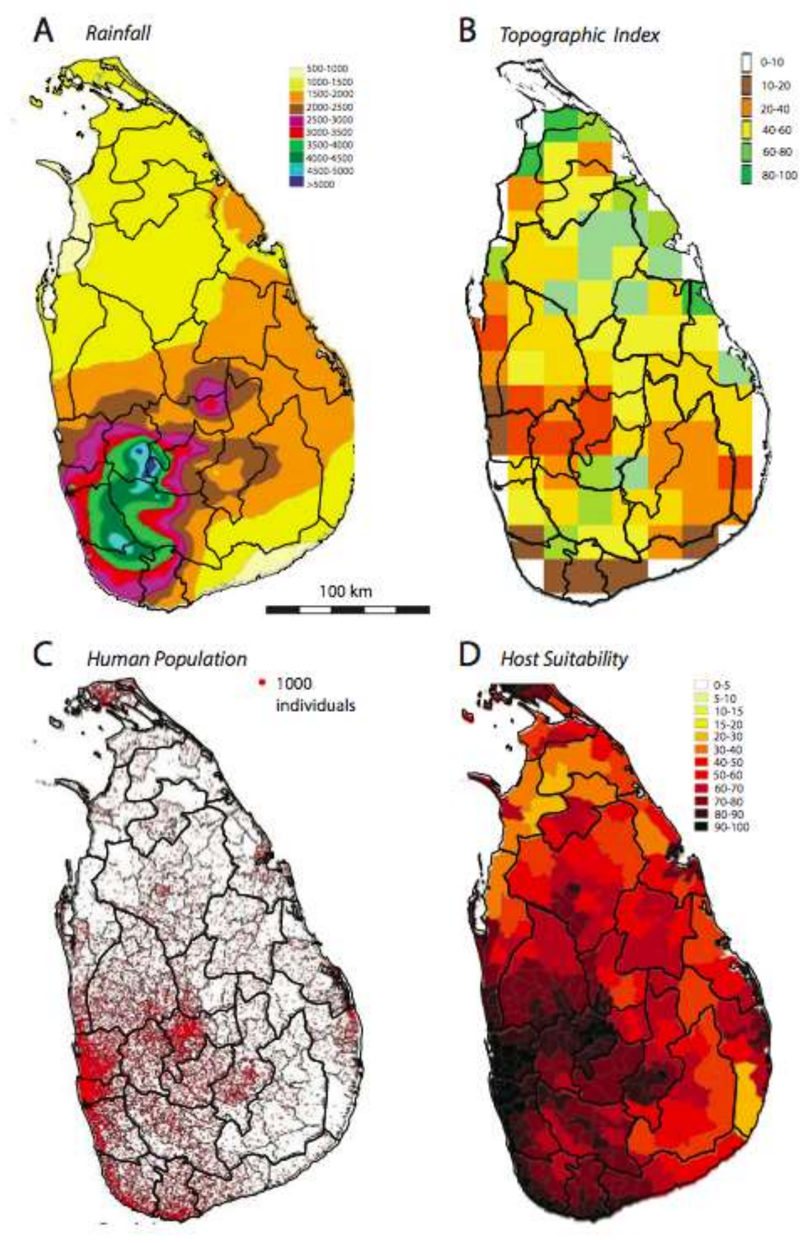
Metamodeling of ID Dynamics



Reddy et al., 2015, submitted to PNAS

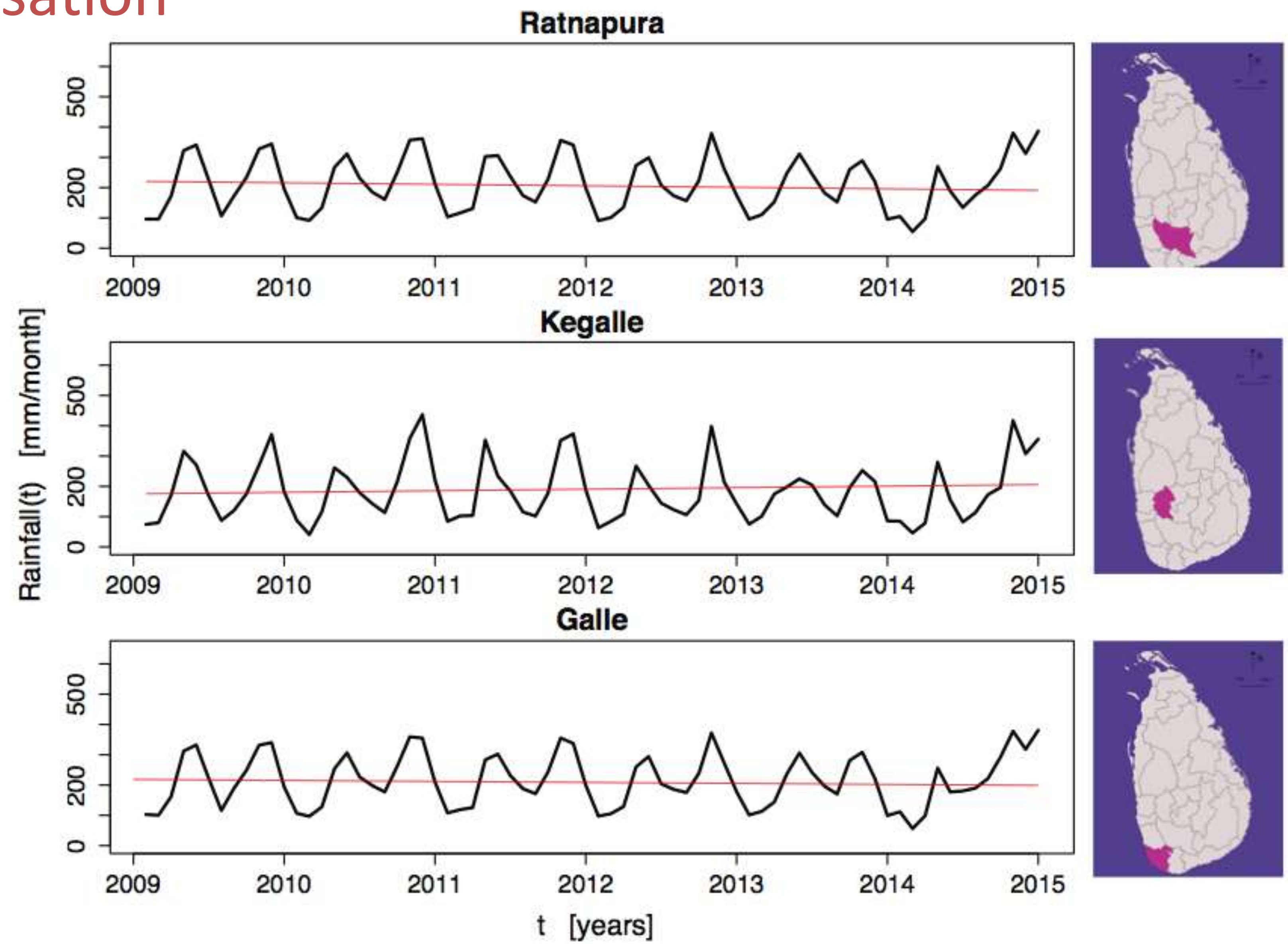
Socio-environmental factors (after metamodeling)

- Topographic Index
- Host Suitability
- Population
- Rainfall



Reddy et al., 2015, submitted to PNAS

Lack of correlation does not imply lack of causation



Topographic Index

- Steady state wetness index characterizing the ecohydrology of ecosystems

$$TI = \log\left(\frac{A_i/b_i}{\tan\beta_i}\right)$$

Ai=drainage area upstream a point

bi=area per unit width orthogonal to the flow direction

Betai=slope

Host Suitability

- Calculated via MaxEnt
- Probability to observe infected rodents (within the rodent population)
- Environmental layers used in MaxEnt: population density and Topographic index

On the Return Time of Cases

- Exceedance probability is the likelihood to have and event greater than or equal to C

$$P(C \geq c).$$

- Return Period

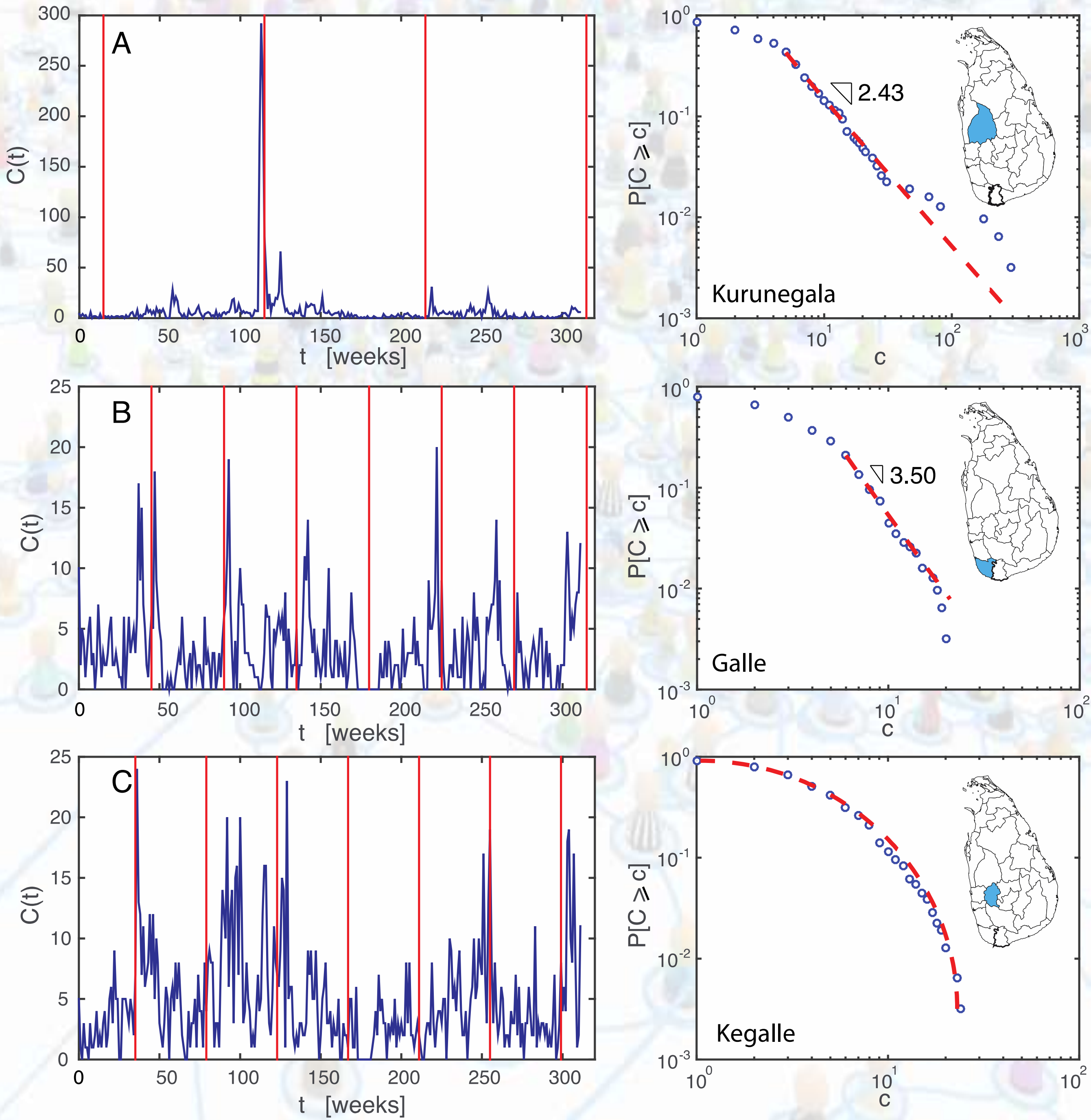
$$T(C) = \frac{1}{P(C \geq c)}$$

Example return periods

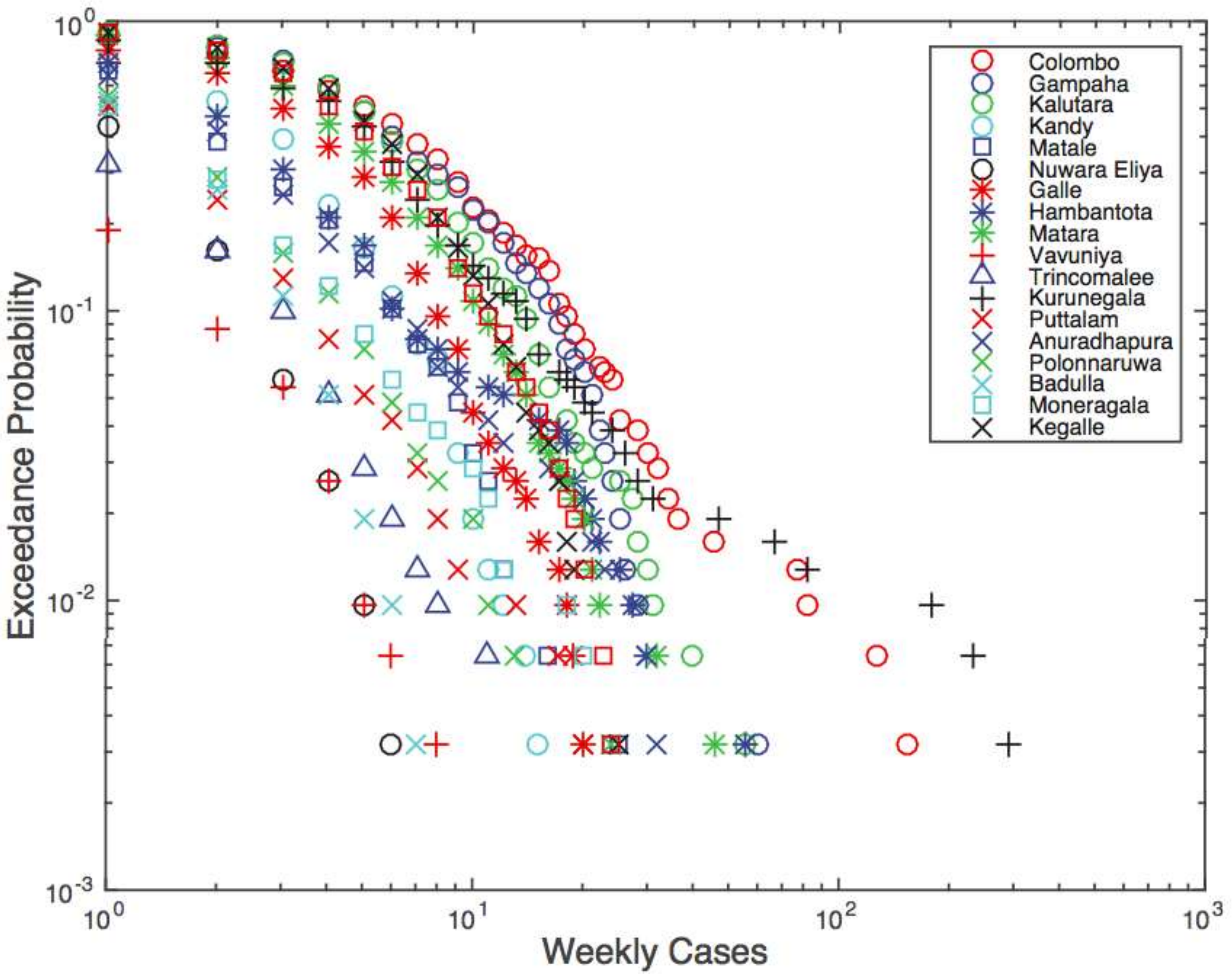
A) 115 weeks (>30)

B) 45 weeks (>15)

C) 43 weeks (>17)



Epdf reflecting disease dynamics and transitions



EWS Model Analytics

- Model introduced by Azaele (PRL, 2010) to describe cholera
- Langevin equation with Gaussian white noise

$$\dot{I}(t) = b - \frac{I(t)}{\tau} + \sqrt{DI(t)}\xi(t)$$

$$\langle \xi(t)\xi(t') \rangle = 2\delta(t-t')$$

EWS Model Factors

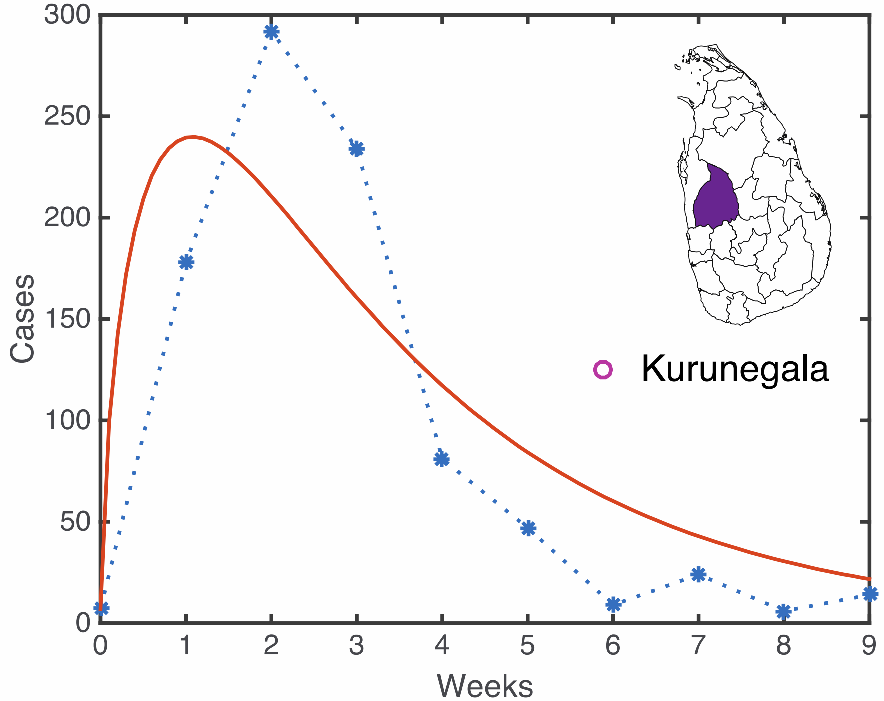
- b ~ (inter community cases) immigration rate of infected hosts and contaminated water flow
- D – (within community case fluctuations) stochasticity of disease incidence
- tau – characteristic time scale of disease decay

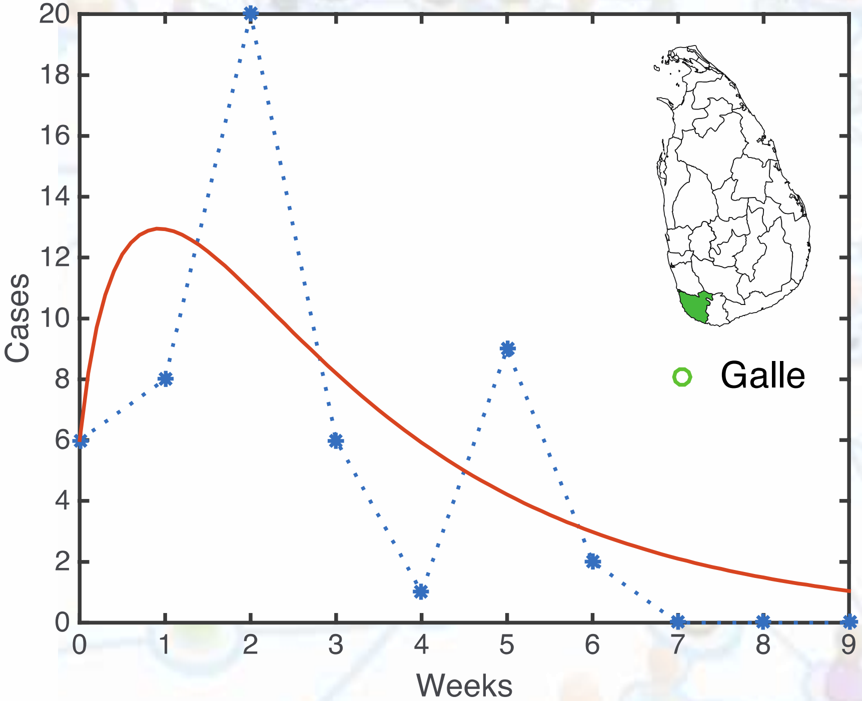
- Solution for mean value of infected

$$\langle I(t)\rangle = \frac{e^{-t/\tau}}{c}\left[1 + cD\tau(e^{t/\tau} - 1)\right]^{b/D}$$

Model Calibration

- b, D, tau found using a least squares optimization for peaks across Sri Lanka





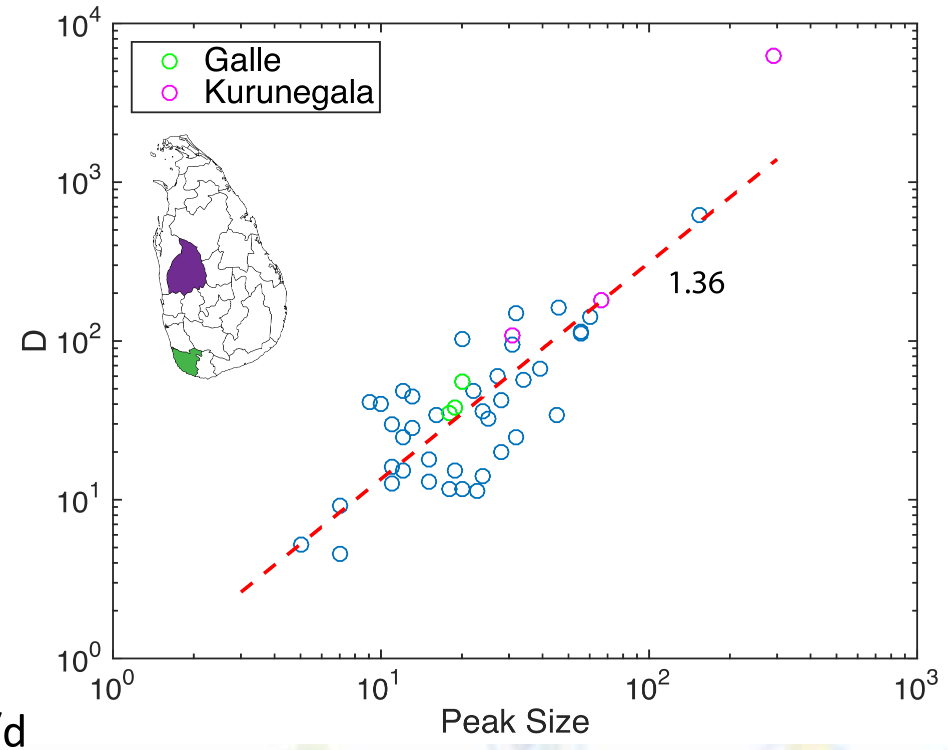
Scaling Model Factors

- D varies with peak size

$$D = 0.59x^{1.36}$$

$$b/D = .663 \pm .116$$

$$\tau = 1.301 \pm .496$$



tau dependent on the disease as well as b/d

D is prop. to the peak size

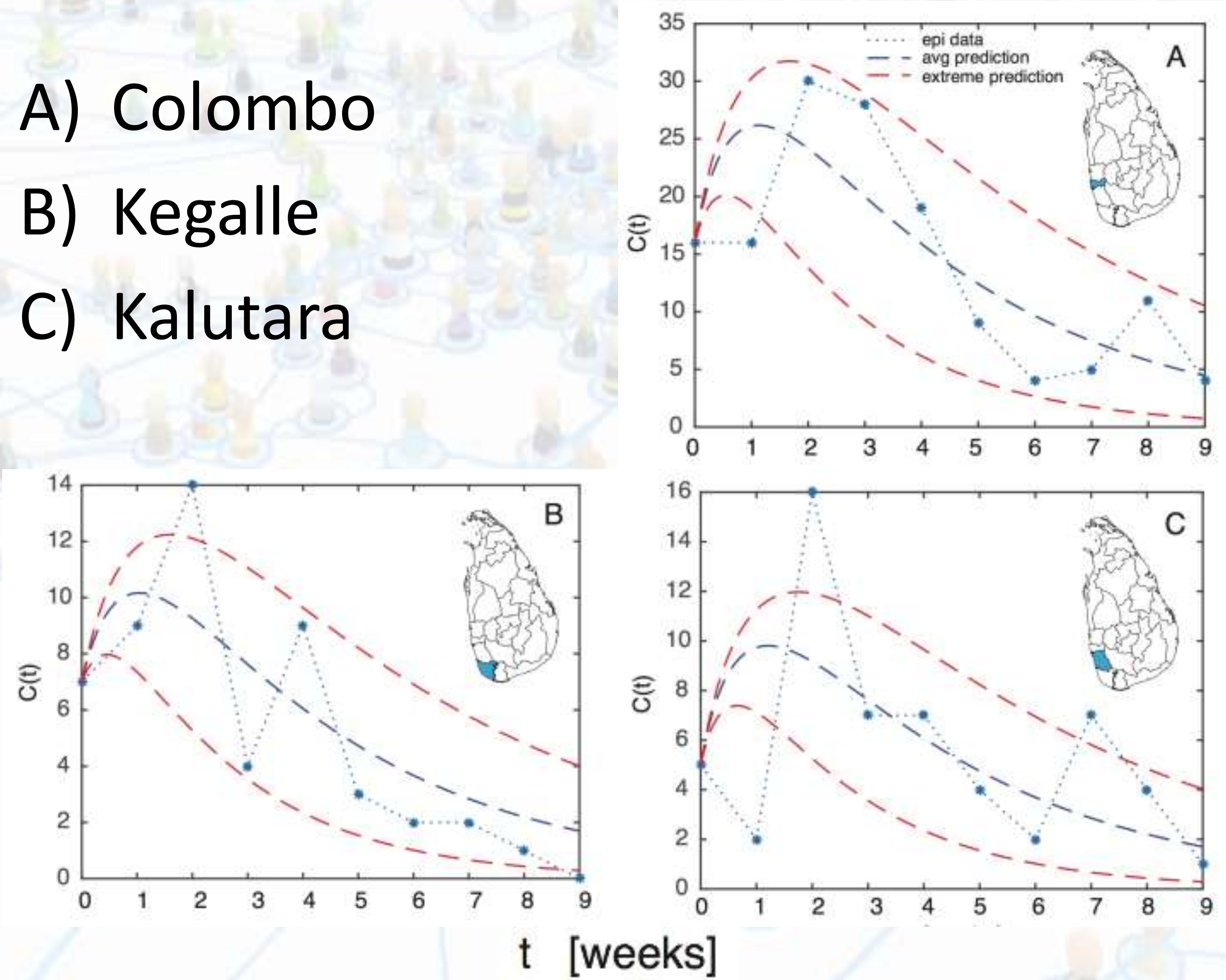
Reddy et al., 2015, submitted to PNAS

Model Prediction

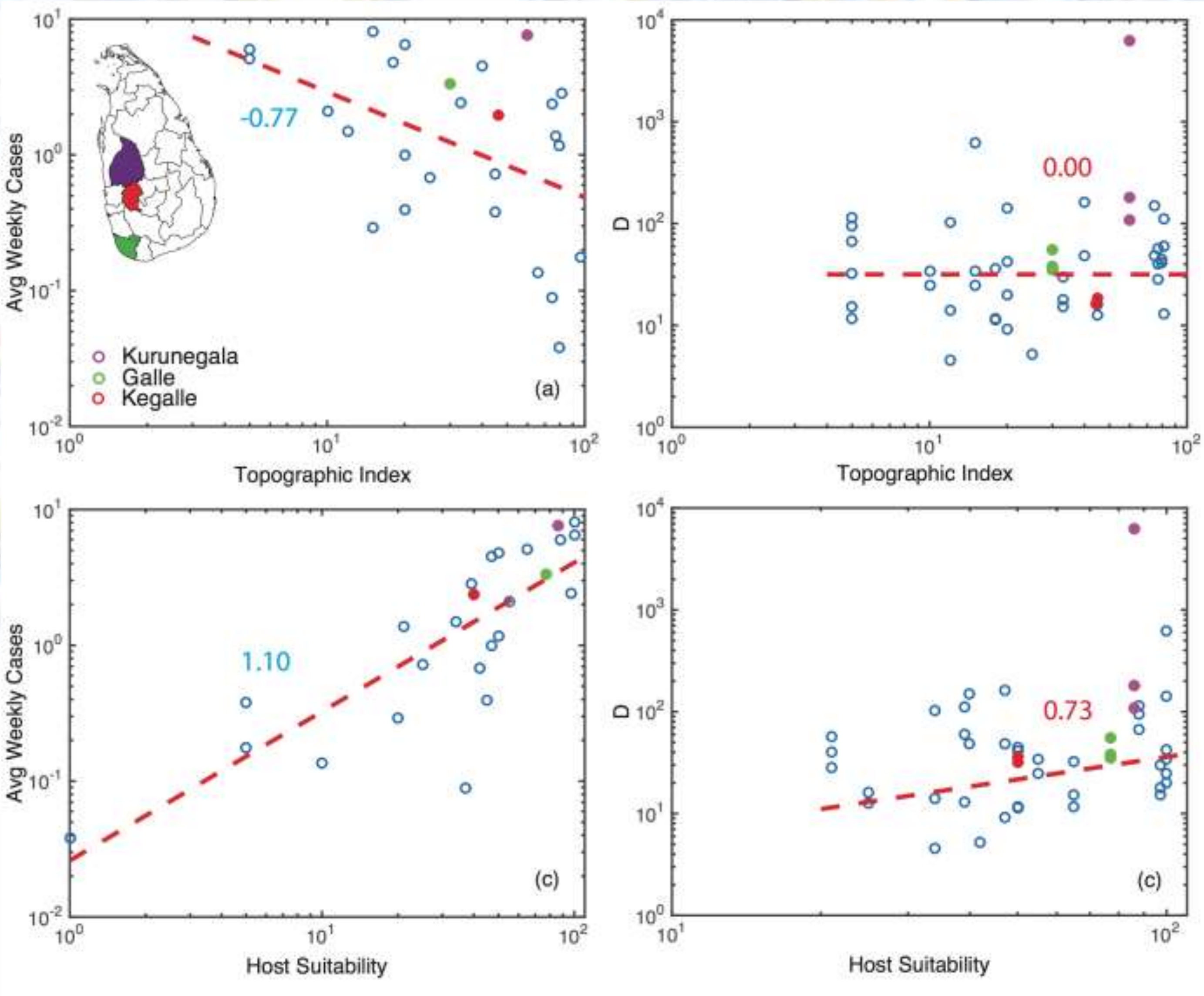
A) Colombo

B) Kegalle

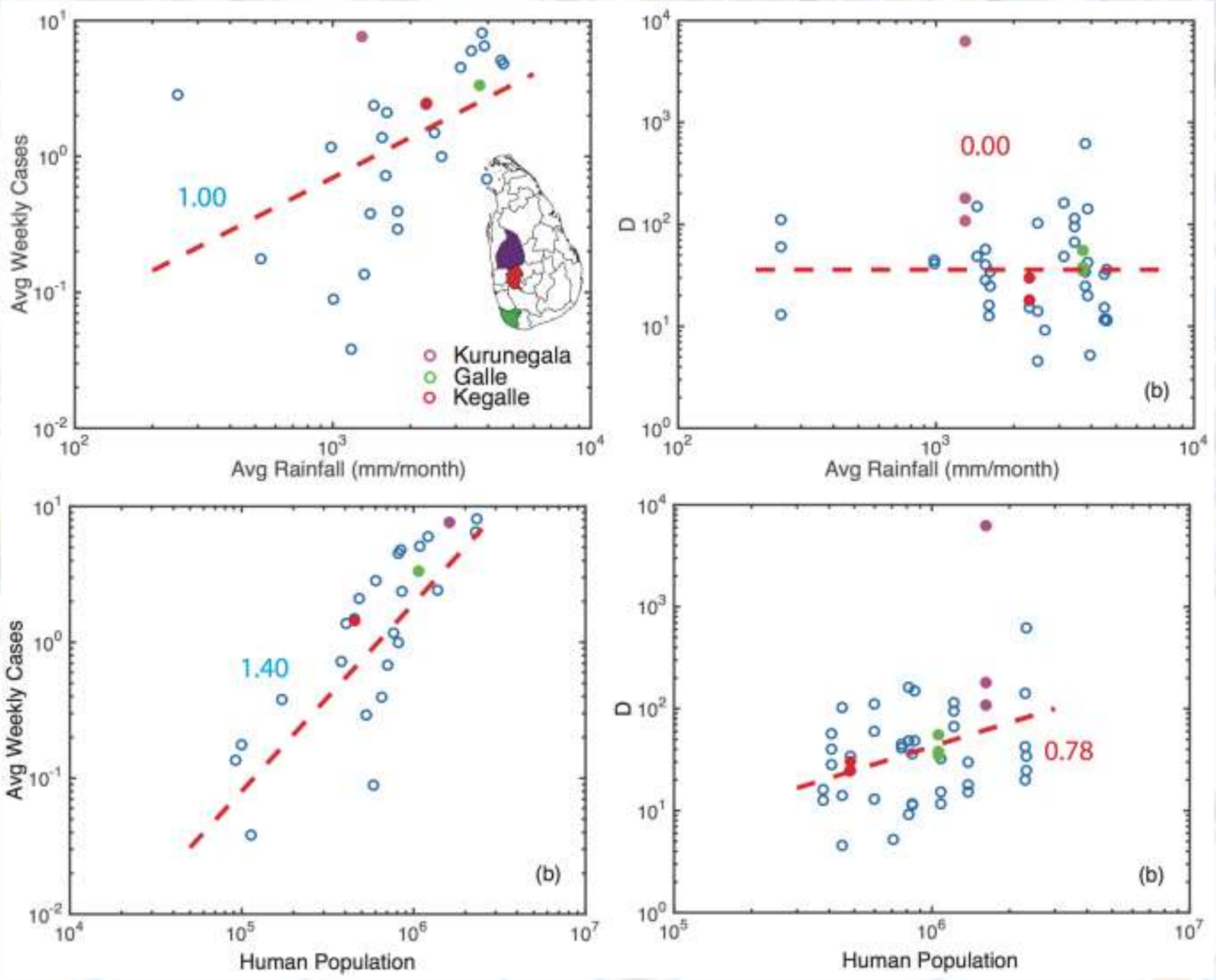
C) Kalutara

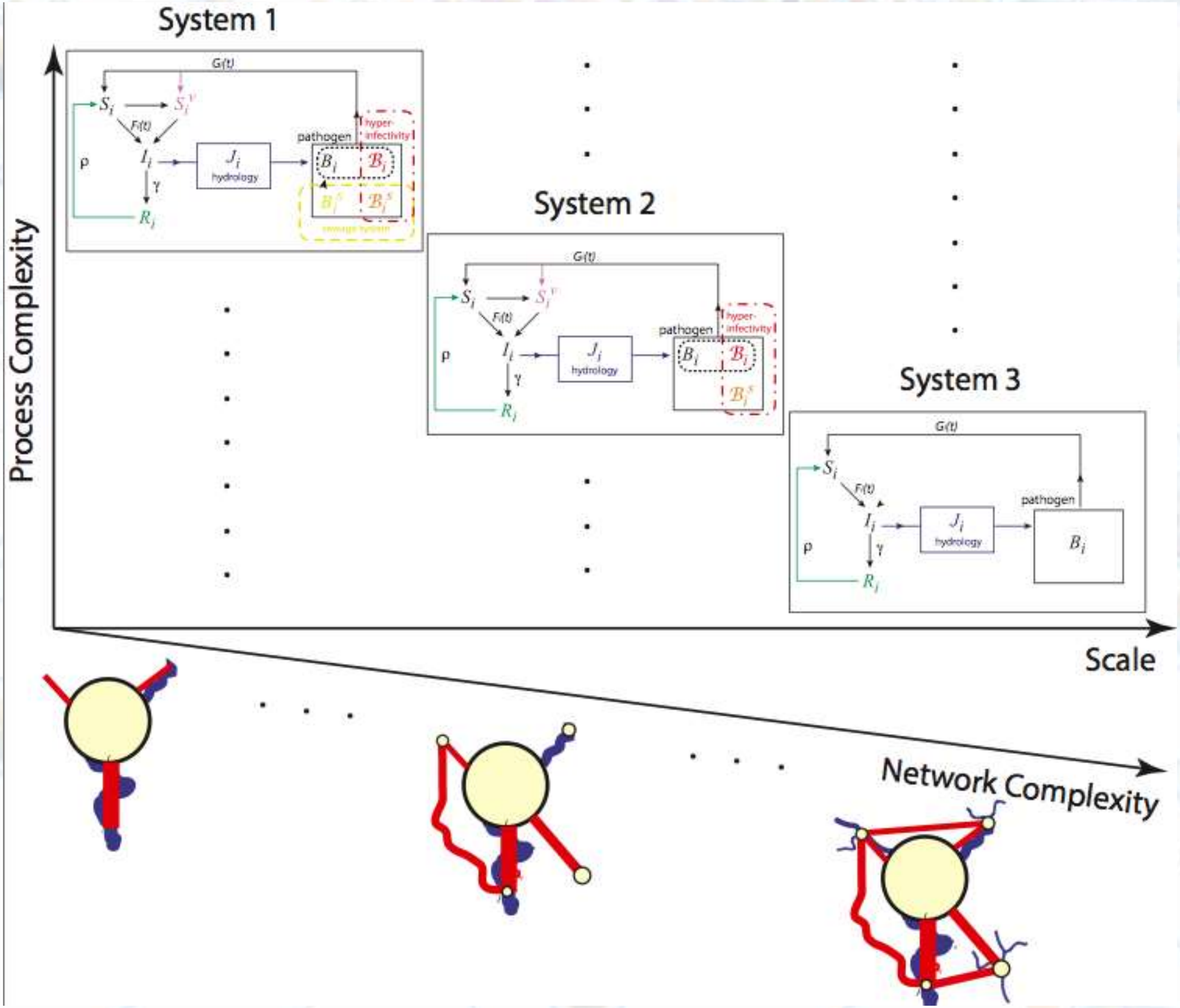


Eco-epidemiological Scaling



Eco-epidemiological Scaling





System 1
System 2
System 3
Process Complexity
Scale
Network Complexity
G(t)
F(t)
pathogen
hyper-infectivity
hydrology
ρ
γ

Take Home Messages

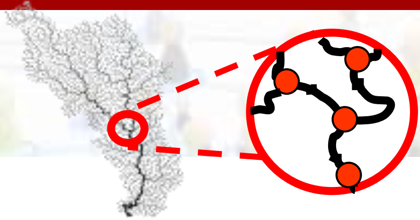
- Peaks shaped by max rainfall, host suitability, and human population
- Baseline shaped by average rainfall, TI, host suitability, and human population
- Scaling relationship to be verified (in terms of their universality) across all Leptospirosis impacted areas. These relationships allows to predict baseline and peak dynamics

Take Home Messages

- Defined a probabilistic criteria for the definition of endemic and epidemic regimes via analyses of surveillance data
- Analyzed outbreak recurrence, magnitude, and decay based on a stochastic pattern-oriented model
- Performed a macro-epidemiological detection of environmental causal factors

Supplementary Material

Local Epidemic Model (Nodal)



$$
\begin{cases}
\dfrac{dS_i}{dt} = \mu\,(H_i - S_i) - \mathcal{F}_i(t)\,S_i + \rho\,R_i\,, \\[2ex]
\dfrac{dI_i}{dt} = \mathcal{F}_i(t)\,S_i - (\gamma + \mu + \alpha)\,I_i\,, \\[2ex]
\dfrac{dR_i}{dt} = \gamma\,I_i - (\rho + \mu)\,R_i\,, \\[2ex]
\dfrac{dB_i}{dt} = -\mu_B\,B_i - l\left(B_i - \displaystyle\sum_{j=1}^{n} P_{ji}\frac{W_j}{W_i}B_j\right) + \dfrac{p}{W_i}\left[1 + \Phi\,J_i(t)\right]\mathcal{G}_i(t)\,, \\[2ex]
\dfrac{dW_i}{dt} = W_i + J_i(t) - T_i(t) + \displaystyle\sum_{j=1}^{n_i^{up}} T_j(t)
\end{cases}
$$

S: susceptibles

I: infected

R: recovered

W: Water

B: water pathogen concentration

Codeço, 2001

(tribute to Snow and Pacini)

Cumulated Cases

$$\frac{dC_i}{dt} = \sigma\,\mathcal{F}_i(t)\,S_i\,,$$

Reproduction Number

$$R_0 = \frac{\beta\,p\,H_i}{K\,W_i\,\mu_B\,(\gamma + \mu + \alpha)} > 1\,.$$

Factor	Description	Value	Distribution	References
μ	Natural mortality rate (day^{-1})	$1/(54 \cdot 365)$	$G(0.2)$	CIA (2013)
α	Cholera-induced mortality rate (day^{-1})	$8.2 \cdot 10^{-3}$	$G(0.5)$	Njoh, M.E. (2010)
ρ	Acquired immunity loss (day^{-1})	$1/(5 \cdot 365)$	$G(0.5)$	Koelle et al. (2005)
σ	Cumulative case rate (day^{-1})	0.2	$U(0.05; 0.4)$	WHO (2013)
β	Exposure rate to contaminated water (day^{-1})	1.0	$U(0.5; 3.0)$	Codeco (2001)
γ	Individual recovery rate (day^{-1})	0.2	$U(0.05; 0.5)$	Codeco (2001)
μ_B	Net growth rate of *V. cholerae* (day^{-1})	0.23	$G(0.25)$	Codeco (2001)
c	Per-capita stored water volume ($m^3/individual$)	$14,9 \cdot 10^3$	$G(0.5)$	GWP (2013)
m	Human mobility rate (-)	0.12	$G(0.5)$	-
b	Pathogen transport bias (-)	0.07	$G(0.25)$	-
l	*V. cholera* mobility (day^{-1})	0.88	$G(0.3)$	-
Φ	Contaminated runoff coefficient (day/mm)	$4.9 \cdot 10^{-2}$	$U(2.9 \cdot 10^{-2}; 6.9 \cdot 10^{-2})$	-
p	Contamination rate ($cells/(day \cdot individual)$)	$9.53 \cdot 10^9$	$U(5.0 \cdot 10^9; 15 \cdot 10^9)$	-
K	Half-saturation constant ($cells/m^3$)	$1.0 \cdot 10^6$	$G(0.3)$	-
$\theta = \frac{p}{K\,c}$*	Aggregated contamination rate (day^{-1})	0.64	$G(0.3)$	-

Radiation Model of Human Mobility

Total Exposure Rate (Contact Rate) or Exposure Function

$$\mathcal{F}_i(t) = \boxed{\beta \left[(1-m)\frac{B_i}{K+B_i}\right.} + \boxed{\left. m\sum_{j=1}^{n} Q_{ij}\frac{B_j}{K+B_j} \right]},$$

Local E-H   Far H-H

Simini et al., 2012, Nature

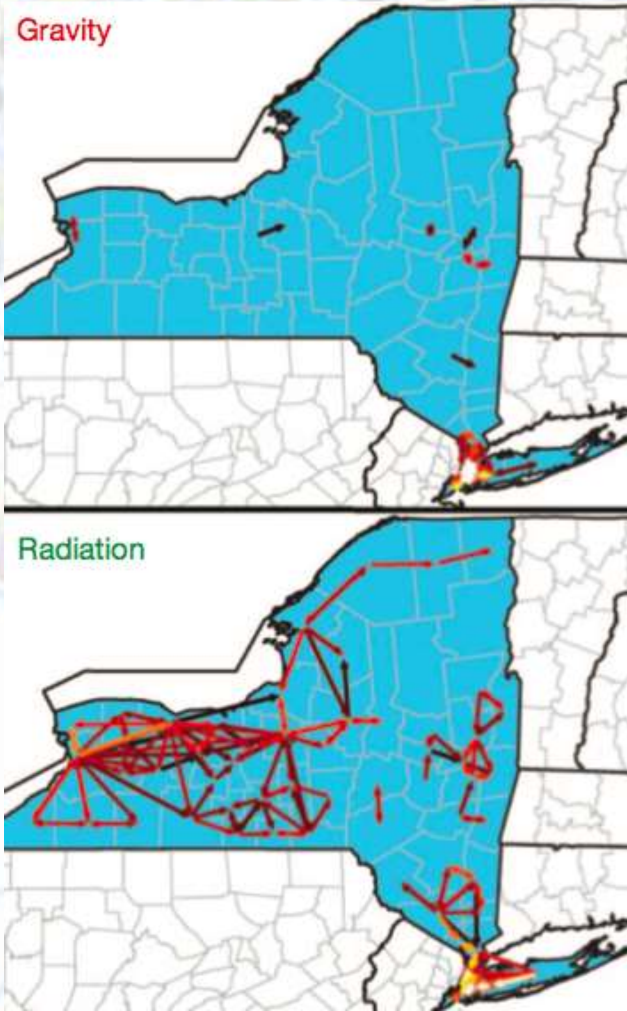
Probability of Human Mobility

$$Q_{ij} = \frac{H_i H_j}{(H_i + H_{ij})(H_i + H_j + H_{ij})},$$

Total Infective Pool (Primary and Secondary Infection Pathway Function for Bacteria Production) or Generation Function

$$\mathcal{G}_i(t) = \boxed{(1-m)\,I_i} + \boxed{m\sum_{j=1}^{n} Q_{ij}\, I_j},$$

Local E-H   Far H-H



The human-human transmission is modeled by enhancing the excretion of vibrios where people move.