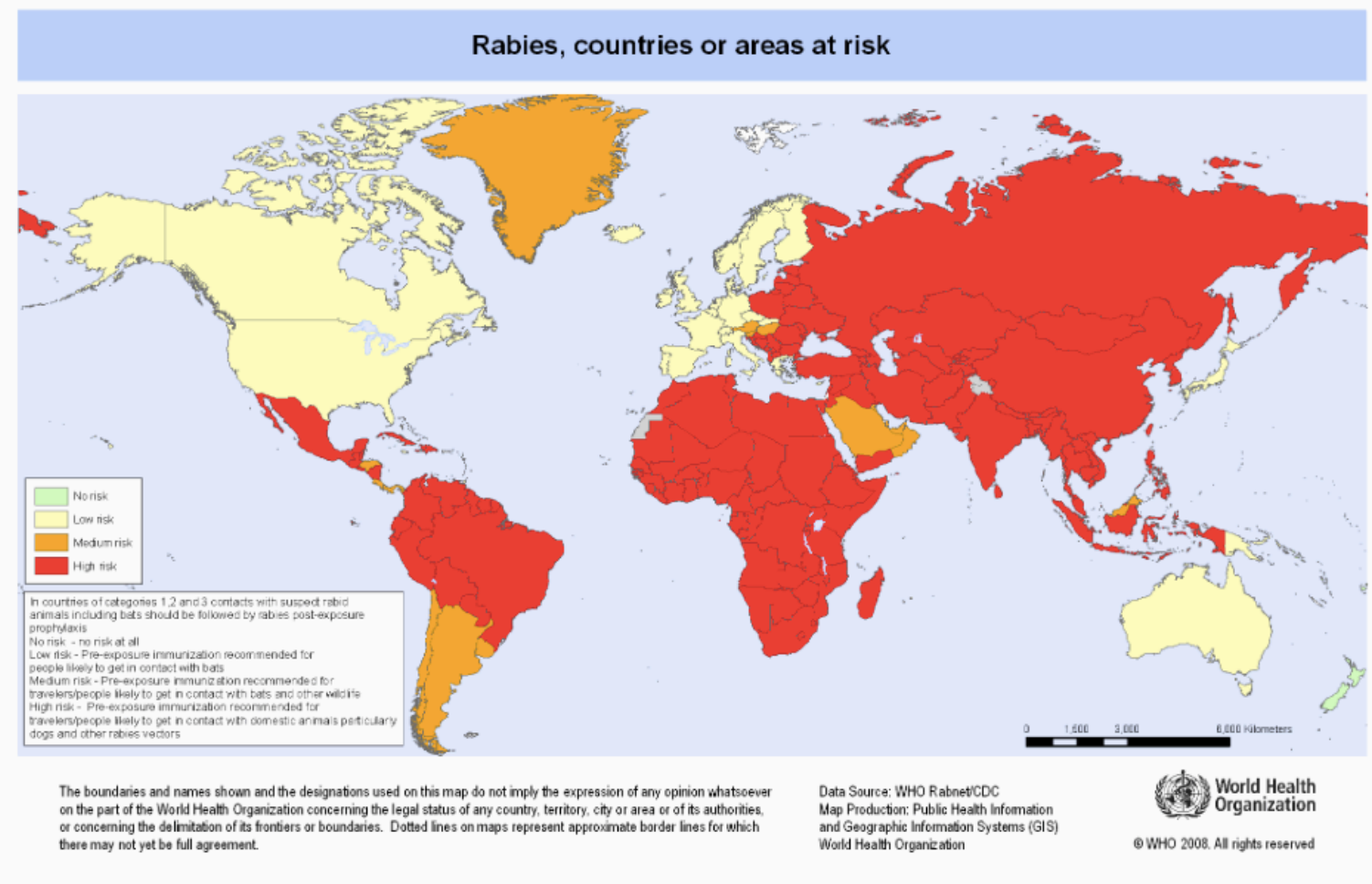
Impact of resource abundance on pathogen invasion risk

MMED Faculty Research Presentation
African Institute for the Mathematical Sciences
Muizenberg, South Africa
1 June 2016

Rebecca Borchering, BS, MS
Department of Mathematics and Emerging Pathogens Institute
University of Florida

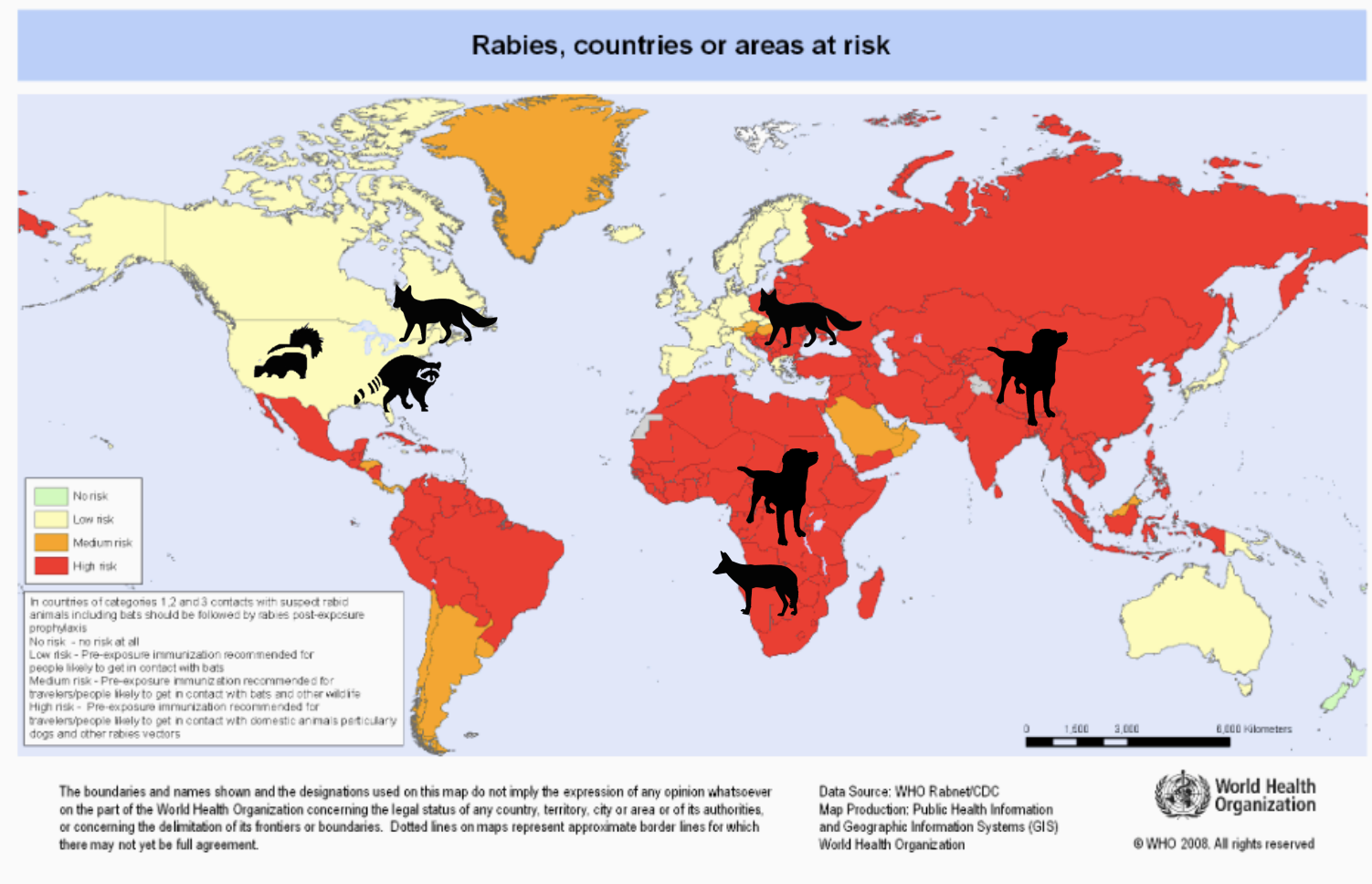
Image Credit: Bellan et al. 2012, Namibian Ministry of Environment & Tourism, Etosha Ecological Institute

Rabies risk



Credit: Rabies risk map, WHO.

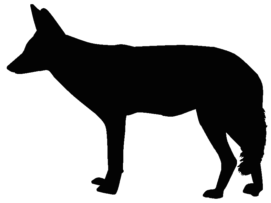
Rabies reservoirs



Credit: Rabies risk map, WHO.

Role of jackals in rabies maintenance

- Lembo et al. 2008 found that domestic dogs are the only rabies **maintenance population** in the Serengeti.
- Rhodes et al. 1998 found rabies to be **sub-critical** for jackals in Zimbabwe.



We investigate conditions for rabies maintenance in jackals in Etosha National Park, Namibia.

Berkeley Etosha Anthrax Project

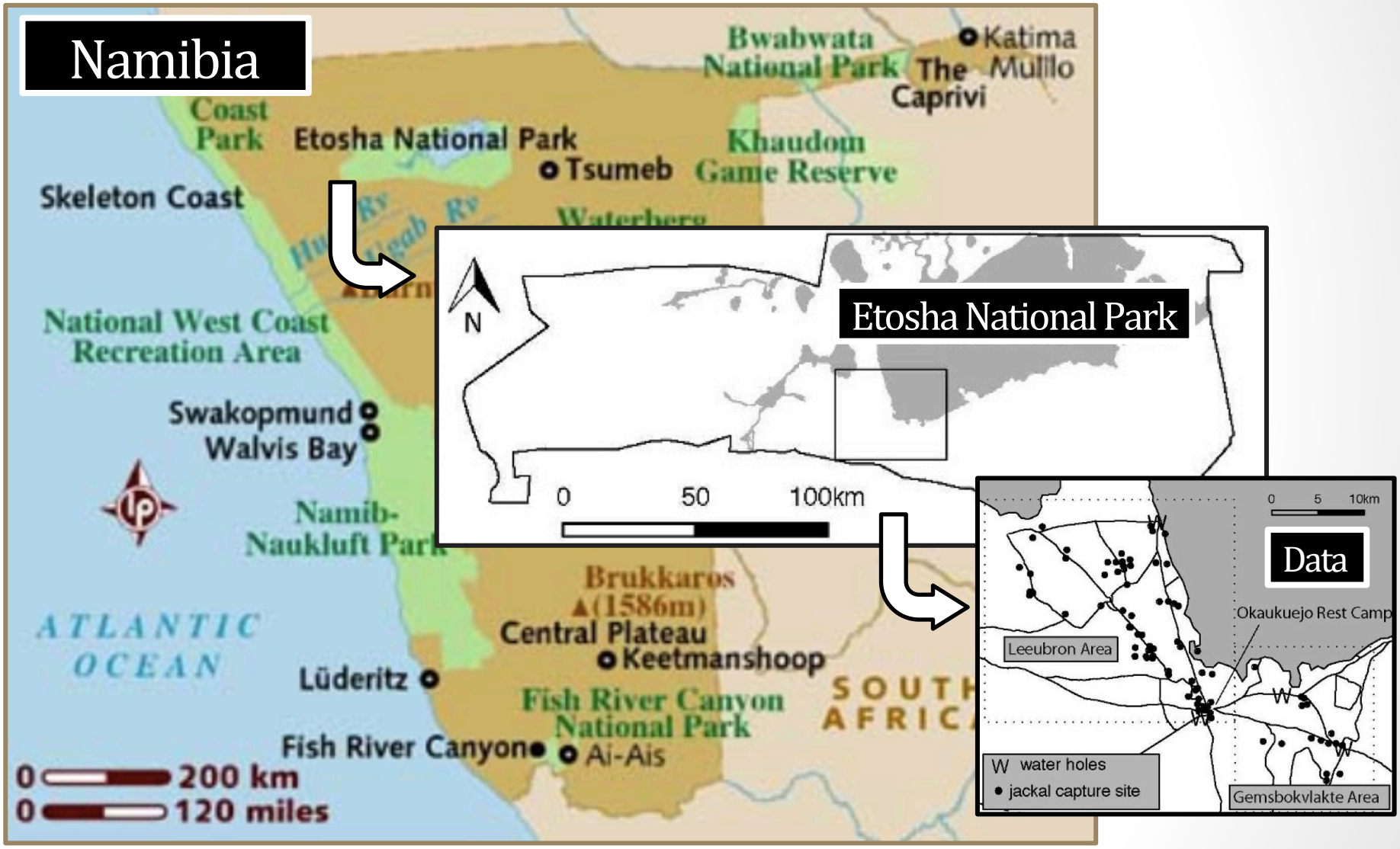
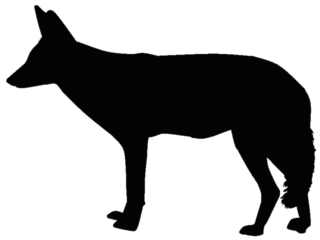
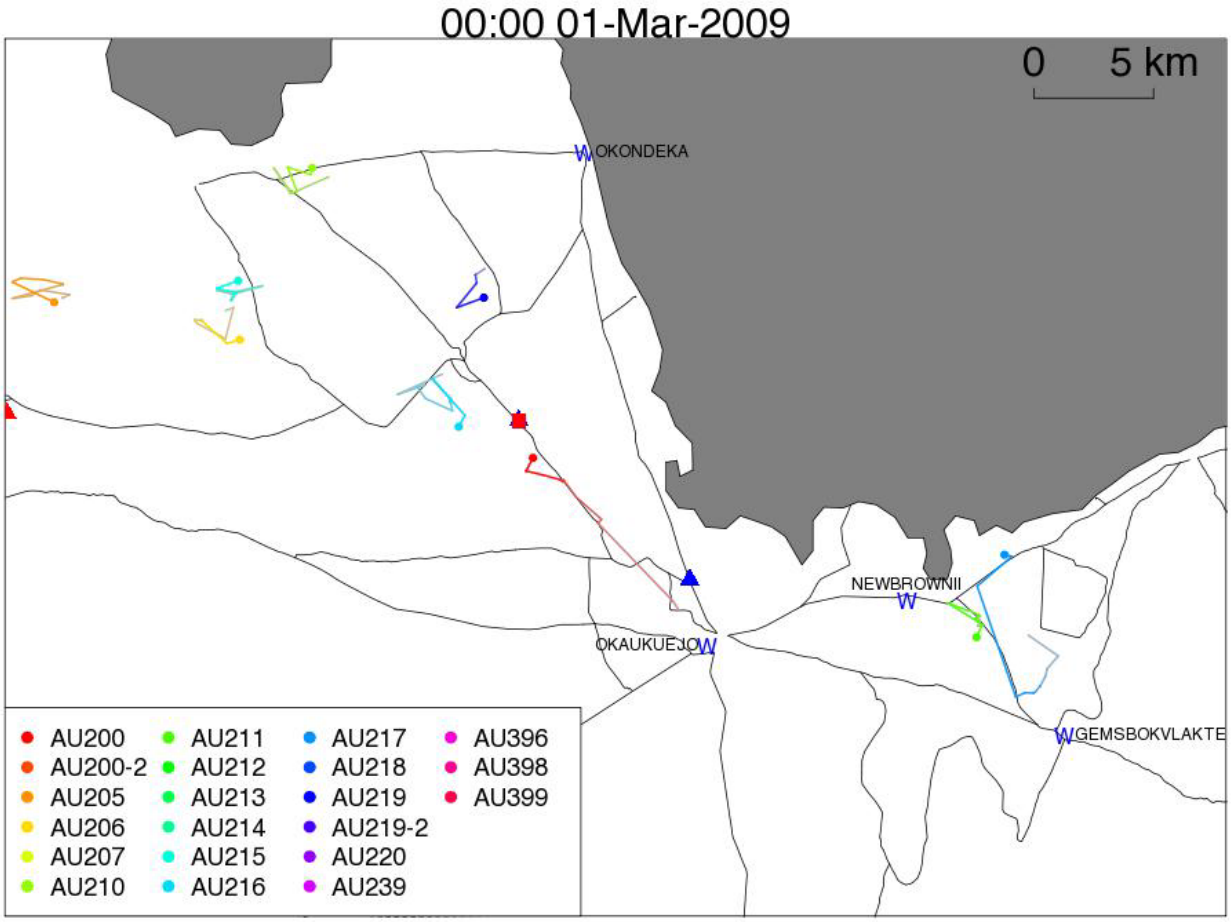


Image Credits: Bellan et al. 2012, lonelyplanet.com

Territorial jackals



Long movement data:



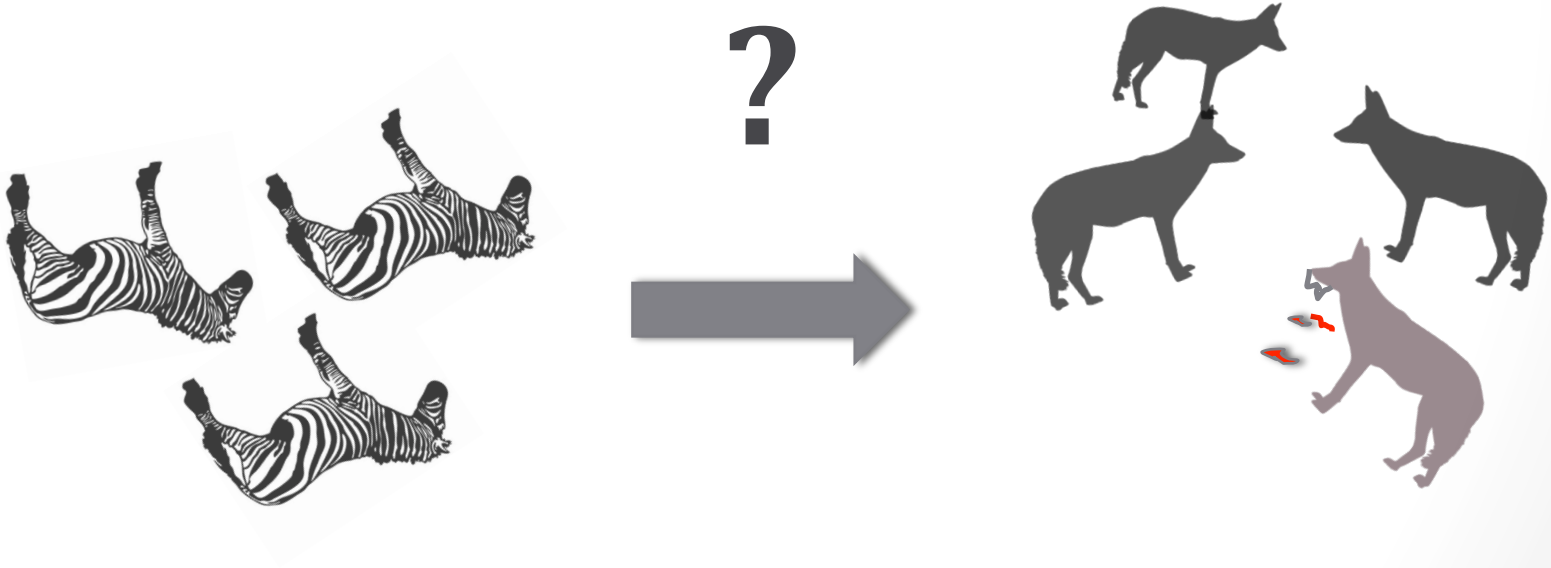
Data Credit: Bellan et al. 2012, Namibian Ministry of Environment & Tourism, Etosha Ecological Institute

Resource-driven encounters

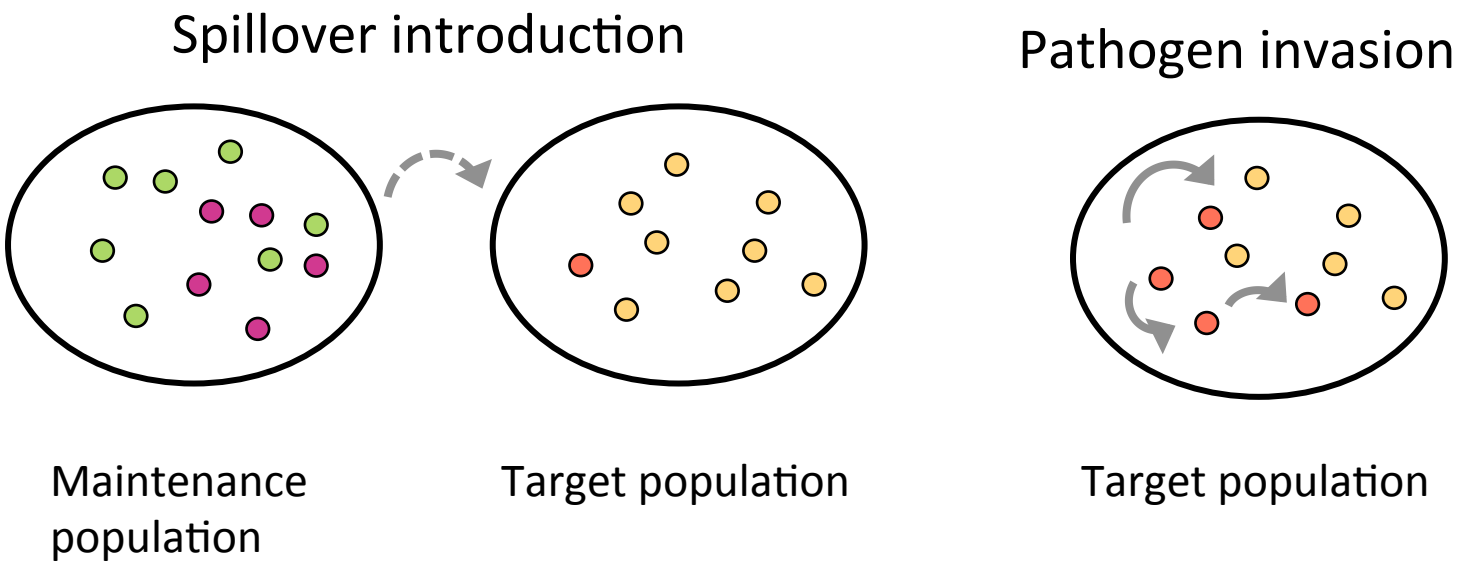
Data Credit: Bellan et al. 2012, Namibian Ministry of Environment & Tourism, Etosha Ecological Institute

Steve Bellan's Question

Can anthrax "cause" rabies?



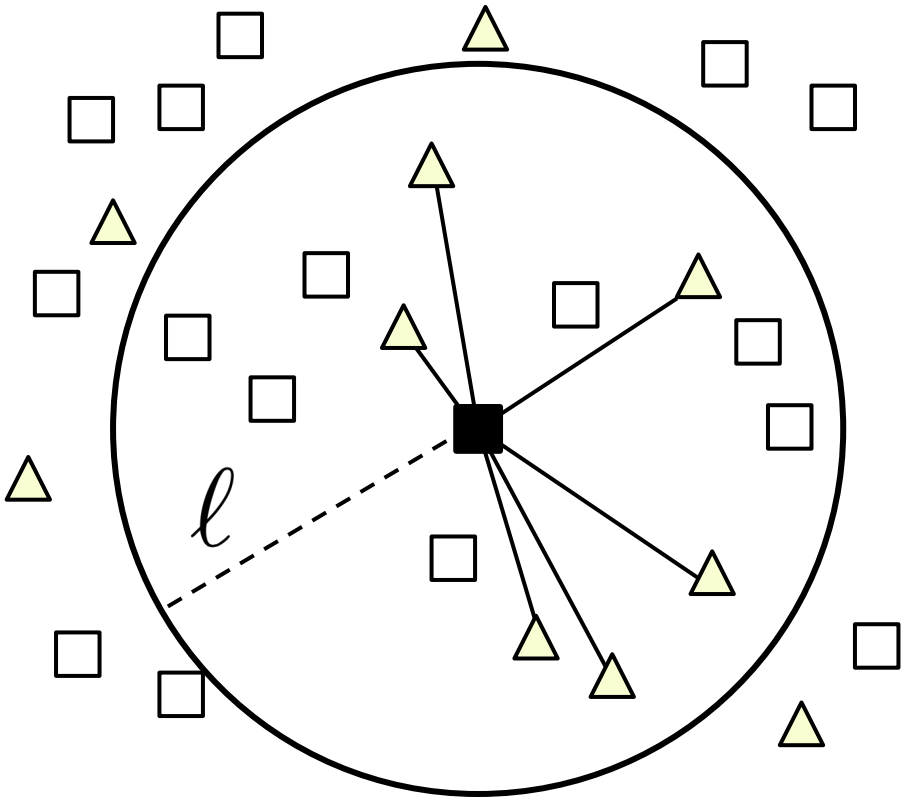
Concepts

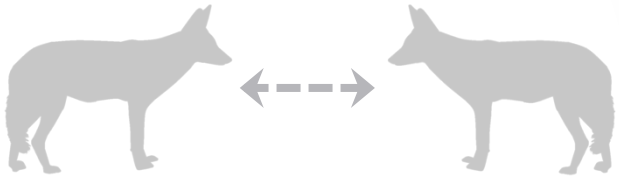


Our challenge -

Develop a consumer-resource model for the target population and quantify its encounter rates.

Resource-driven encounters





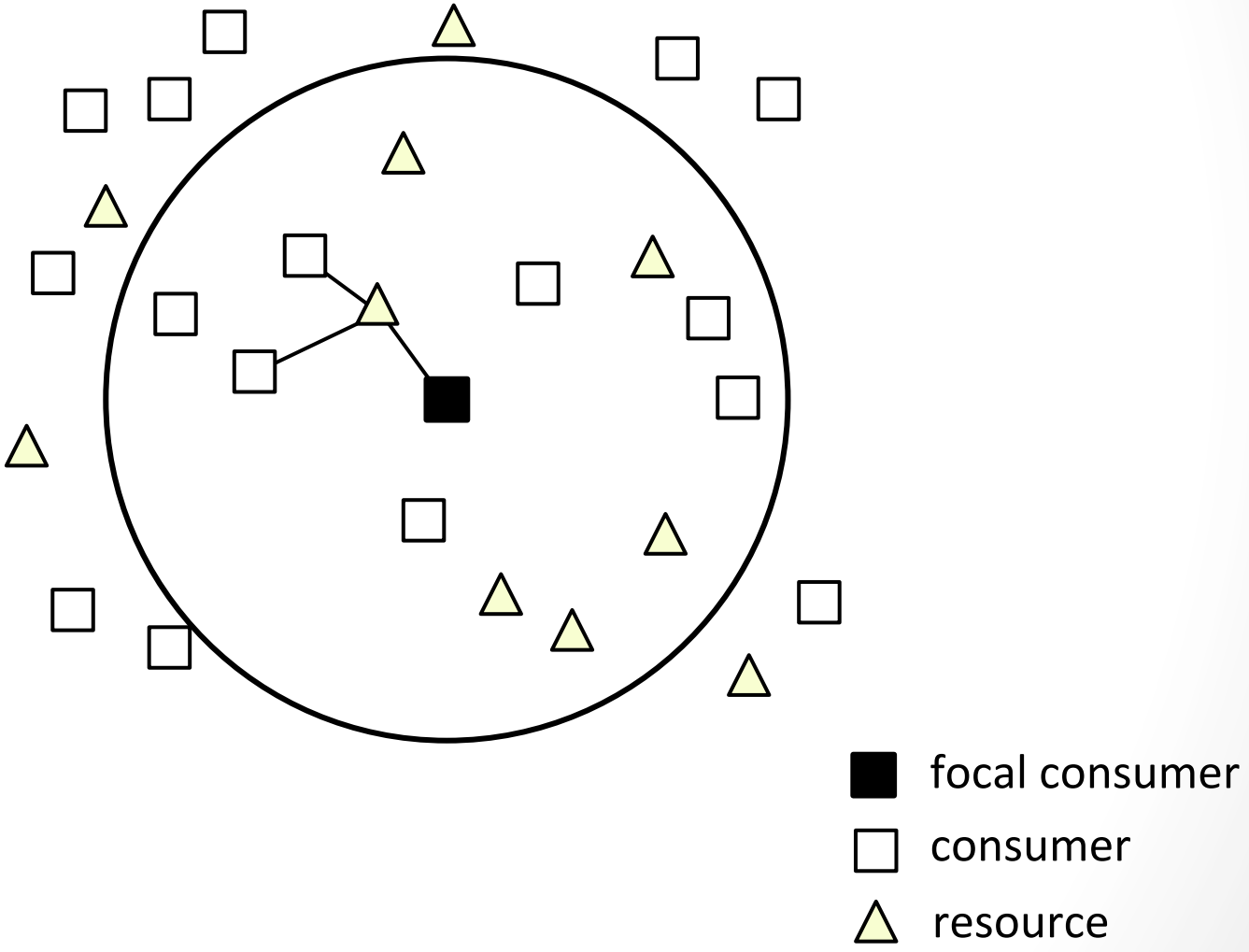
focal consumer

consumer

resource

Non-focal consumers and resources are distributed uniformly on a landscape as spatial Poisson processes with densities one consumer per unit area and κ resources per unit area.

Resource-driven encounters

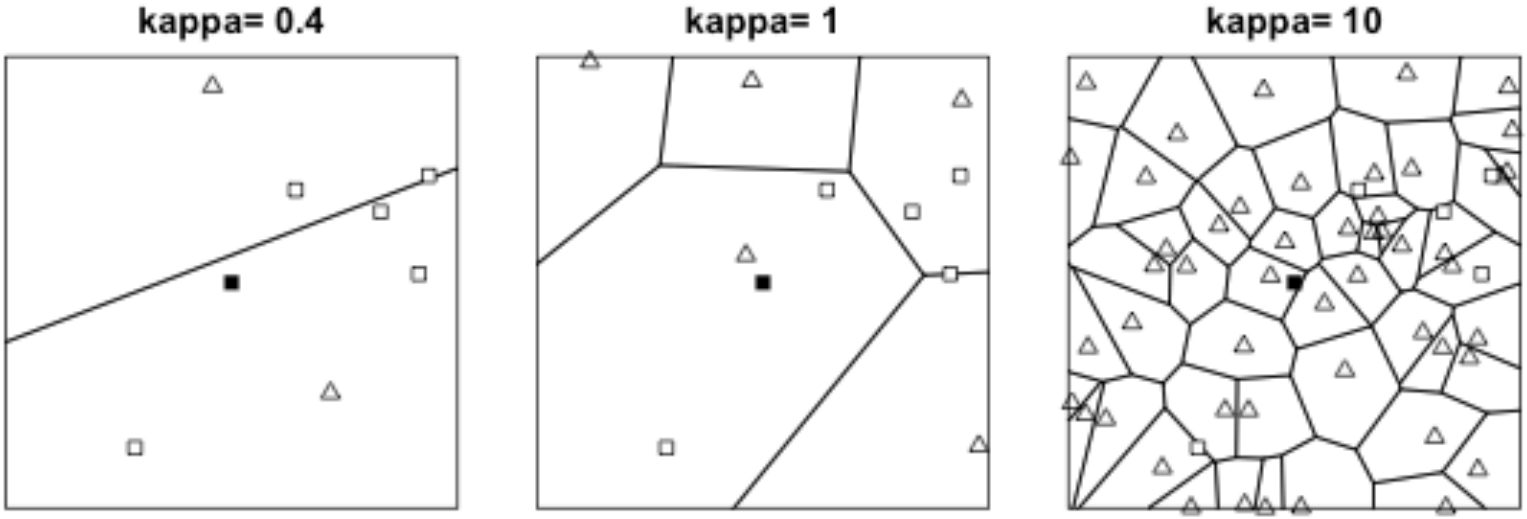


Model assumptions

- Spatial
  - Random distribution of both the non-focal consumers and resources

- Consumers
  - have a limited range of observation
  - prefer to visit the nearest resource they observe
  - respond to resources independently of other consumers
  - are satiated after visiting a resource

Regions of attraction



Voronoi diagram

"A partitioning of a plane into regions based on distance to points in a specific subset of the plane. That set of points is specified beforehand, and for each seed there is a corresponding region consisting of all points closer to that seed than to any other."

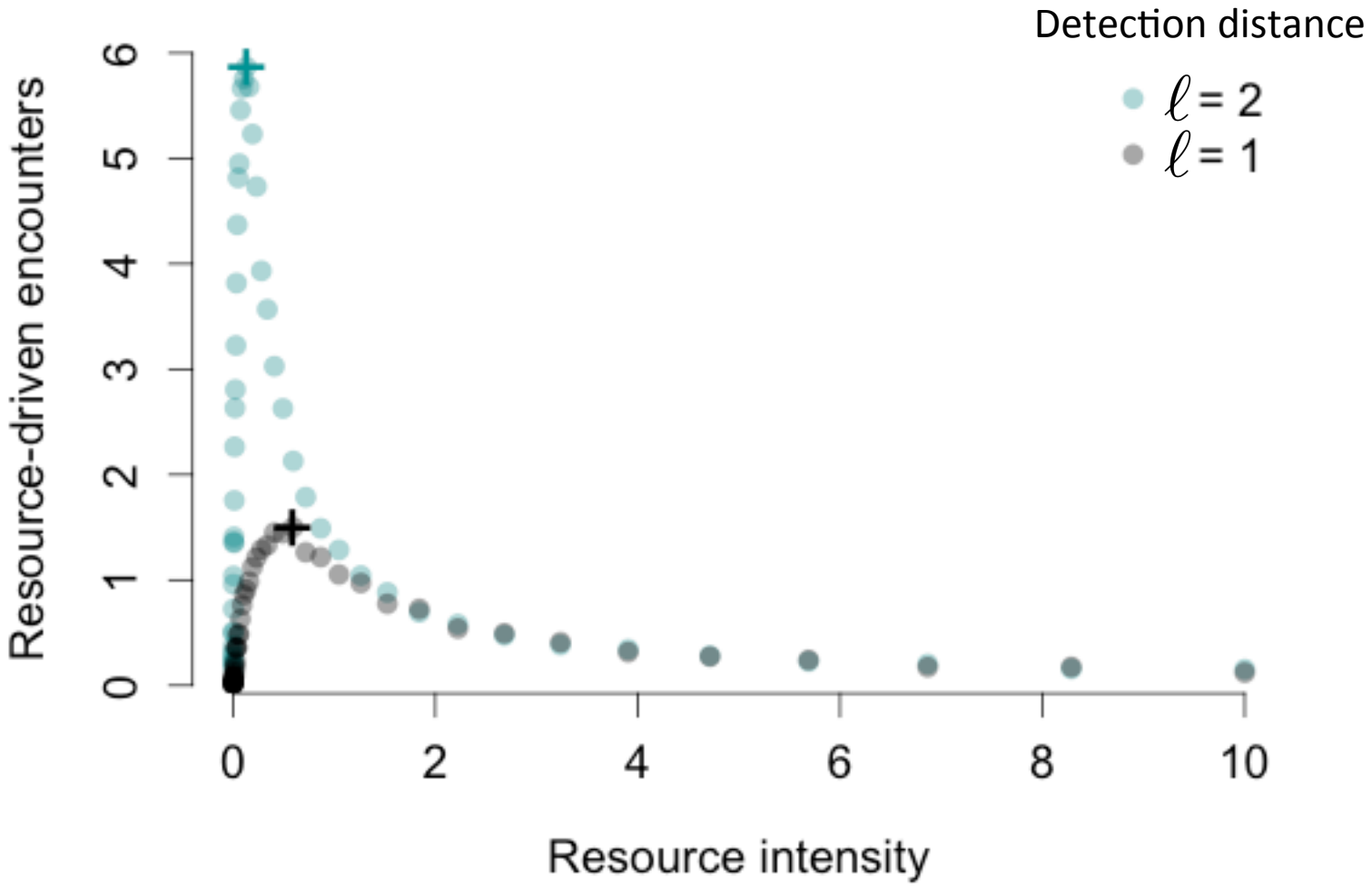
- Wikipedia

■ focal consumer

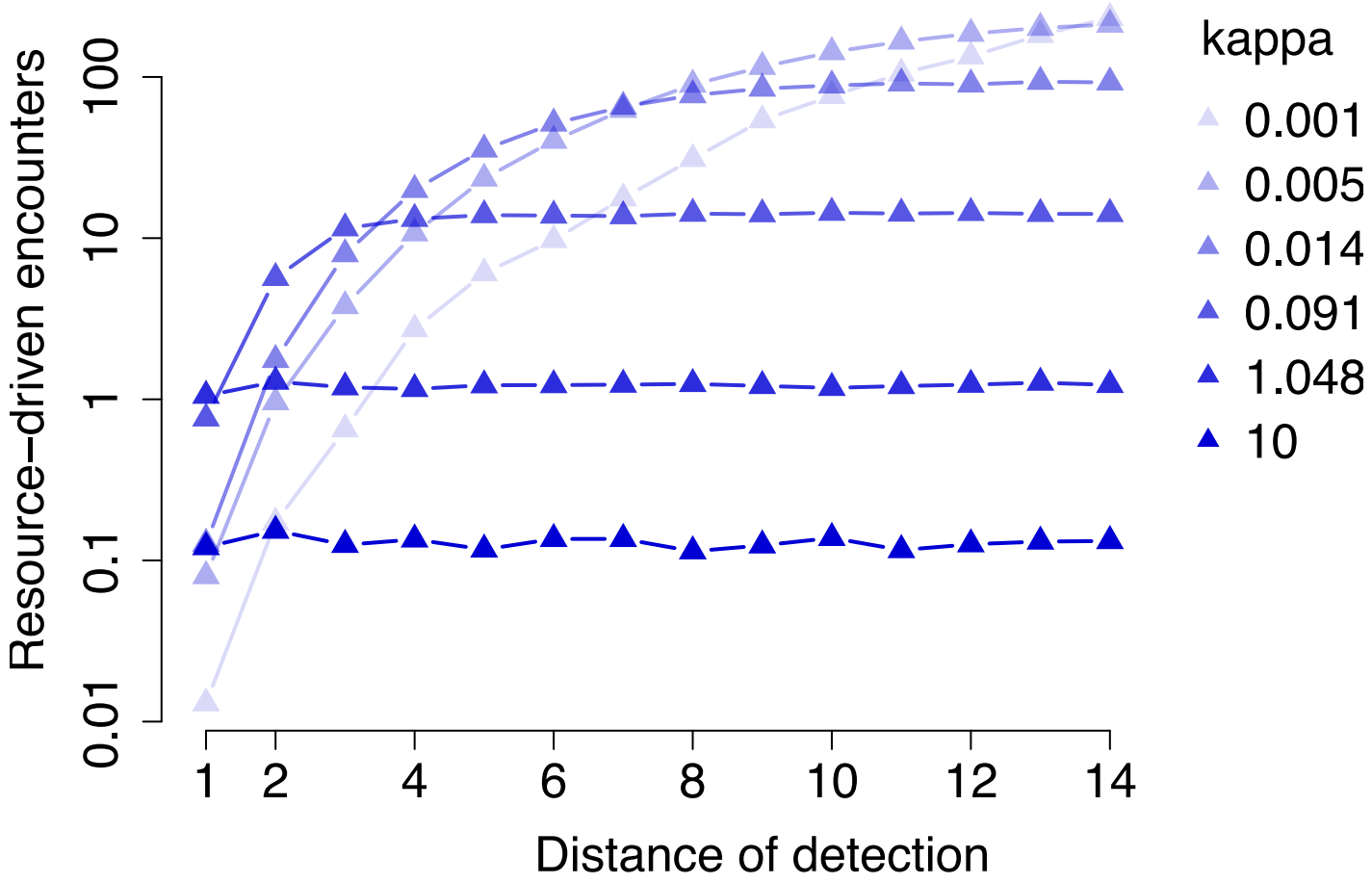
□ consumer

△ resource

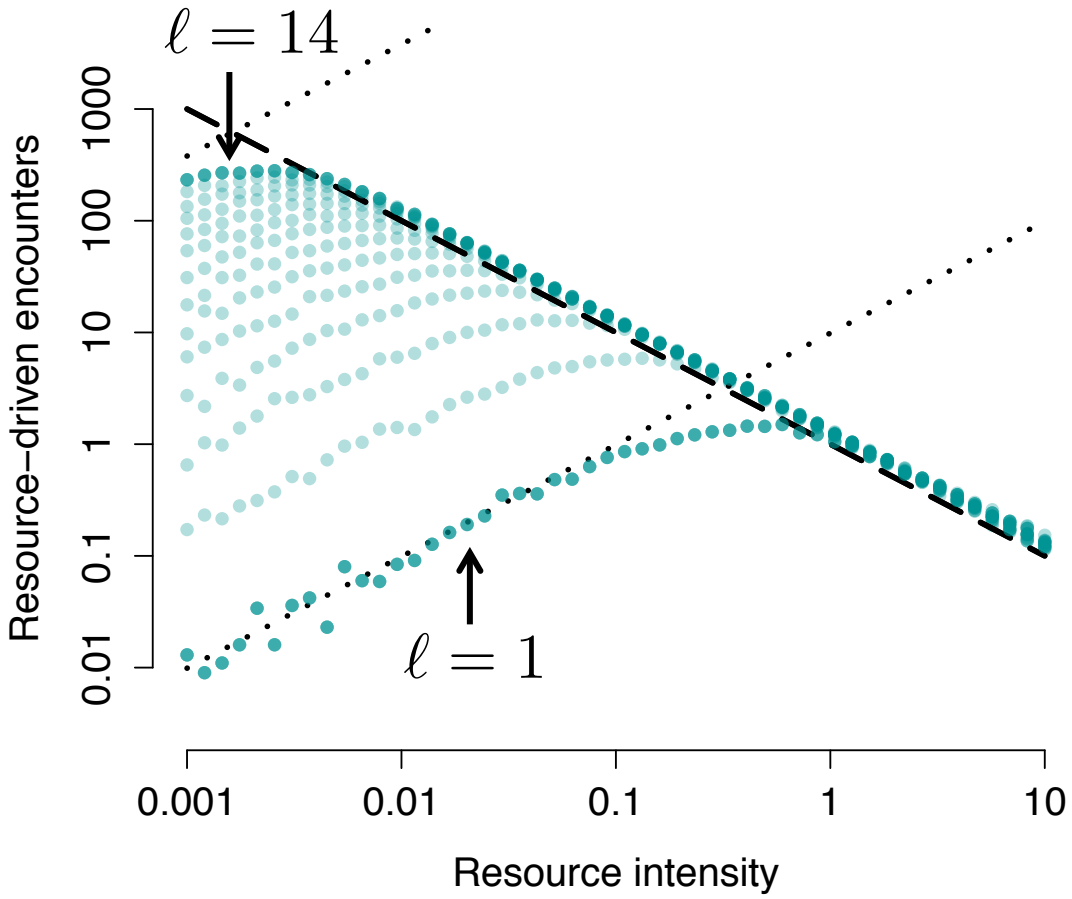
First result: non-monotonicity



Second result: detection distance matters



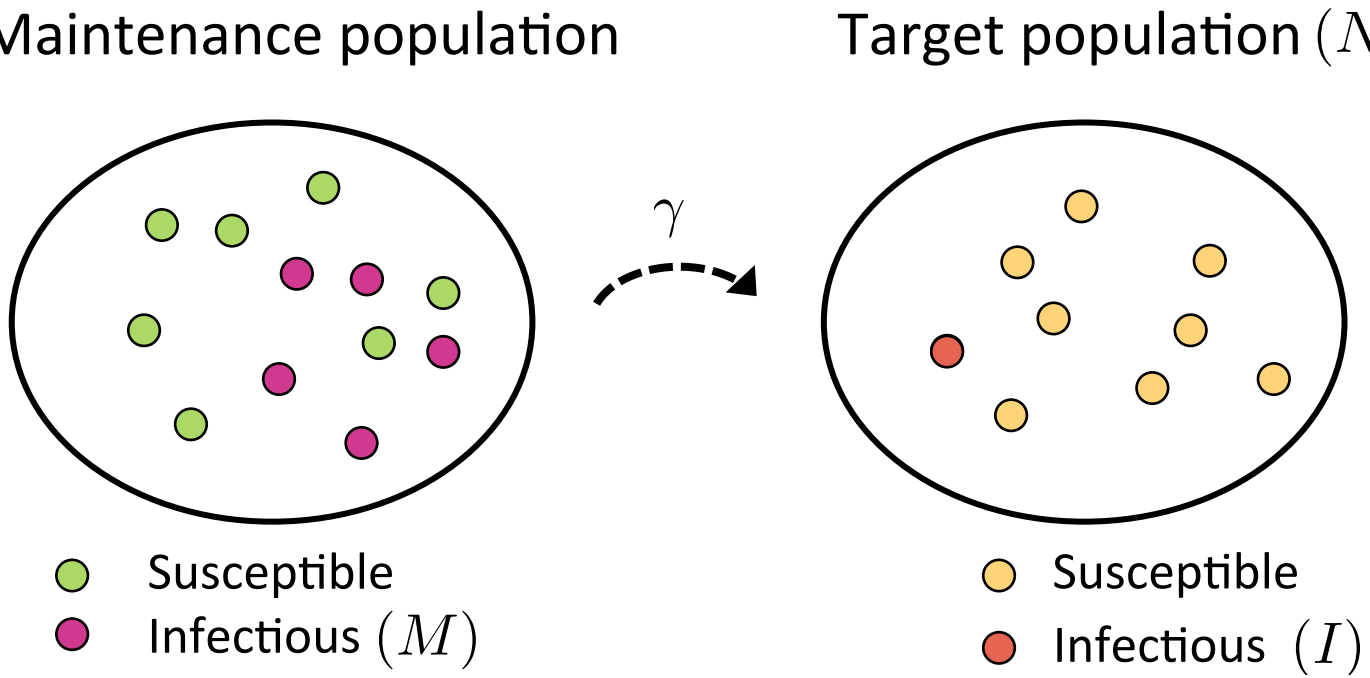
Simulations and predictions



low resource intensity approximation

high resource intensity approximation

Pathogen invasion



Spillover events are
modeled as a Poisson process with rate $\gamma M(N-I)$.

Successful pathogen invasion: when a spillover event produces a lineage which does not go extinct before reaching a quasi-stationary state.

SIS Model

CTMC

$$I \to I+1 \text{ at rate } b\left(\frac{N-I}{N}\right) I$$

$$I \to I-1 \text{ at rate } \nu I$$

ODE

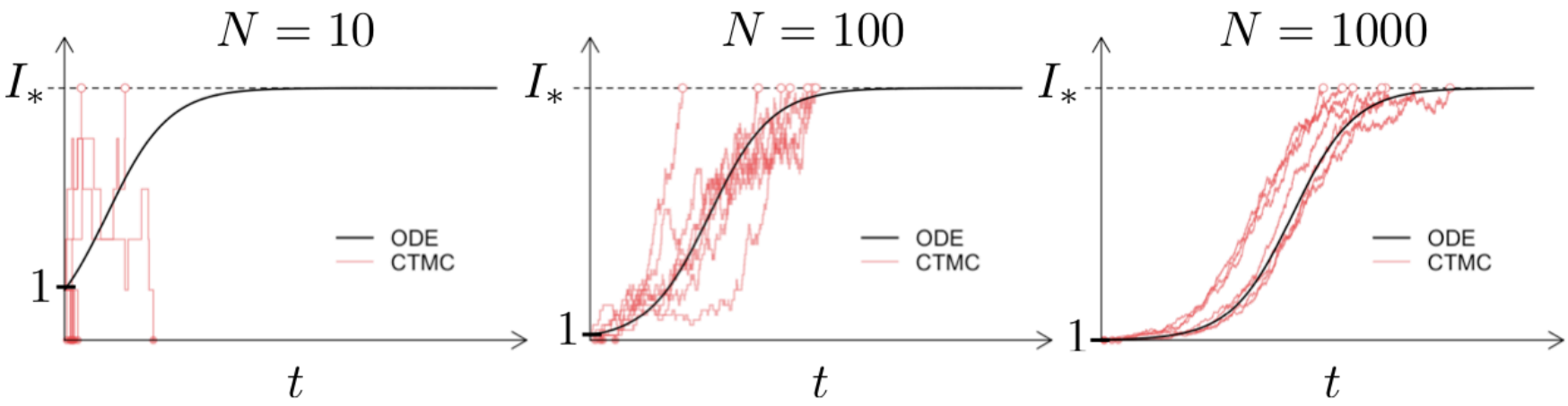
$$\dot{I} = \beta(N-I)I - \nu I$$

$$\beta \approx \frac{b}{N}, \quad \text{requires very large } N$$

$b =$ expected number of infections due to a single individual in a large population per time

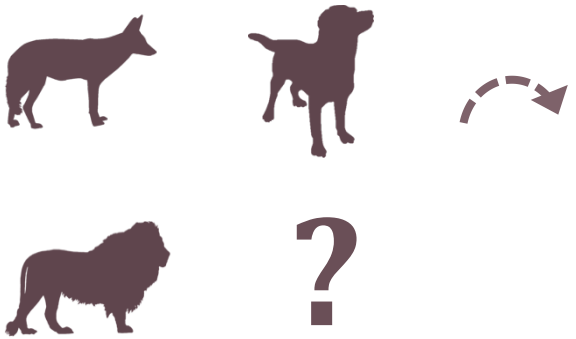
$\nu =$ disease-related mortality rate

$$I_* = N\left(1 - \frac{\nu}{b}\right)$$

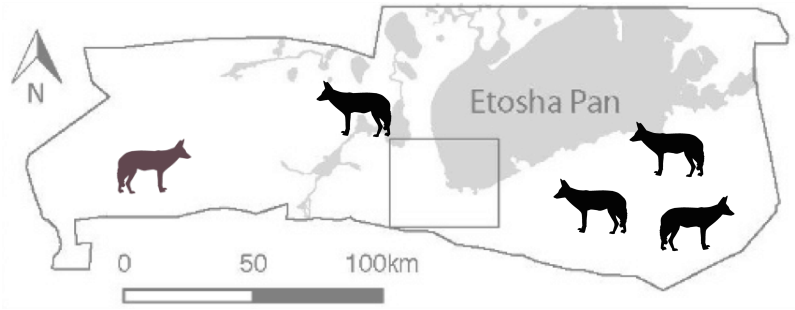


Connecting back to rabies in Etosha jackals…

Maintenance population



Target population



Jackal system

Parameter	Value	Meaning	Source
b	1	infection per week	Rhodes et al. 1998
ν	1.4	rabies related deaths per week	Rhodes et al. 1998
ρ	1	jackal density	Rhodes et al. 1998

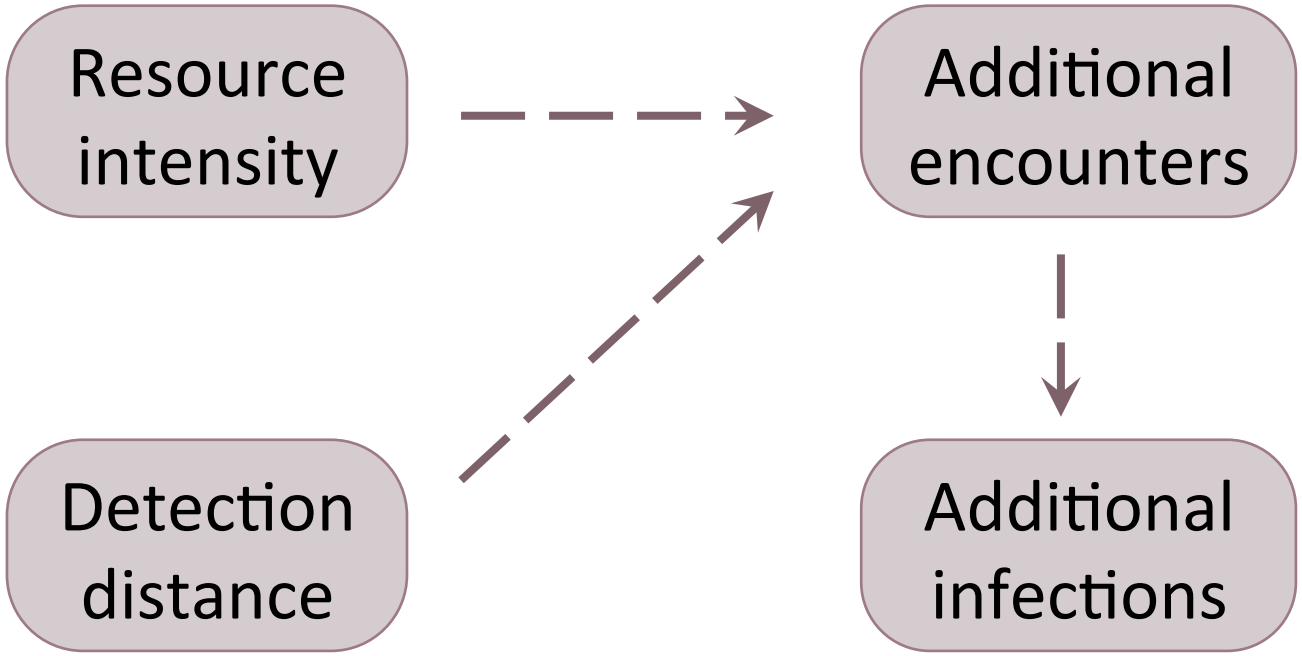
$$R_0 = \frac{b}{\nu} = \frac{1}{1.4} \approx 0.7 \qquad \text{(rabies is sub-critical)}$$

p_{inf} = prob. of infection
$\mathcal{E}$ = # resource-driven encounters

How does $\dfrac{b + p_{\text{inf}} \cdot \mathcal{E}}{\nu}$ compare to $\dfrac{b}{\nu}$?

Rhodes et al. (1998) "Rabies in Zimbabwe: reservoir dogs and the implications for disease control." *Philosophical Transactions of the Royal Society B*.

Calculating a temporal reproduction number



Resource intensity

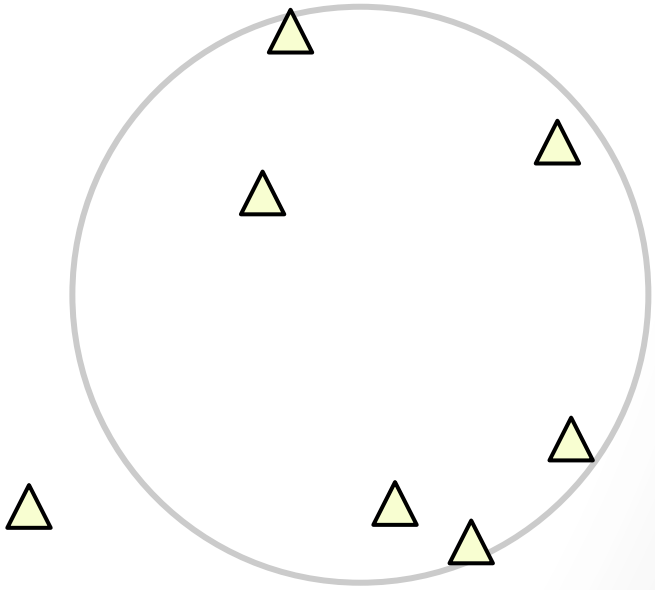
$$\kappa = \frac{\text{\# of carcasses}}{\text{\# of jackals}}$$

$$\kappa = \frac{\text{\# of carcasses / study area}}{\text{\# of jackals / study area}}$$

Resource intensity

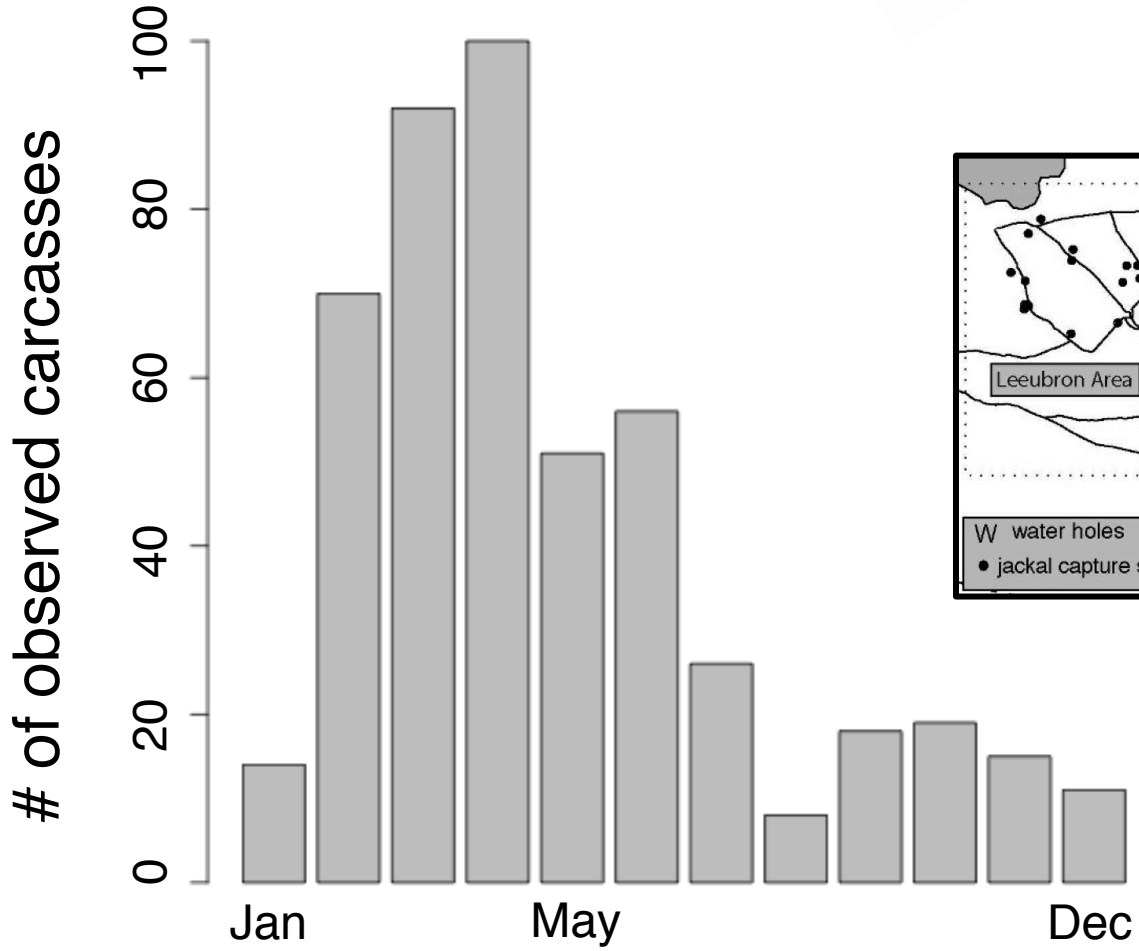
$$\kappa = \frac{\text{\# of carcasses}}{\text{\# of jackals}}$$

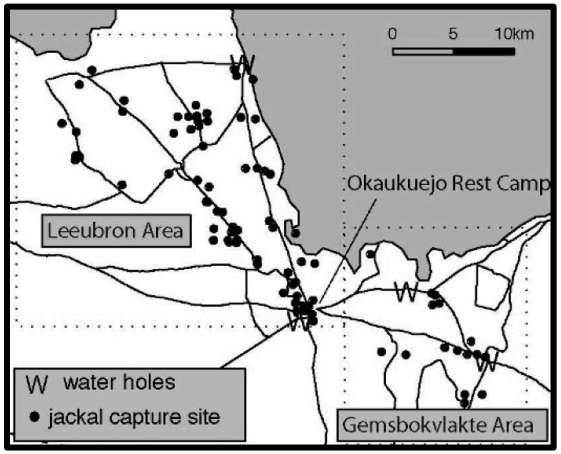
△ resource



of carcasses

Resource intensity

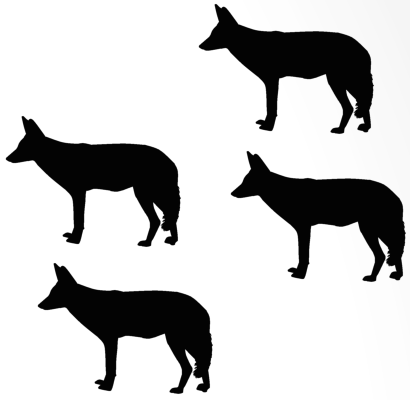




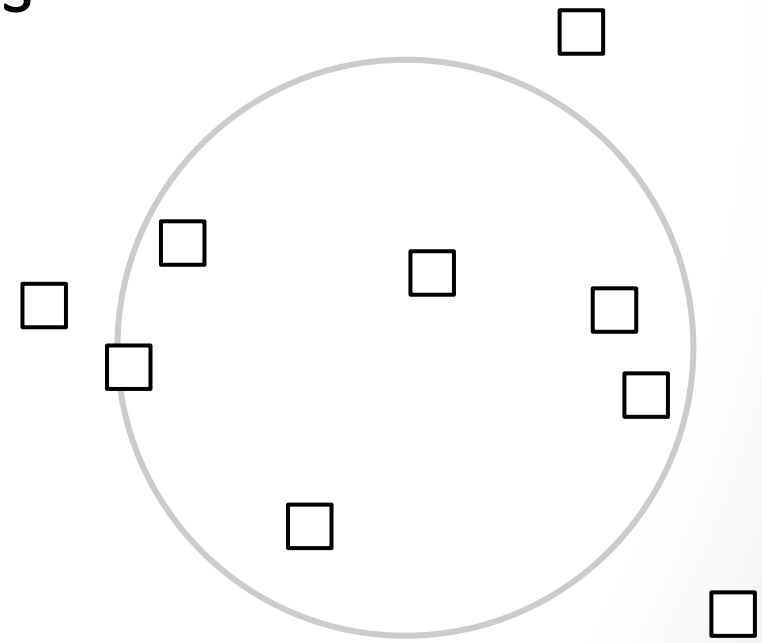
Scale up:
observed x 4
Bellan et al. 2013

Bellan, Steve E., et al. "A hierarchical distance sampling approach to estimating mortality rates from opportunistic carcass surveillance data." *Methods in Ecology and Evolution* 4.4 (2013): 361-369.

Resource intensity



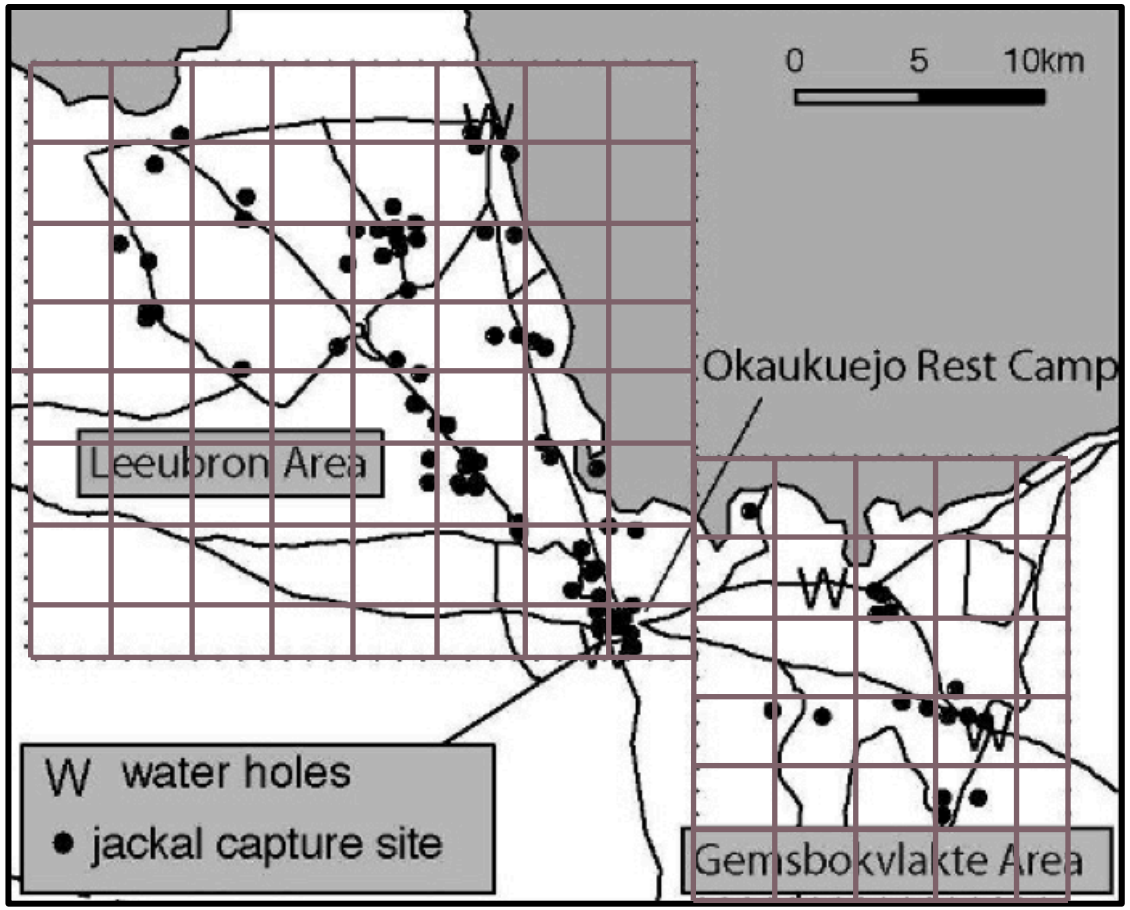
$$\kappa = \frac{\text{\# of carcasses}}{\text{\# of jackals}}$$



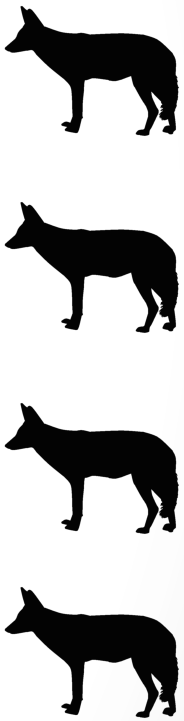
□ consumer

of jackals

Resource intensity



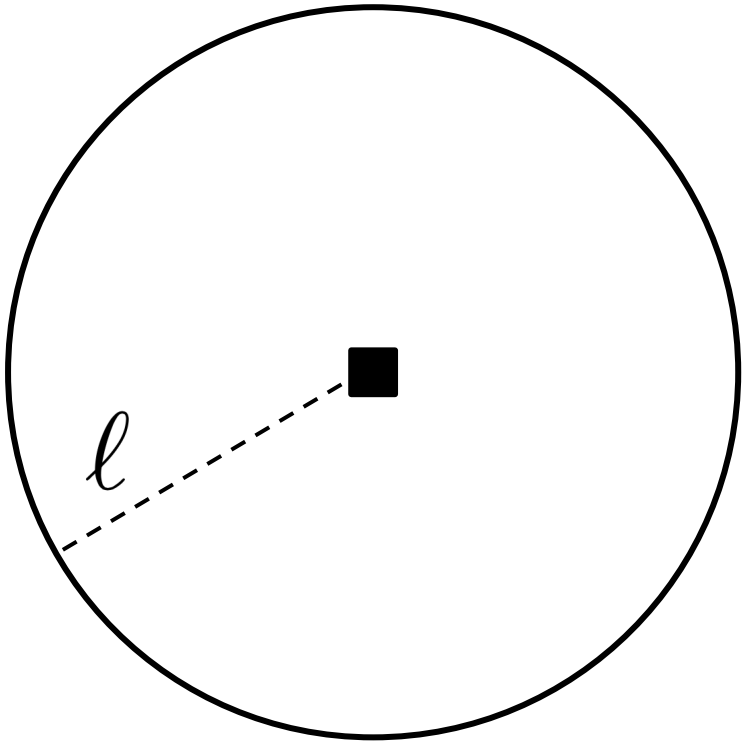
×



defendable territories

family size

Detection distance

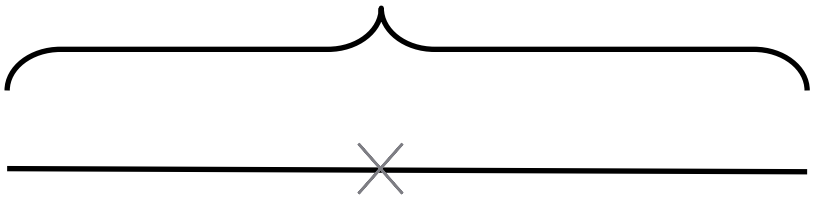


focal consumer

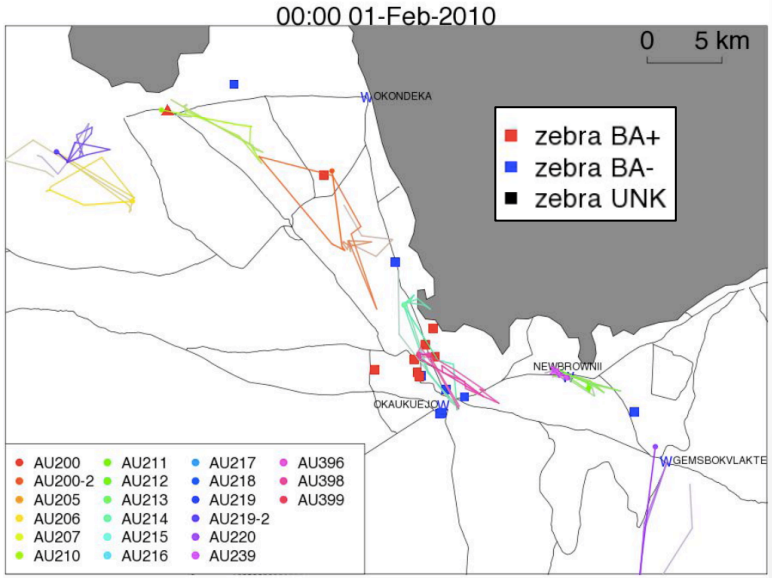
Time scale of reference

"carcass active interval"

~ one week



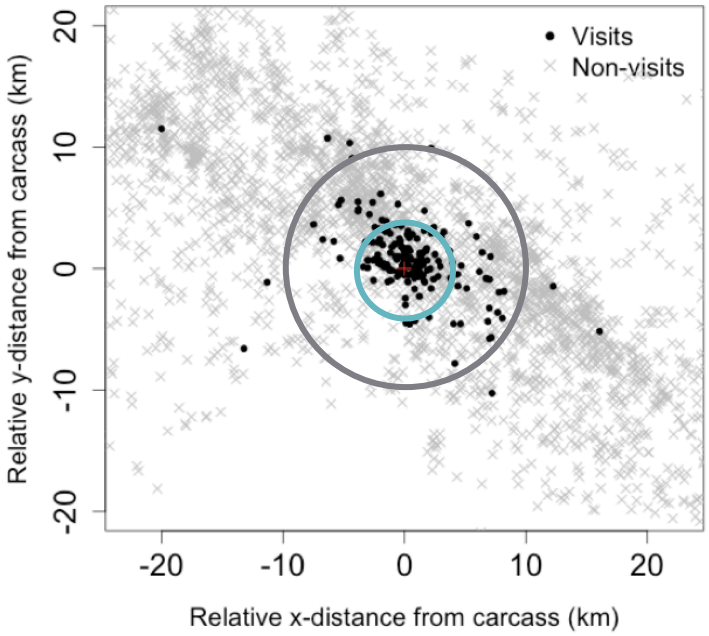
carcass observed

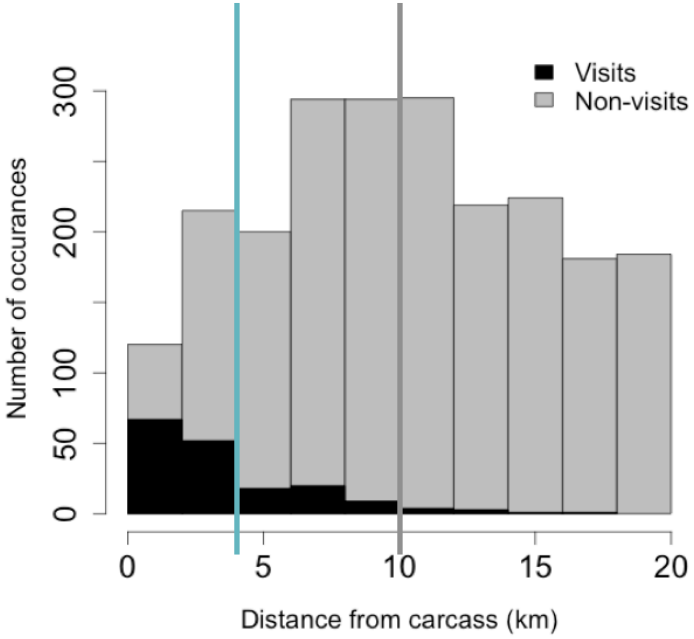


Data Credit: Bellan et al. 2012, Namibian Ministry of Environment & Tourism, Etosha Ecological Institute

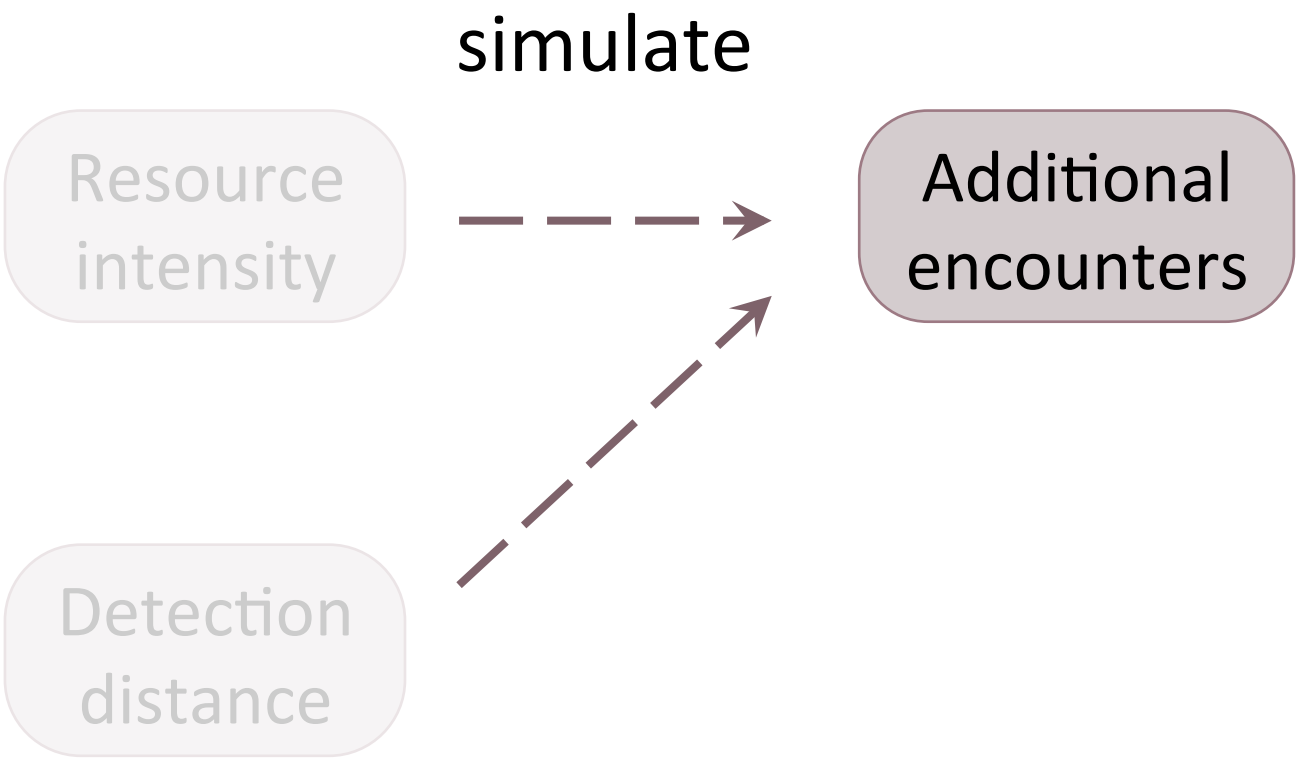
Carcass visitation

Detection distance





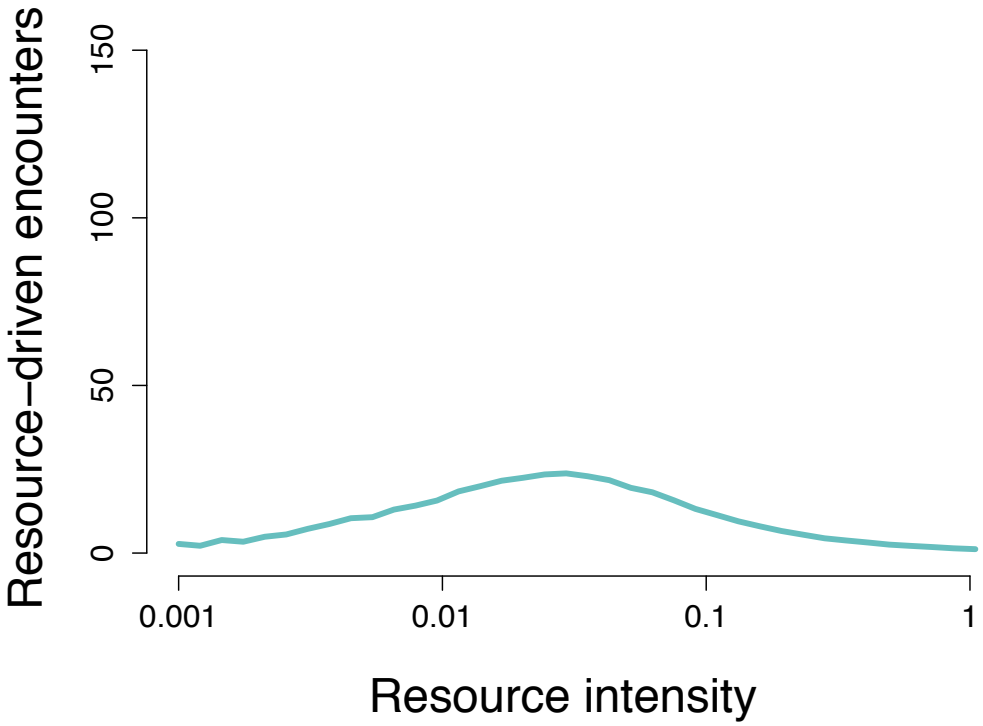
Calculating a temporal reproduction number



Simulation results

Additional encounters

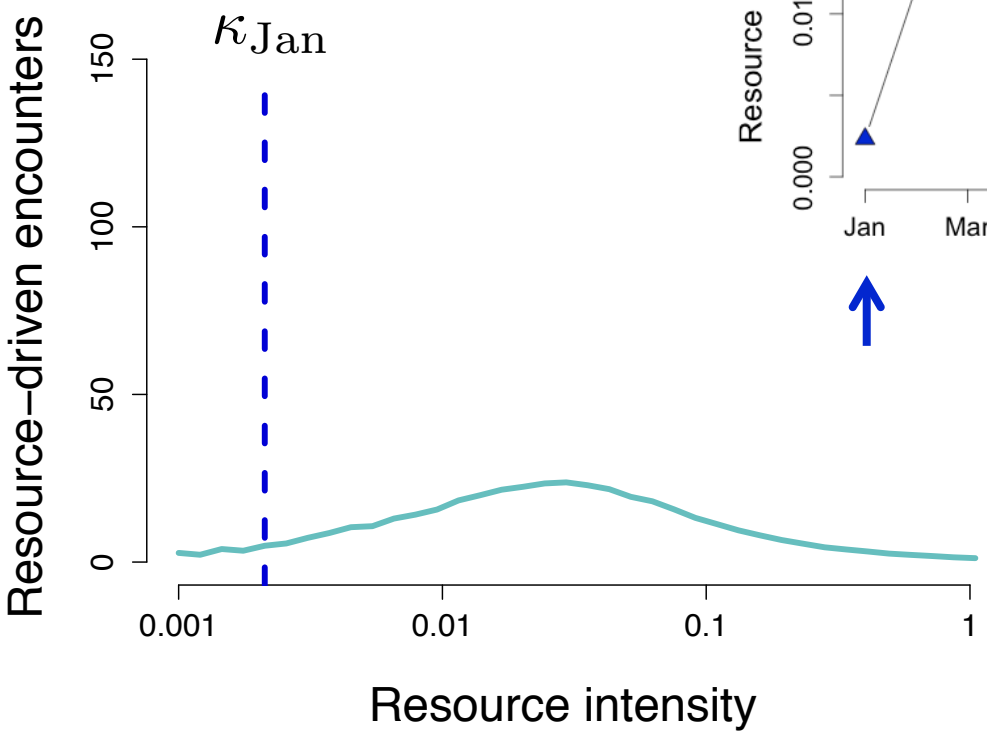
$$\ell = 4$$

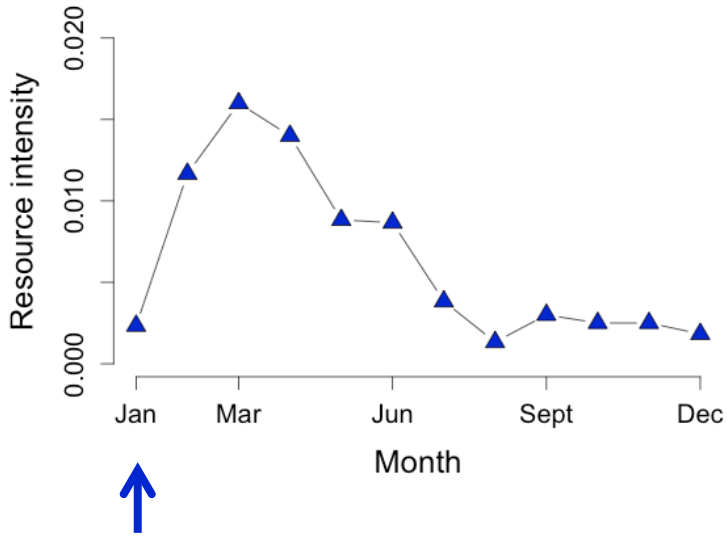


Simulation results

Additional encounters

$\ell = 4$

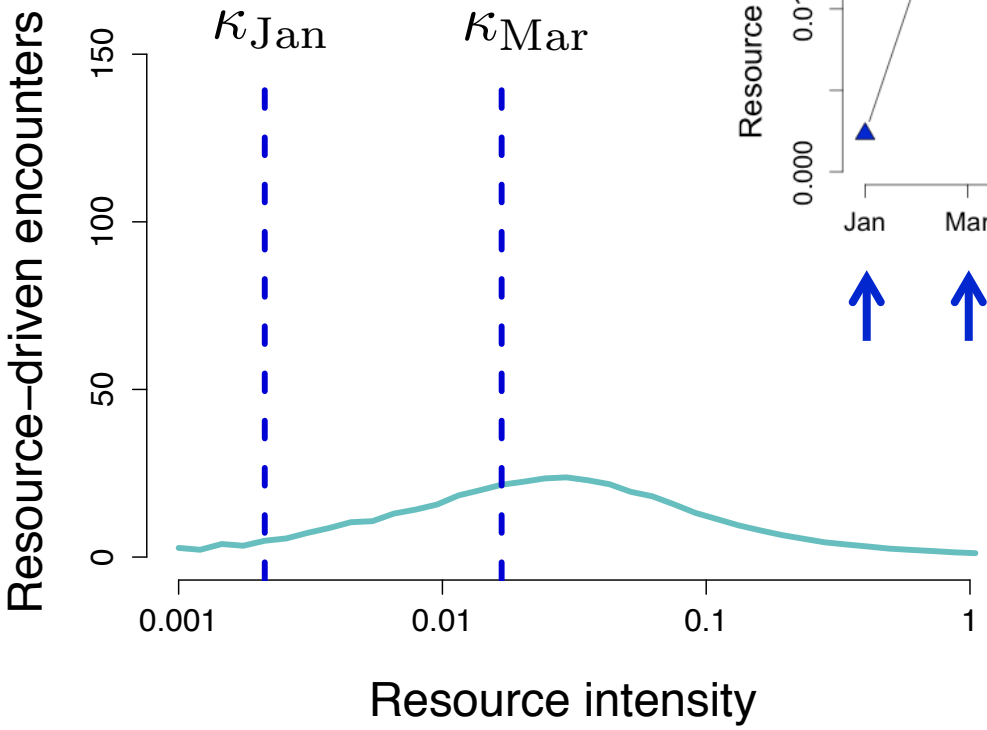


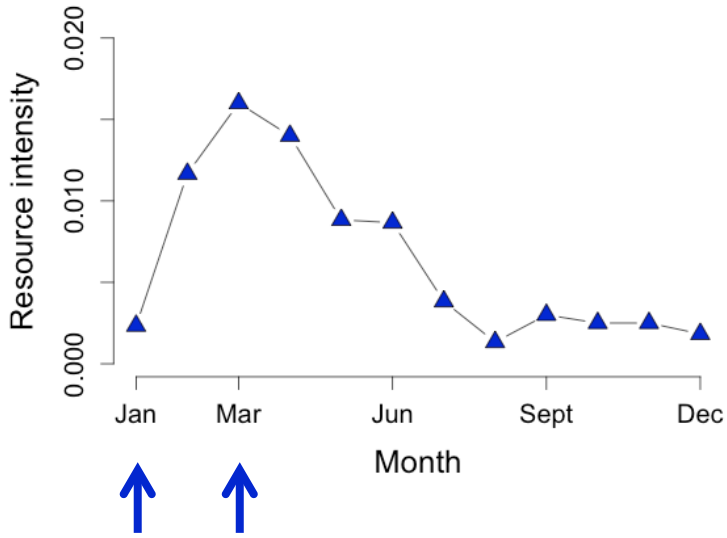


Simulation results

Additional encounters

$\ell = 4$

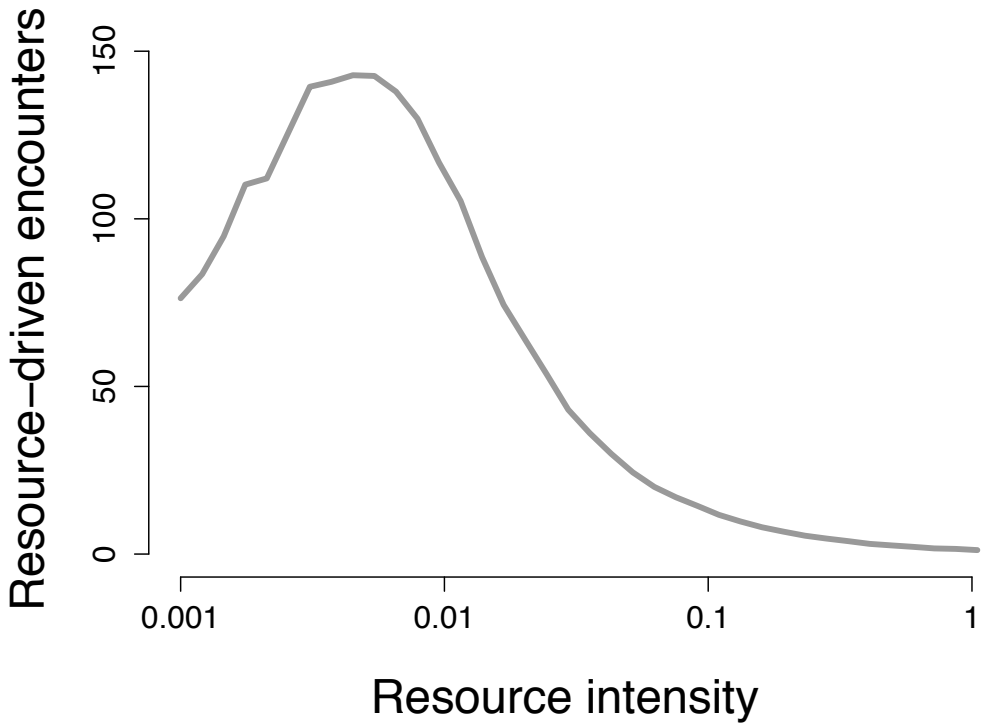




Simulation results

Additional encounters

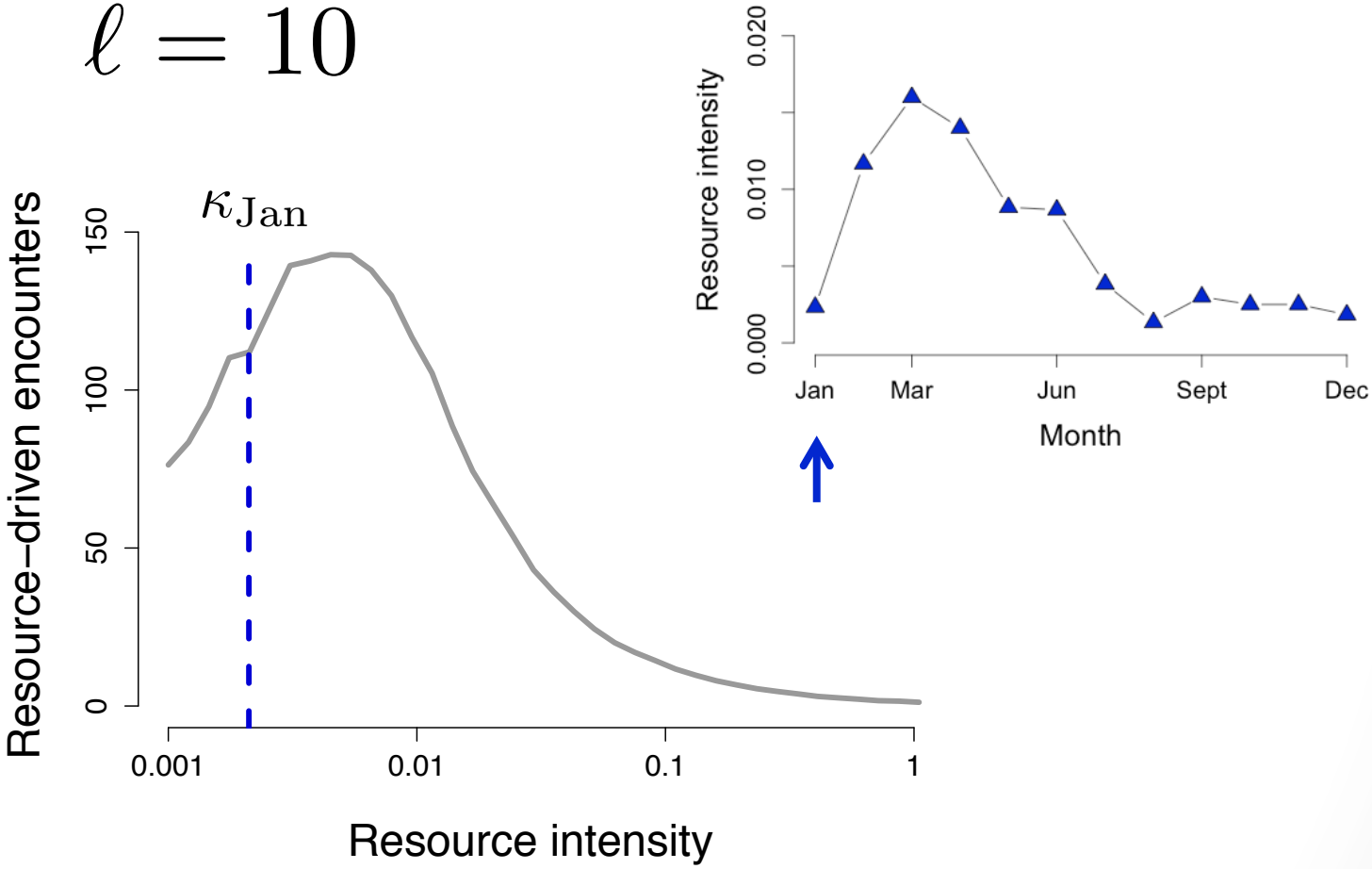
$$\ell = 10$$



Simulation results

Additional encounters

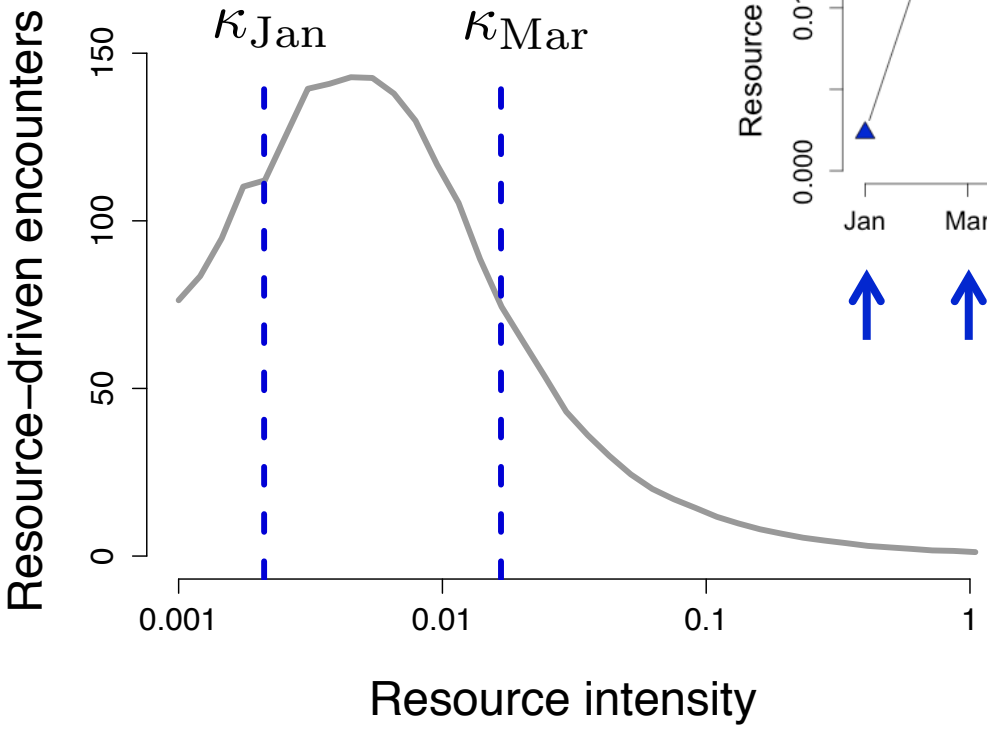
$\ell = 10$

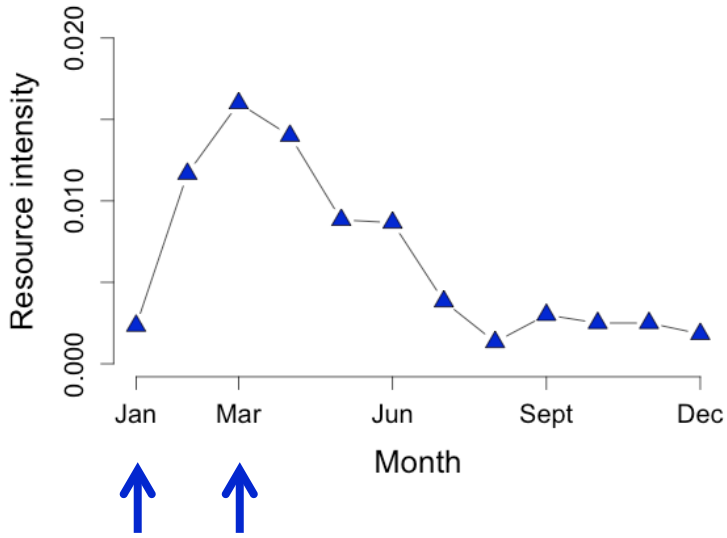


Simulation results

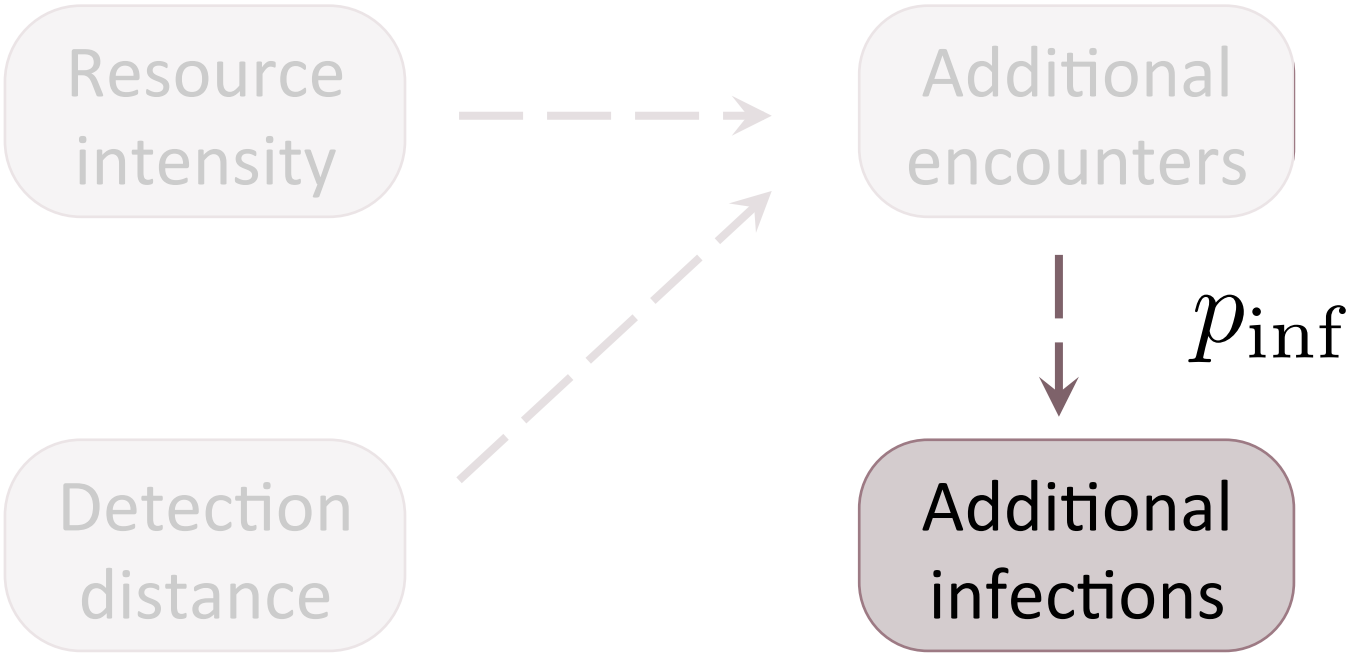
Additional encounters

$\ell = 10$



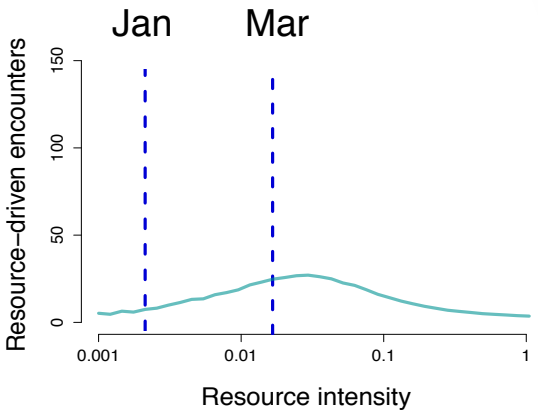


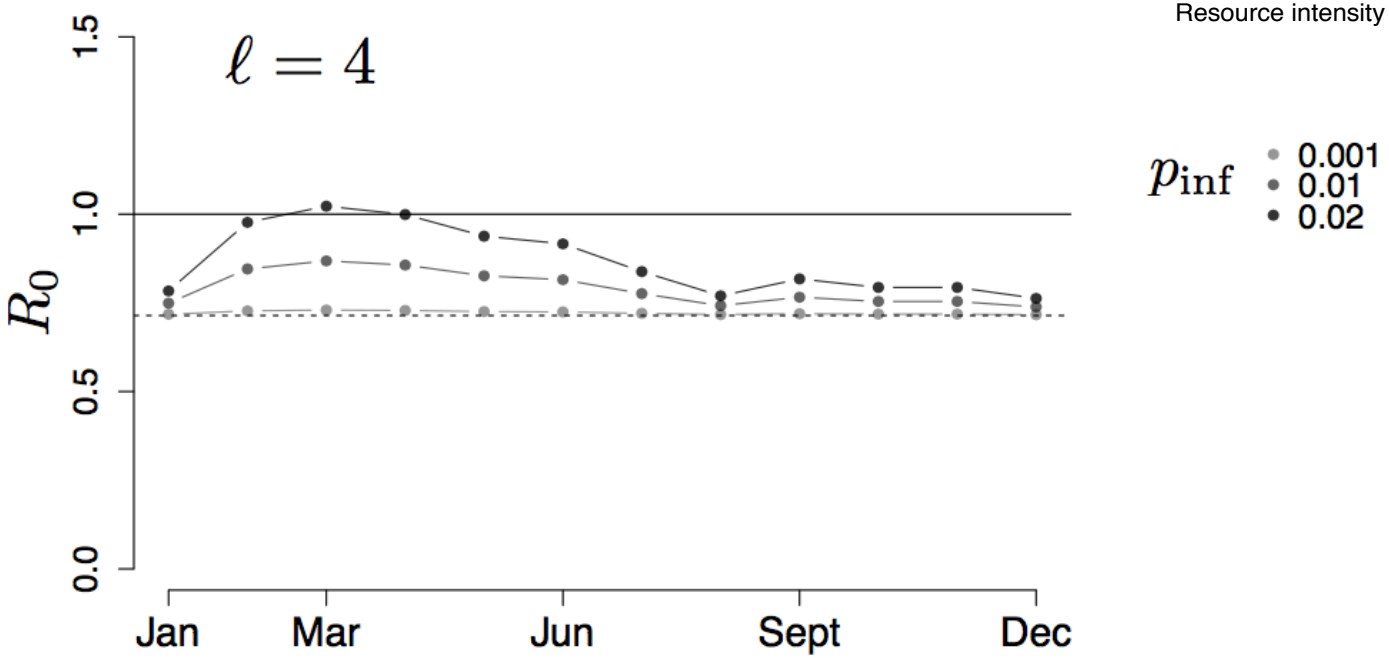
Calculating a temporal reproduction number



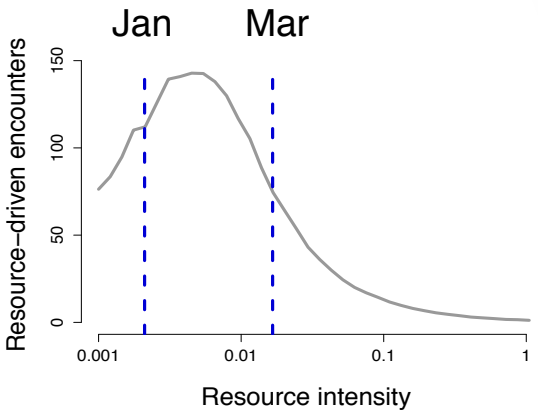
Adjust by the probability of infection given a resource-driven encounter (p_{inf}).

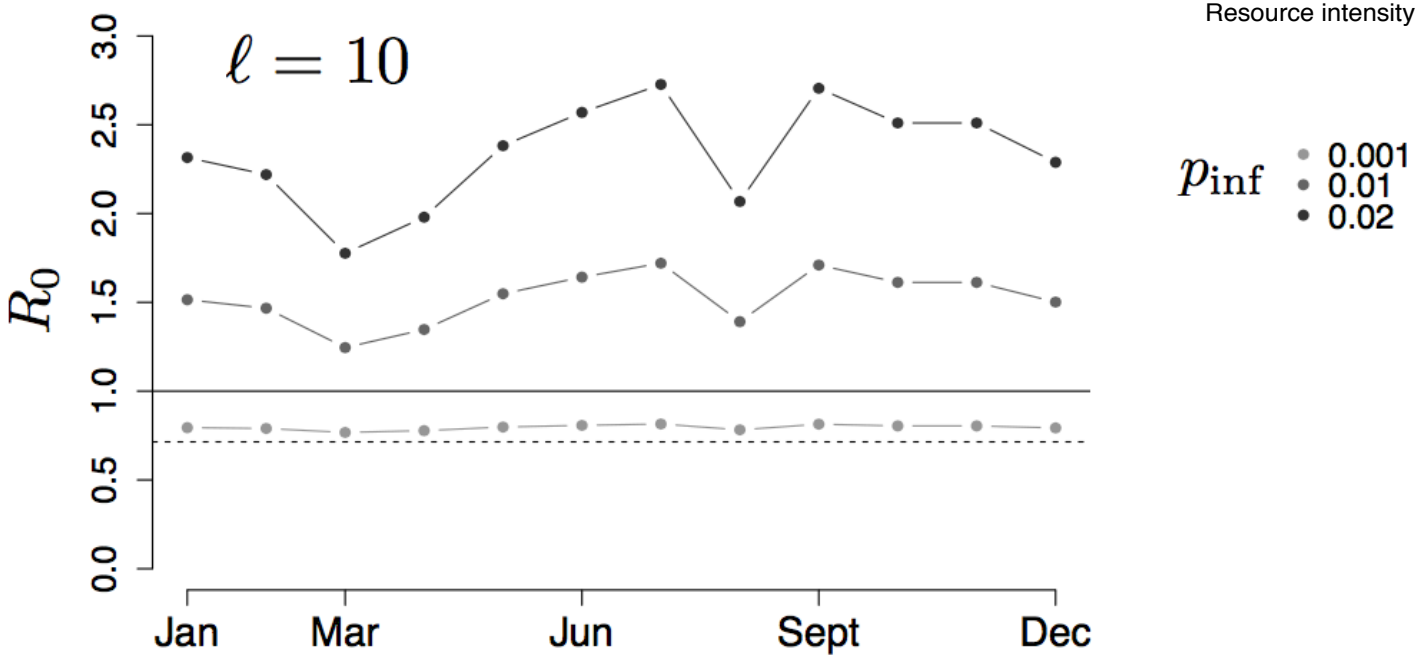
Temporal reproduction number



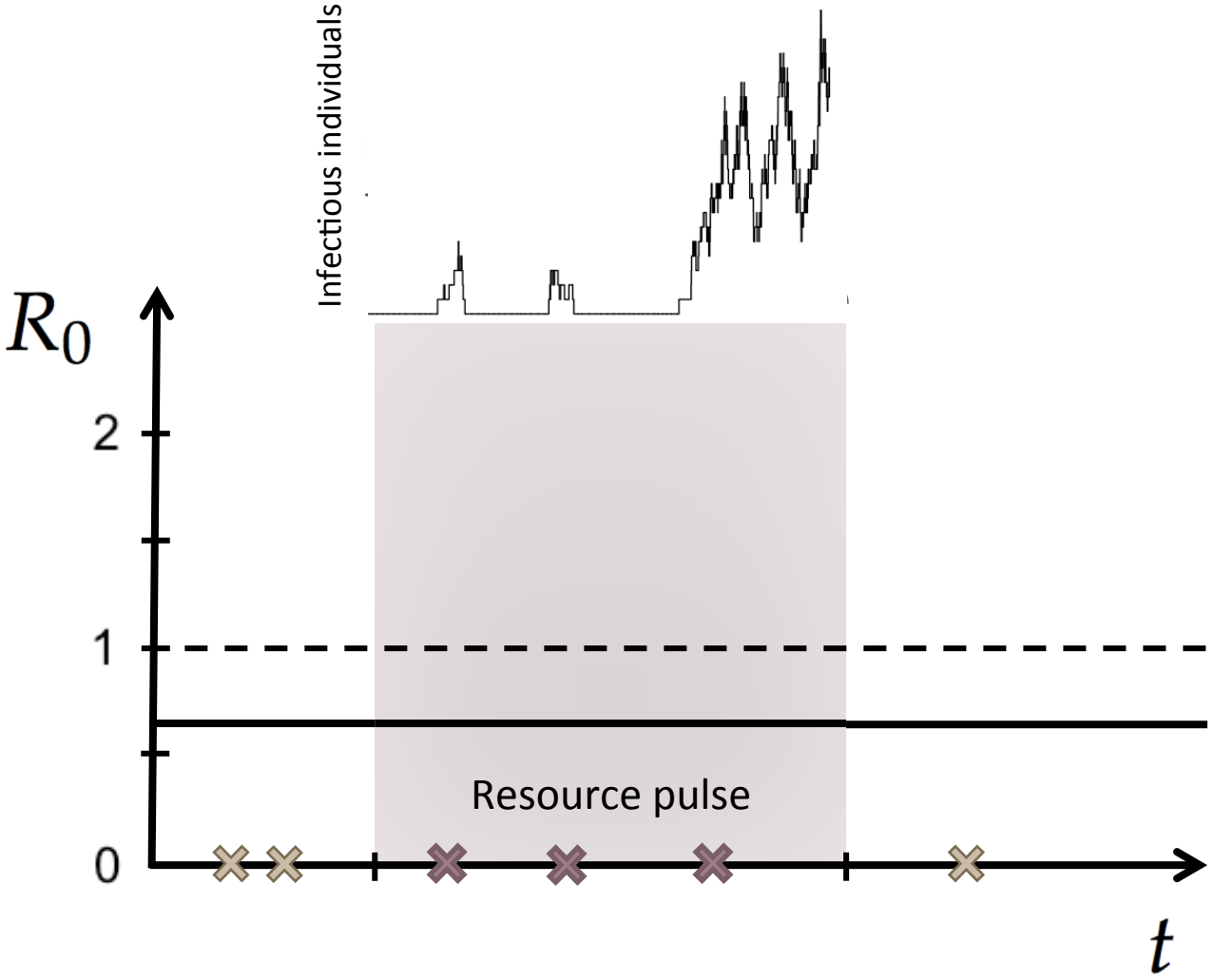


Temporal reproduction number





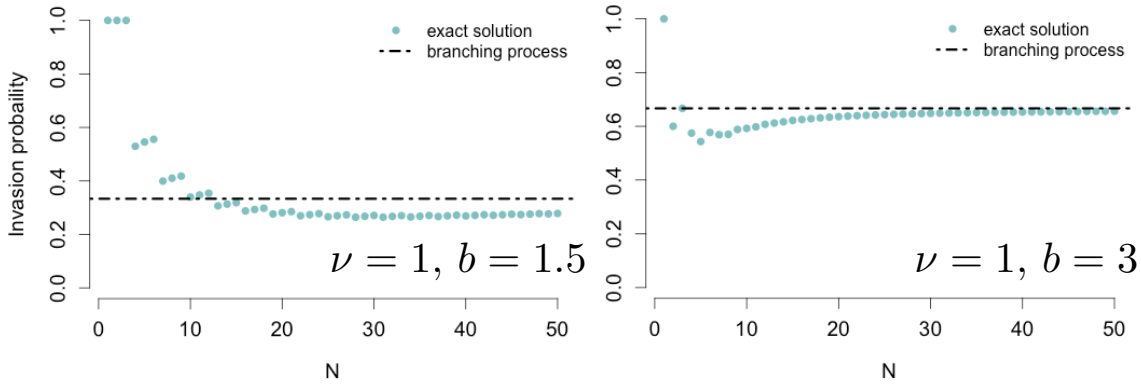
Implications for invasion



Pathogen introduction / spillover event

Future work

- Disease model with consumer encounter rate
  - Investigate approximation methods for the probability of invasion



  - Move from estimating susceptible-susceptible encounter rate to susceptible-infectious encounter rate
    - Rabies virus changes behavior
    - Improve model to account for behavioral changes

Acknowledgements

Collaborators

University of Florida, SACEMA

- Juliet Pulliam (Biology and EPI)

Tulane University

- Scott McKinley (Math)
- Jason Flynn (Math)

University of Texas at Austin

- Steve Bellan (Biology)

Additional Data Sources and Supporters: Berkeley Etosha Anthrax Project (PI: Wayne Getz, Grant No. GM83863), Etosha Ecological Institute, Namibian Ministry of Environment and Tourism, Directorate of Parks, Wildlife and Management.

Etosha National Park

Republic of Namibia
Ministry of Environment & Tourism

Funding

NIH/FIC-DHS/S&T
International Clinics on Infectious Disease Dynamics and Data (ICI3D)
African Institute for Mathematical Sciences

NSF

NATIONAL INSTITUTES OF HEALTH

AIMS SOUTH AFRICA

QSE3 IGERT, National Science Foundation
Grant No. 0801544

UF Emerging Pathogens Institute

UF UNIVERSITY of FLORIDA