

Lecture 7: Multihost and environmentally transmitted pathogens

April 30, 2020

Announcements

Superspreaders

Single Conference Linked To Most Mass. Coronavirus Cases Looks Like A 'Superspreading Event'

March 12, 2020 Updated Mar 12, 2020 10:59 AM

By [Carey Goldberg](#) 



The Marriott Long Wharf hotel in Boston. (Robin Lubbock/WBUR)

How a Premier U.S. Drug Company Became a Virus 'Super Spreader'

Biogen employees unwittingly spread the coronavirus from Massachusetts to Indiana, Tennessee and North Carolina.

'Super Spreader' Events Increase COVID-19 Cases



By [Steven Reinberg](#)

HealthDay Reporter



The Terrifying Story of an Unwitting Potential ‘Super-Spreader’ in Chicago

| SILENT KILLER |

Before social distancing set in, a reporter found out she had COVID-19 — and was asymptomatic.



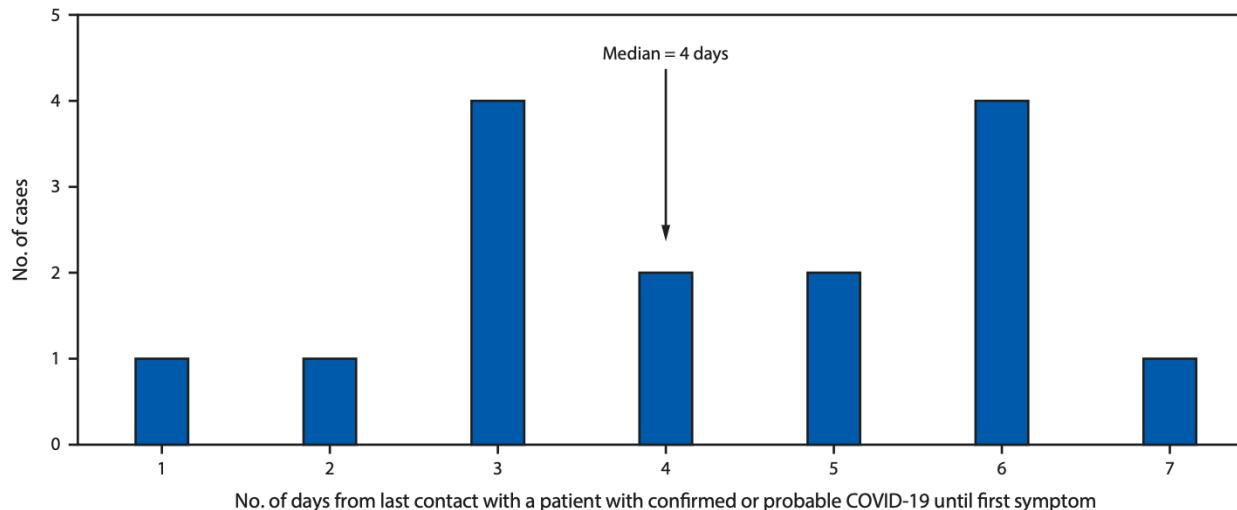
Olivia Messer
Reporter

Morbidity and Mortality Weekly Report

Community Transmission of SARS-CoV-2 at Two Family Gatherings — Chicago, Illinois, February–March 2020

Isaac Ghinai, MBBS^{1,2}; Susan Woods¹; Kathleen A. Ritger, MD¹; Tristan D. McPherson, MD^{1,2}; Stephanie R. Black, MD¹; Laura Sparrow¹; Marielle J. Fricchione, MD¹; Janna L. Kerins, VMD¹; Massimo Pacilli, MPH¹; Peter S. Ruestow, PhD¹; M. Allison Arwady, MD¹; Suzanne F. Beavers, MD³; Daniel C. Payne, PhD⁴; Hannah L. Kirking, MD⁴; Jennifer E. Layden, MD, PhD¹

FIGURE 2. Likely incubation periods for confirmed and probable cases of COVID-19 following transmission of SARS-CoV-2 at two family gatherings (N = 15)* — Chicago, Illinois, February–March 2020



Could you be a coronavirus superspreader? And why are some of us so infectious?

It's just as important to identify people who are infected but unlikely to spread Covid-19

⌚ Tue, Apr 14, 2020, 12:09

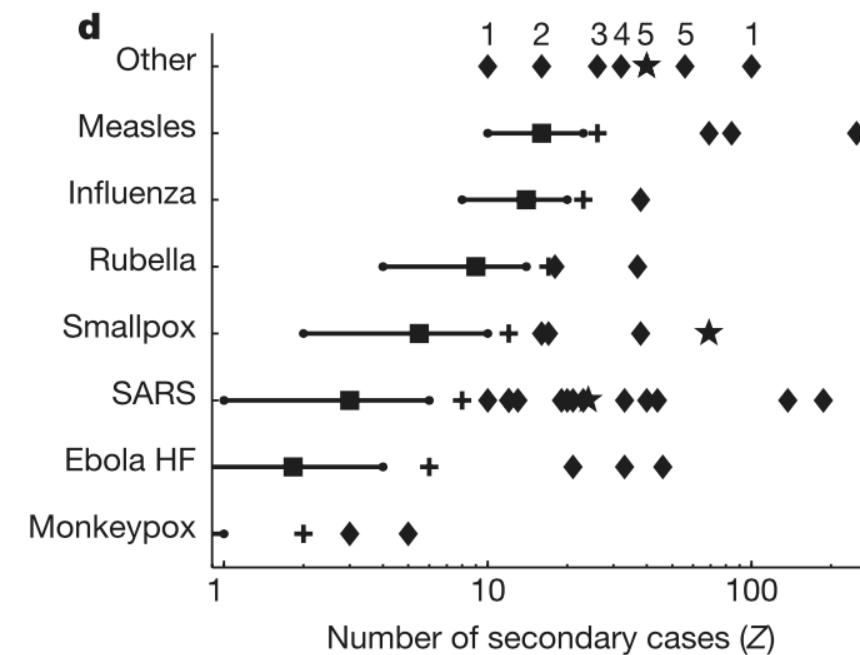
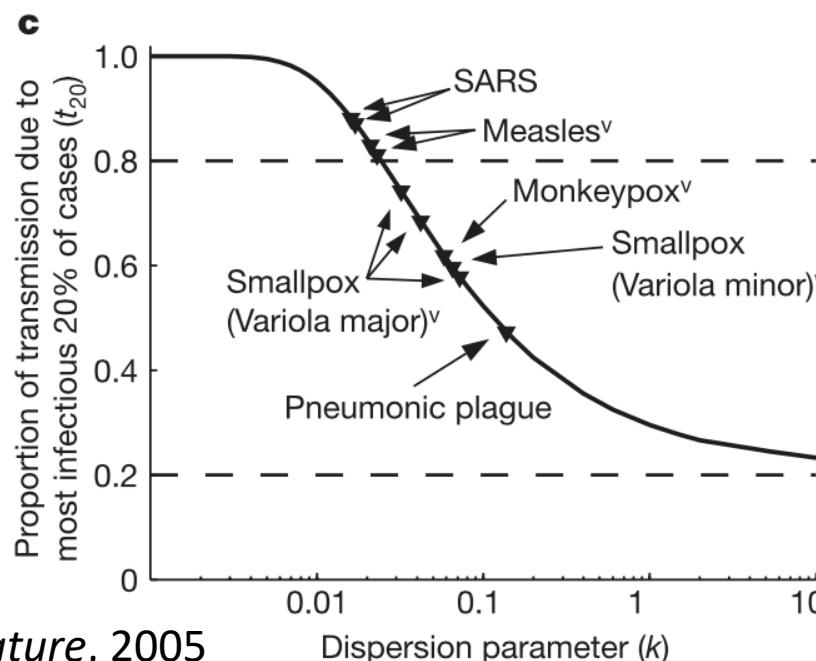
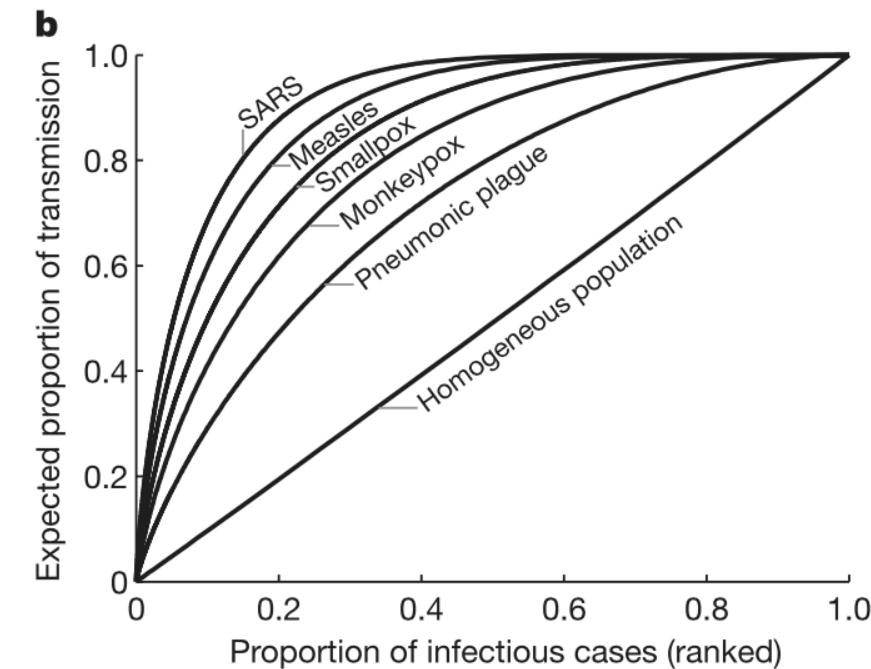
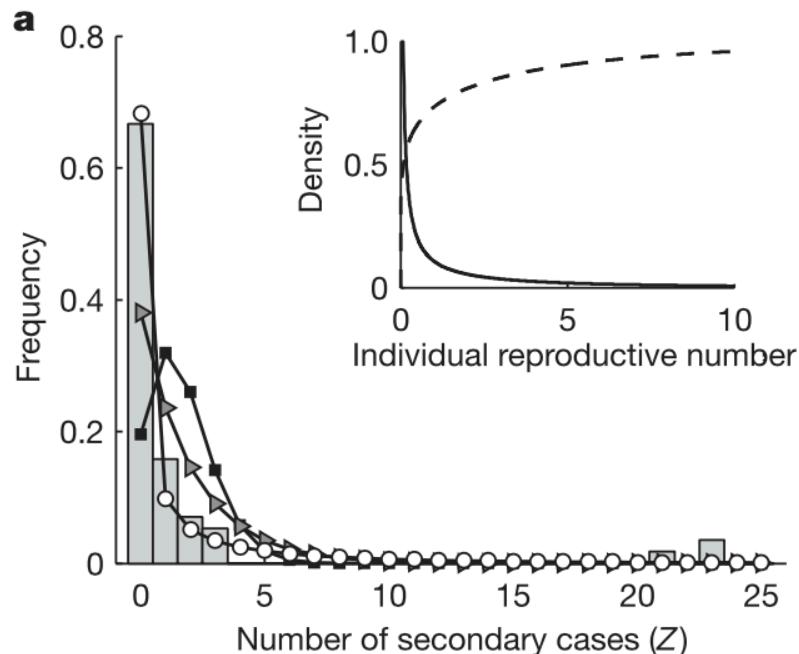
Gina Kolata

Why Are Some People So Much More Infectious Than Others?

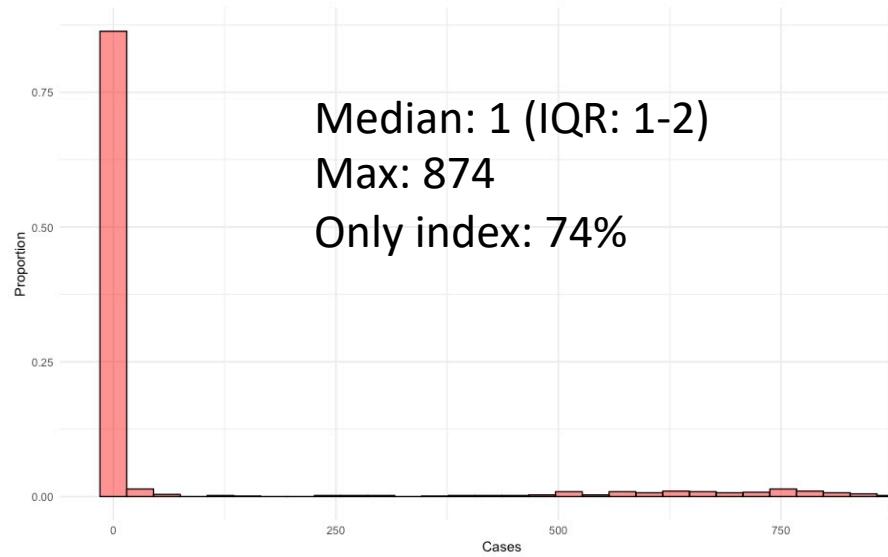
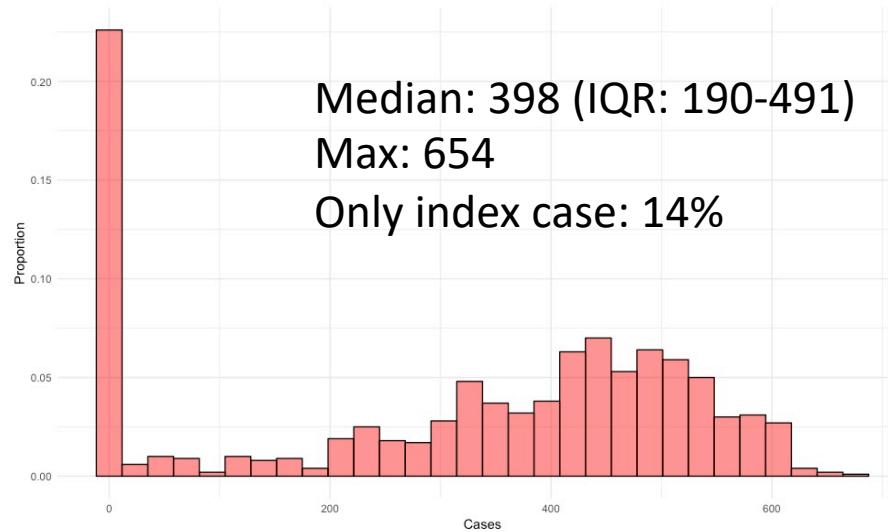
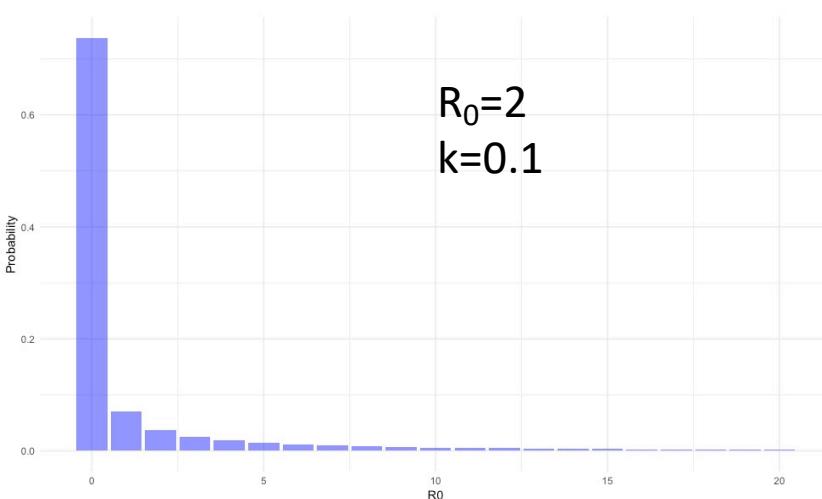
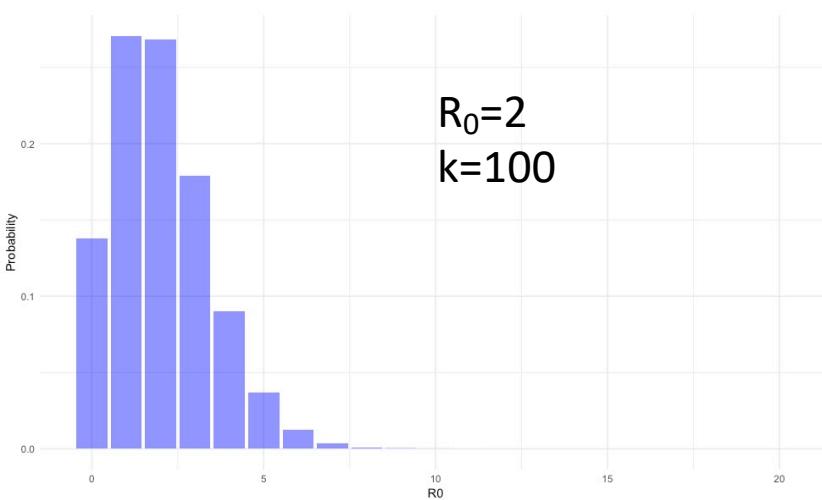
Solving the mystery of “superspreaders” could help control the coronavirus pandemic.

Variation in secondary cases

- R_0 is the **average** number of secondary cases generated by one infectious person in an entirely susceptible population
- What if there is substantial variation in infectiousness between individuals?
- Will outbreaks and epidemics be more or less likely to occur?

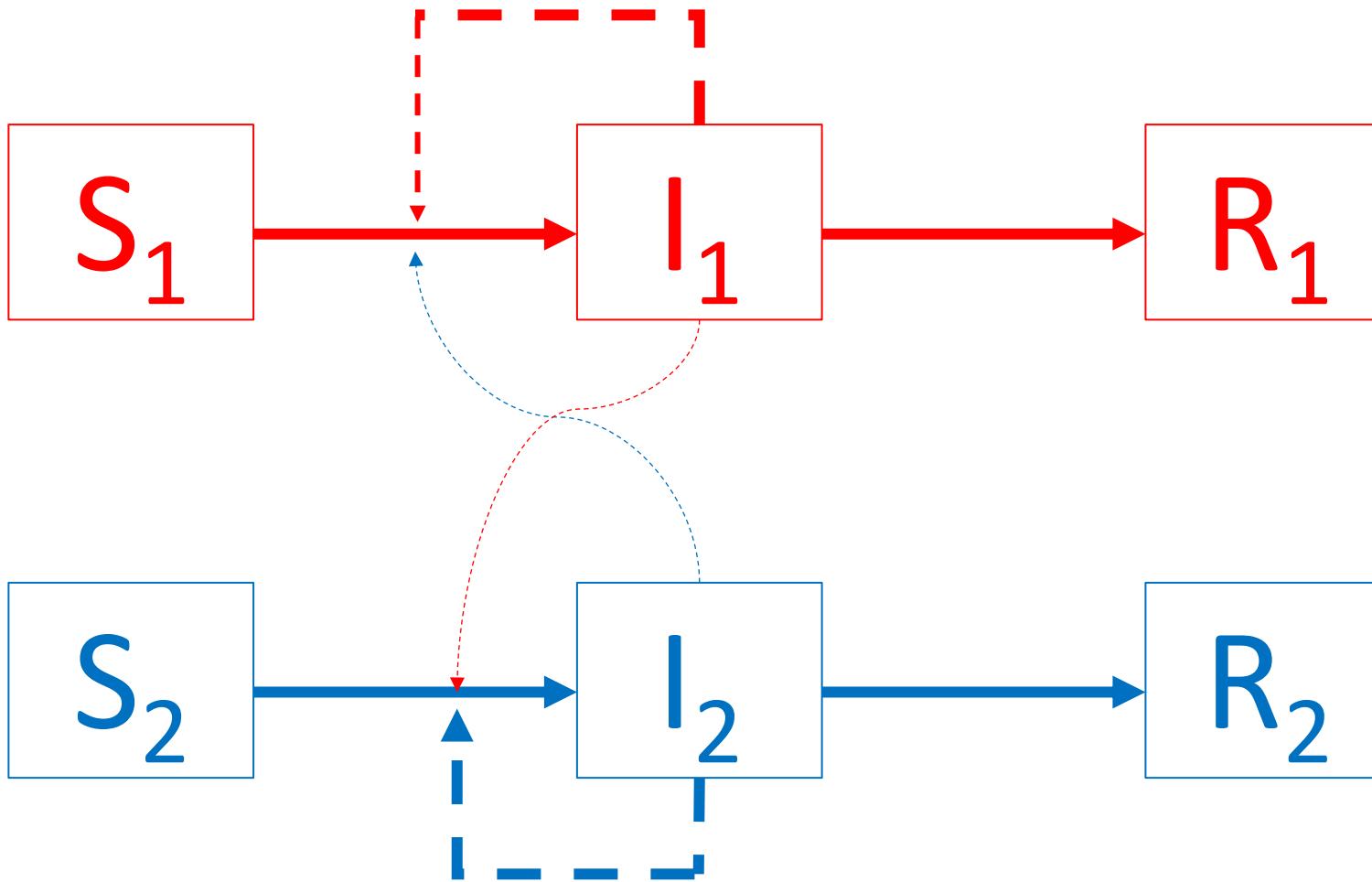


More variability = More chances for extinction

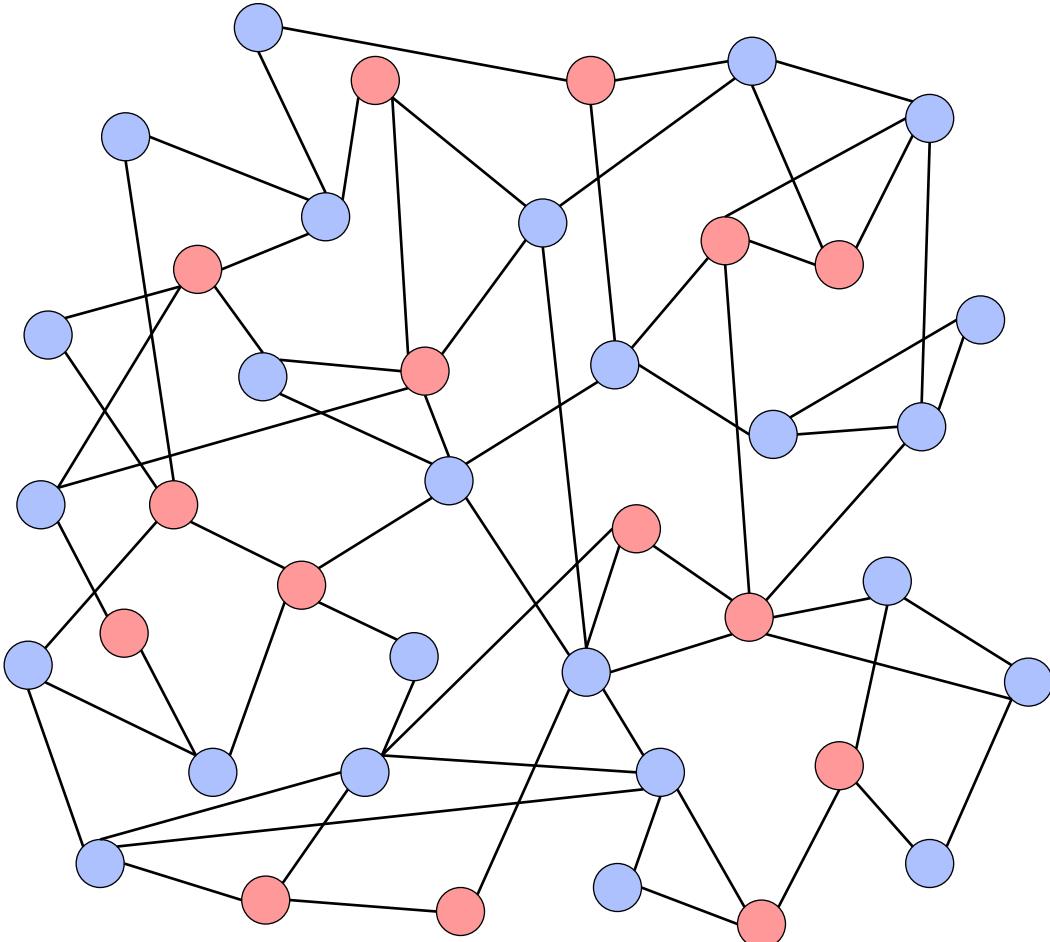


Review of Heterogeneity

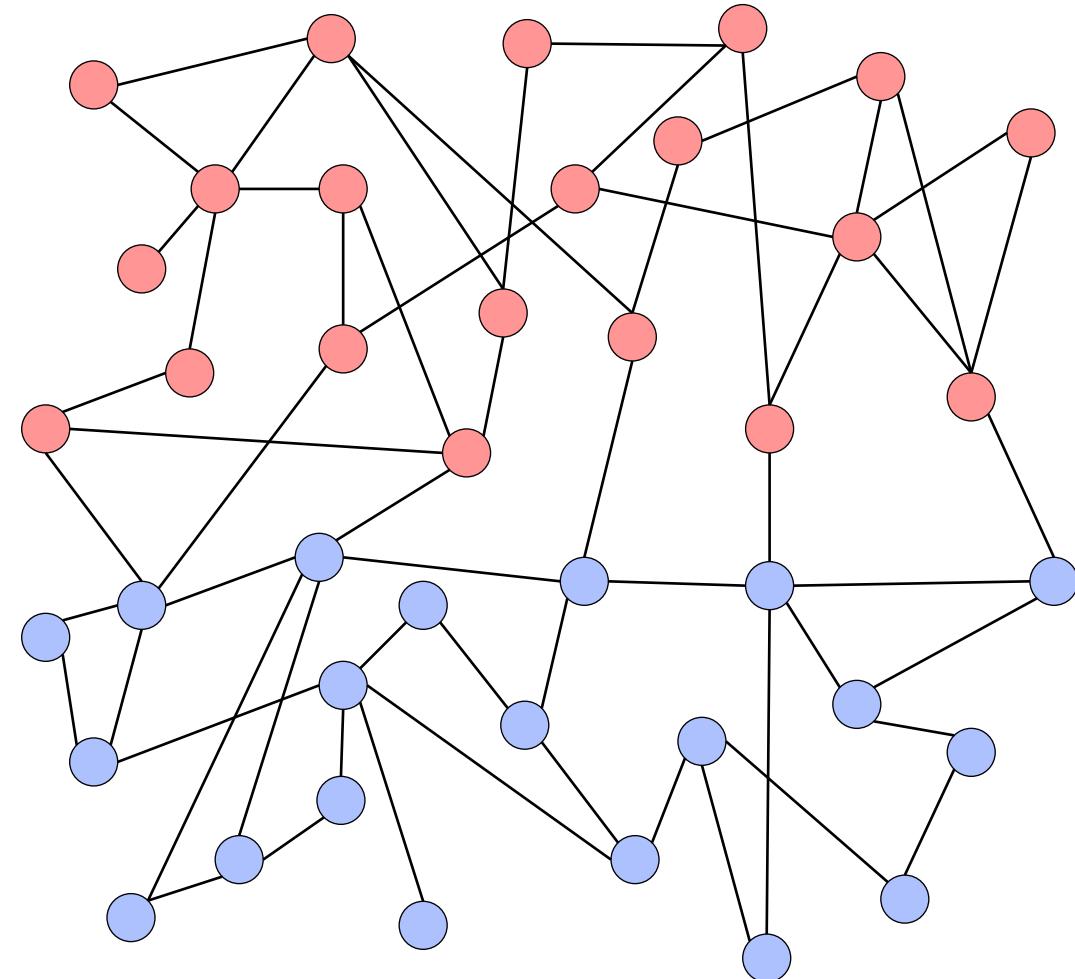
Two populations with heterogenous mixing



Assortativeness



Proportionate mixing



Assortative mixing

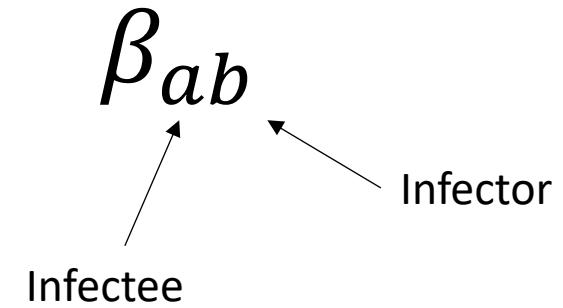
WAIFW (Who Acquires Infection From Whom)

Infector

$$\begin{bmatrix} & \beta_{12} \\ \beta_{11} & \end{bmatrix}$$

Infectee

$$\begin{bmatrix} & \beta_{22} \\ \beta_{21} & \end{bmatrix}$$



Often assume symmetry $\beta_{12} = \beta_{21}$

What are instances of assortative mixing?
Disassortative?

$$\begin{bmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{bmatrix}$$

β_{ab}

Infectee

Infector

$$\begin{bmatrix} 10 & 1 \\ 1 & 10 \end{bmatrix}$$

Assortative

$$\begin{bmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{bmatrix}$$

β_{ab}

Infectee

Infector

$$\begin{bmatrix} 1 & 10 \\ 10 & 1 \end{bmatrix}$$

Dissortative

$$\begin{bmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{bmatrix}$$

$$\beta_{ab}$$

$$\begin{bmatrix} 10 & 1 \\ 1 & 0.1 \end{bmatrix}$$

- 10/11 (91%) with Group 1
- 1/11 (9%) with Group 2

Group 2 has 1.1 contacts

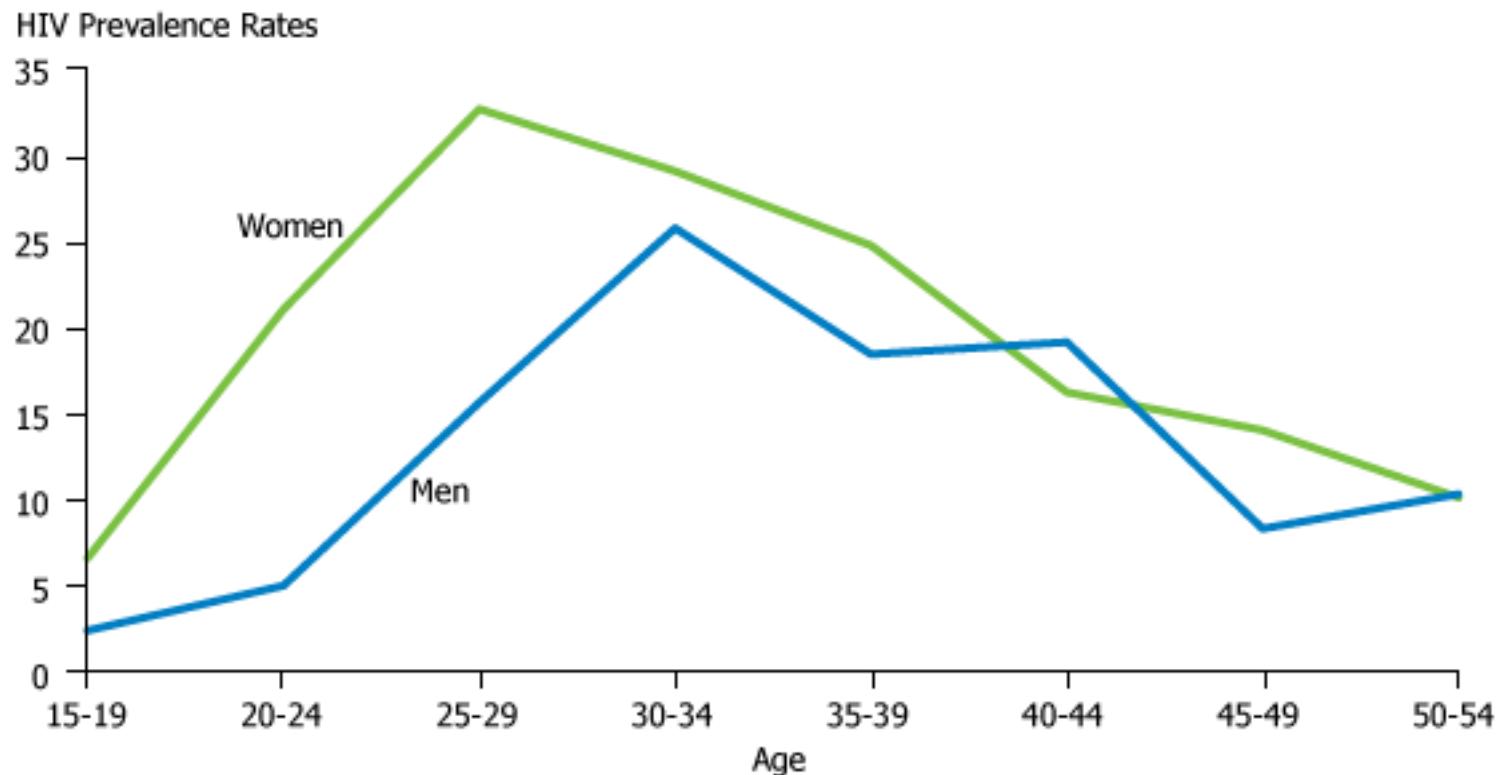
- 1/1.1 (91%) with Group 1
- 0.1/1.1 (9%) with Group 2

Proportionate (random partnership)

See Box 3.4 in Keeling and Rohani for general formula

Assortative Mixing and STIs

- What would be the impact on STIs if all sexual contacts were age assortative?

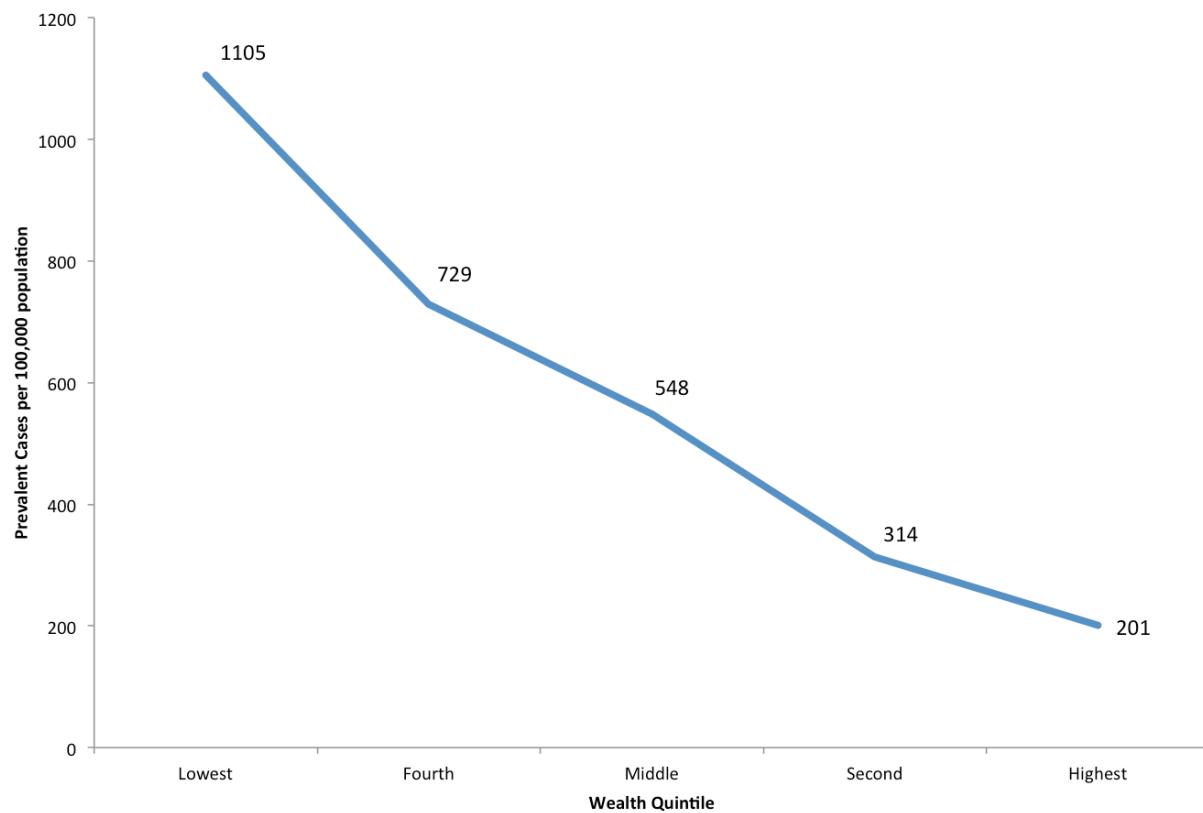


Source: Fustos K, Population Reference Bureau

The epidemiological advantage of preferential targeting of tuberculosis control at the poor

J. R. Andrews,* S. Basu,† D. W. Dowdy,‡ M. B. Murray§

*Division of Infectious Diseases and Geographic Medicine, †Stanford Prevention Research Center, Stanford University School of Medicine, Stanford, California, ‡Department of Epidemiology, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland, §Department of Global Health and Social Medicine, Harvard Medical School, Boston, Massachusetts, USA



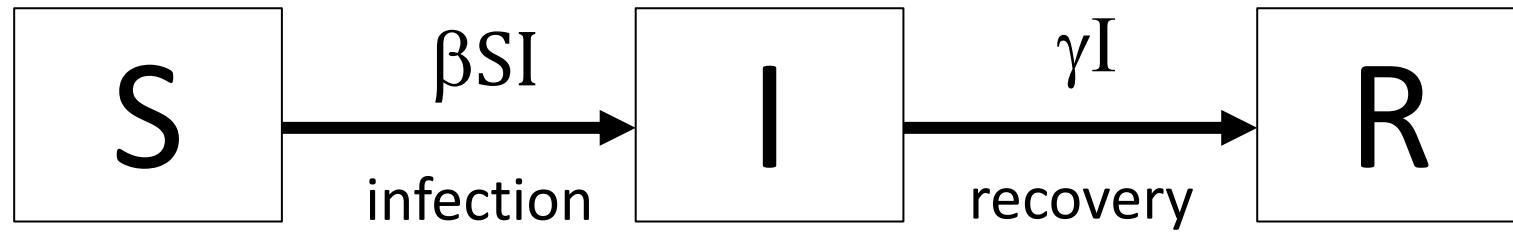
- Wealth-assortative mixing help explain TB disparities in India
- Greater disparities increase R_0
- We may overestimate the impact of our interventions without considering this
- Current interventions are more accessible by the wealthy, who benefit the least

Summary of Heterogeneity

- Each group will have a reproductive number
- The overall R_0 is between the extremes, but is generally higher than what would be the average (i.e. if there was no heterogeneity)
- Heterogeneity can make epidemics more difficult to control
- It can also lower equilibrium prevalence
- If high-risk groups are effectively targeted, can have an outsized impact on epidemic
- Models that fail to incorporate important heterogeneities may underestimate R_0 and fail to accurately project the impact of interventions

Learning Objectives for Today

- Become familiar with models with alternative transmission routes:
 - Multiple hosts
 - Environmentally mediated transmission
- Understand how their dynamics differ from direct person-to-person transmitted organisms
- Be able to think about how structure and write parameters for various types of models



Alternative Transmission Cycles

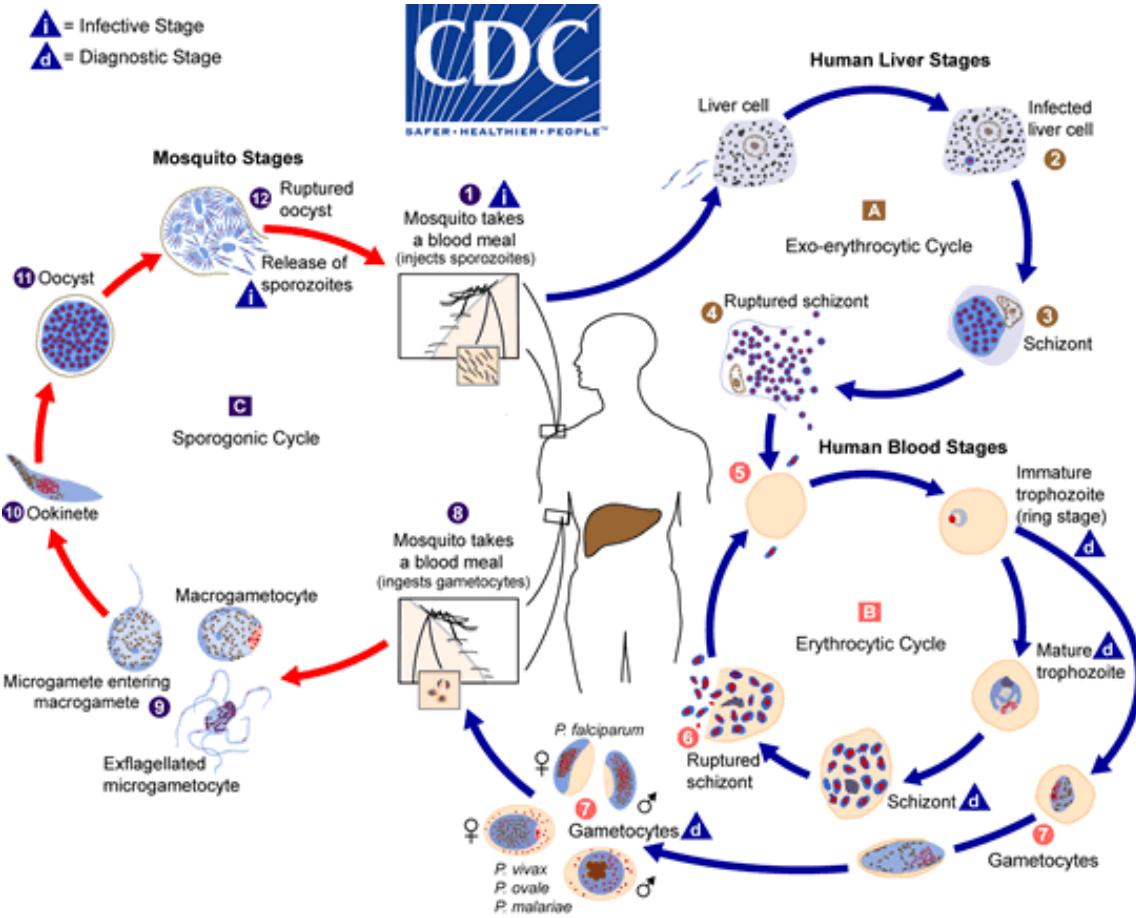
- Vector-borne infections (e.g. malaria, dengue, zika, schistosomiasis)
- Zoonoses (hantavirus, brucellosis)
- Environmentally transmitted diseases (typhoid, cholera)
- Foodborne illnesses (non-typhoidal Salmonellosis)
- Fomites

Malaria

Parasitic infection caused by *Plasmodium* species

Estimated to cause >200 million illnesses and >400,000 deaths per year

Over 90% of cases and deaths occur in Africa





Pancreatic Cysts, with some Remarks upon Treatment. *Edinburgh Medical Journal*, vol. ii, 1895, p. 125. McPhedran, Dr. A. Notes on Cases of Pancreatitis followed by Cyst of the Pancreas. *British Medical Journal*, vol. i, 1897, p. 1420. Ormby: Removal of a Large Omental Tumour by Abdominal Incision. *British Medical Journal*, vol. i, 1897, p. 1421. Roswell: Treatise on Surgery (article on Pancreatic Tumour) by Maurice Richardson and Farrar Cobb, 1896. Poncet et Clibert: Gros Kyste Gastropancréatique. *Archives de Chirurgie*, vol. viii, 1897, p. 279. Ralton, Dr. T. C.: A Case of Pancreatic Cyst in an Infant. *British Medical Journal*, vol. ii, 1897, p. 1318. Von Recklinghausen: *Die Abnormalen Organen des Menschen*, 1897. De Wied: *Die Cysten und von Besten des Wolfischen Körpers*, 1896. Reddingius: *Tijdschrift voor Geneeskunde*, No. 1, 1897. Reichenbach: *Ueber die Peritonealruptur: Peritonitis; Death*. *Lancet*, vol. ii, 1897, p. 666. Sender: Zur Pathologie und Chirurgie des Pankreas. *Deutsche Zeitschrift für Chirurgie*, vol. xlii, 1897, p. 125. Calmette: *Extrait d'un Mémoire sur l'Acidité Oxalate from a Cyst of the Pancreas*. *Journal of Pathology and Bacteriology*, vol. iv, p. 219, and *Trans. Path. Soc.*, vol. xvii, 1896, p. 101. Treves: *A Study of the Pancreas*. *Archives of Anatomy*, vol. iii, 1897, p. 651. De Wild: *Een Gevaar van Pancrasycte*. *Wetkundige en Medische Tijdschrift voor Geneeskunde*, No. 5, 1892. Zweifel: *Exstirpation einer Pankreaszyste*. *Centralbl. f. Gynekol.*, 1894, No. 27.

ON SOME PECULIAR PIGMENTED CELLS FOUND IN TWO MOSQUITOS FED ON MALARIAL BLOOD.

By SURGEON-MAJOR RONALD ROSS, I.M.S.,
(With Note by Surgeon-Major SMYTH, M.D., I.M.S.)

For the last two years I have been endeavouring to cultivate the parasite of malaria in the mosquito. The method adopted has been to feed mosquitoes, bred in bottles from the larva, on patients having crescents in the blood, and then to examine the tarsi for the parasites in the blood. The study is a difficult one, as there is no *a priori* indication of what the derived parasite will be like precisely, nor in what particular species of insect the experiment will be successful, while the investigation requires a thorough knowledge of the minute anatomy of the mosquito. Hitherto the species employed have been mostly brindled and grey varieties of the *Anopheles*, but although I have been able to find no fewer than six new parasites of the mosquito, namely, a coccidian, a fungus, a gregarine, a sarcosporidium (?), a coccidium (?), and certain swarm spores in the stomach, besides one or two doubtfully parasitic forms, I have not yet succeeded in tracing any parasite to the ingestion of malarial blood, nor in observing any special protozoa in the evacuations due to such ingestion. Lately, however, on abandoning the brindled and grey mosquitoes, and employing similar, though not brown, species of which I have as yet obtained very few individuals, I succeeded in finding in two of them certain remarkable and suspicious cells containing pigment identical in appearance to that of the parasite of malaria. As these cells appear to me to be very worthy of attention, while the peculiar species of mosquito seems most unfortunately to be so rare at this place that may be a long time before I can procure any more for further study, I think it would be advisable to place on record a brief description both of the cells and of the mosquitos.

The latter are a large brown species, biting well in the daytime, and incidentally found to be capable of harbouring the filaria sanguinum hominis. The back of the thorax and abdomen is a light fawn colour; the lower surface of the same, and the wings, a dark chocolate brown. The wings are light brown to white, and bear dark spots on the anterior nervure. The halterum and tarsi are brindled dark and light brown. The eggs—at least, when not fully developed—are shaped curiously like ancient boats with raised stern and prow, and many lines radiating from the concave border like banks of oars—so far as I have seen a unique shape for mosquito's eggs. The species appears to belong to a family distinct from the ordinary brindled and grey insects, but there is an allied species here, only more slender, whiter, and much less voracious. My observations on the characteristics of these mosquitos were not very careful, as when I first obtained them I did not anticipate any difficulty in procuring more.

On August 16th eight of them were fed on a patient whose blood contained fair to few crescents (and also filariae). Unfortunately four were killed at once for the study of nage-

late bodies (flagellule cysts). Of the remainder two were examined on the 18th and 20th respectively, without any change in their condition. The seventh mosquito was also killed on the 20th, four days after having been fed. On turning to the stomach with an oil-immersion lens I was struck at once by the appearance of some cells which seemed to be slightly more substantial than the cells of the mosquito's stomach usually are. There were a dozen of them lying among (or within?) the cells of the upper half of the organ, and, though somewhat more solid than these, still very delicate and transparent. They were round or oval, 12 μ to 16 μ in diameter when not compressed (that is, considerably larger than the largest haemocyte in man); the outline sharp but very fine; the contents full of stationary vacuoles; and no sign of apparent nucleus, contractile vesicle or amoeboid or intracellular movement. So far it would have been impossible for any but a person very familiar with the insect's anatomy to have distinguished them from the neighbouring cells. But my note of attention was that each of these bodies contained a few granules of black pigment absolutely identical in appearance with the well-known and characteristic pigment of the parasite of malaria (large quartans and crescent-derived spheres).

The granules were more scanty in comparison to the size of the cell than in the haemocyte, and numbered from 10 to 20. They were all dispersed, arranged in lines transversely or peripherally, or in a small circle round the centre (just as in some forms of the haemocyte). They were black or dark brown, and not refractive on change of focus. In some cases they showed rapid oscillation within a small range, but did not change their position. Owing to their blackness, so different from the bluish yellow or green granules of *Allopora* found in the gut, the neighbouring cells, by arrested the eye at once; and it must clearly be understood that I have not confounded them with normal objects. In short (except perhaps that rods were shorter or absent) these granules of pigment were indistinguishable from those of the haemocyte.

The eighth and last mosquito was killed next day, five days after having been fed. The stomach contained probably the same number of these cells as in the seventh mosquito, but all were larger and more substantial than in the seventh mosquito, and had a decidedly thicker outline. The size (along the major axis) appeared now sometimes to reach nearly 20 μ , on a rough computation made without a micrometer. There thus appeared to be a marked increase in bulk and definition between these cells of the eighth and fifth days, suggesting that they had grown in the interval.

Both specimens were irrigated with 40 per cent. formalin, and sealed. The result of the formalin was, as anticipated, that the bodies became slightly more visible than before, as compared with the stomach cells.

In spite of all attempts, I have not yet succeeded in obtaining any more of the species of mosquito referred to. Thinking however that the overgrowth of these pigmented cells in former dissections, I have again examined a large number of brindled and grey mosquitos, fed on malarial blood. Their stomachs certainly contained no such cells. Next I caught by hand a number of the more slender and white, but allied, species already referred to (I have failed in finding their grubs also), and examined them. Some had not been fed at all, others had fed three times on (presumably) healthy blood, two, three, or four days previously. The results were again negative. I may add that I have not yet succeeded in getting this species fed on malarial blood.

To sum up: The cells appear to be very exceptional; they have as yet been found only in a single species of mosquito fed on malarial blood; they seem to grow between the fourth and fifth day; and they contain the characteristic pigment of the parasite of malaria. It would be difficult to draw any final conclusions as yet; but I think we may venture to draw some cautious inferences on these observations. First, as to the nature of the cells. Judging from the facts that the elementary cells of allied species of mosquitos are always alike, or very similar, and that I have never observed such bodies in previous or subsequent dissections of mosquitos (I suppose I must have examined quite a thousand

Nobel Prize in 1902

REPORT ON THE PREVENTION OF MALARIA IN MAURITIUS

BY

RONALD ROSS

D.P.H., F.R.C.S., D.Sc., LL.D., F.R.S., C.B.

Nobel Laureate

Président Honoraire de la Société Médicale de l'Île Maurice

Corr. Etr., Académie de Médecine

Corr. Estro, Accademia di Medicina di Torino

Assoc. Fil., College of Physicians of Philadelphia

Officier de l'Ordre de Léopold II

Major, Indian Medical Service, Retired

Professor of Tropical Medicine, University of Liverpool and Liverpool School of Tropical Medicine

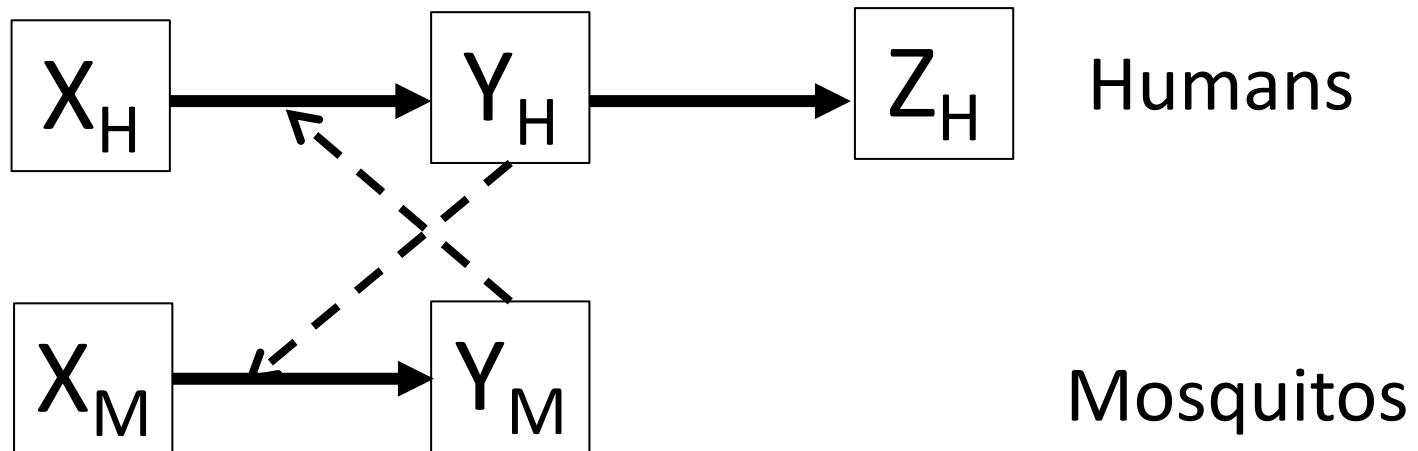
Review

Ross, Macdonald, and a Theory for the Dynamics and Control of Mosquito-Transmitted Pathogens

David L. Smith^{1,2,3*}, Katherine E. Battle⁴, Simon I. Hay^{3,4}, Christopher M. Barker^{3,5,6}, Thomas W. Scott^{3,7}, F. Ellis McKenzie³

1 Department of Epidemiology, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland, United States of America, **2** Malaria Research Institute, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland, United States of America, **3** Fogarty International Center, National Institutes of Health, Bethesda, Maryland, United States of America, **4** Spatial Ecology and Epidemiology Group, Department of Zoology, Oxford University, Oxford, United Kingdom, **5** Center for Vectorborne Diseases, University of California, Davis, California, United States of America, **6** Department of Pathology, Microbiology, and Immunology, School of Veterinary Medicine, University of California, Davis, California, United States of America, **7** Department of Entomology, University of California, Davis, California, United States of America

A Model for Malaria



b = biting rate (bites/time)

$r = \frac{b}{N_H}$ = rate at which a particular human is bit by a particular mosquito

T_{HM} = probability that human bit by a mosquito is infected

T_{MH} = probability that mosquito is infected if it bites infected human

v = birth rate

$$\frac{dX_H}{dt} = v_H - r T_{HM} Y_M X_H - \mu_H X_H$$

$$\frac{dY_H}{dt} = r T_{HM} Y_M X_H - \mu_H X_H - \gamma X_H$$

$$\frac{dX_M}{dt} = v_M - r T_{MH} Y_H X_M - \mu_M X_M$$

$$\frac{dY_M}{dt} = r T_{MH} Y_H X_M - \mu_M X_M$$

$$\begin{bmatrix} & & \\ & 0 & \beta_{MH} \\ \beta_{HM} & & 0 \end{bmatrix}$$

b = biting rate (bites/time)

R_0 for Malaria Model

$r = \frac{b}{N_H}$ = rate at which a particular human is bit by a particular mosquito

R_0 = Human infections generated by first infectious mosquito * Mosquito infections generated by each infected human

$$\frac{bT_{HM}}{\mu_M}$$

$$\frac{rN_MT_{MH}}{(\mu_H + \gamma_H)} = \frac{bN_MT_{MH}}{N_H(\mu_H + \gamma_H)}$$

$$R_0 = \frac{b^2N_MT_{MH}T_{HM}}{N_H(\mu_H + \gamma_H)\mu_M}$$

Implications

- Sensitive to the square of the biting rate
- Mosquito density relative to humans is critical, and below a certain density, $R_0 < 1$

$$\frac{b^2N_MT_{MH}T_{HM}}{N_H(\mu_H + \gamma_H)\mu_M} > 1$$

$$\frac{N_M}{N_H} > \frac{(\mu_H + \gamma_H)\mu_M}{b^2T_{MH}T_{HM}}$$

Mosquito targeting interventions

- Interventions can target:
 - Biting (bednets)
 - Duration of infectiousness (antimalarial treatment)
 - Mosquito populations (larvacides, indoor residual spraying)
 - Probability of infection (chemoprophylaxis, vaccines)

$$R_0 = \frac{b^2 N_M T_{MH} T_{HM}}{N_H (\mu_H + \gamma_H) \mu_M}$$



Quasi-Equilibrium

- One challenge with having four differential equations and dynamics of prevalence in mosquitos and humans is that it is difficult to analytically evaluate important entities
- Because the mosquito replication cycle is so much shorter than human, dynamics in mosquitos are much faster and can evaluate them assuming human prevalence remains constant for their short time frame

$$\frac{dX_H}{dt} = v_H - r T_{HM} Y_M X_H - \mu_H X_H$$

$$\frac{dY_H}{dt} = r T_{HM} Y_M X_H - \mu_H X_H - \gamma X_H$$

$$\frac{dX_M}{dt} = v_M - r T_{MH} Y_H X_M - \mu_M X_M$$

$$\frac{dY_M}{dt} = r T_{MH} Y_H X_M - \mu_M X_M$$

Mosquitoes

$$\frac{dX_M}{dt} = v_M - r T_{MH} Y_H X_M - \mu_M X_M = 0$$

$$\frac{dX_M}{dt} = r T_{MH} Y_H X_M - \mu_M X_M = 0$$



Equilibrium

$$X_M^* = \frac{v_M}{r T_{MH} Y_H + \mu_M}$$

$$Y_M^* = \frac{r T_{MH} Y_H v_M}{(r T_{MH} Y_H + \mu_M) \mu_M}$$



Humans

$$\frac{dX_H}{dt} = v_H - r T_{HM} Y_M X_H - \mu_H X_H$$



$$\frac{dX_H}{dt} = v_H - r T_{HM} \frac{r T_{MH} Y_H v_M}{(r T_{MH} Y_H + \mu_M) \mu_M} X_H - \mu_H X_H$$

$$\frac{dY_H}{dt} = r T_{HM} Y_M X_H - \mu_H X_H - \gamma X_H$$

$$\frac{dY_H}{dt} = r T_{HM} \frac{r T_{MH} Y_H v_M}{(r T_{MH} Y_H + \mu_M) \mu_M} X_H - \mu_H X_H - \gamma X_H$$

Force of infection saturates

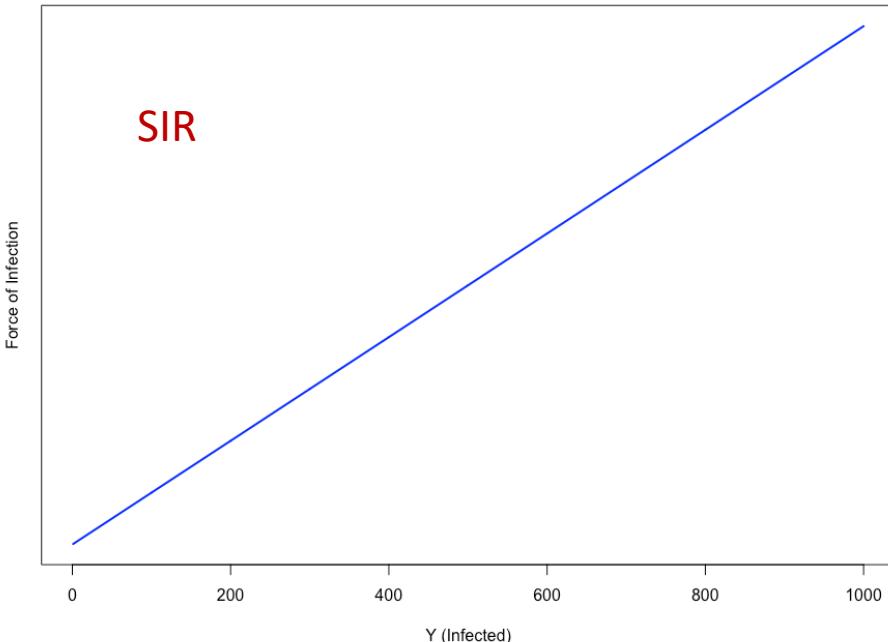
$$\frac{dY_H}{dt} = r T_{HM} \frac{r T_{MH} Y_H v_M}{(r T_{MH} Y_H + \mu_M) \mu_M} X_H - \mu_H X_H - \gamma X_H$$

$$r T_{HM} \frac{r T_{MH} Y_H v_M}{(r T_{MH} Y_H + \mu_M) \mu_M} X_H \quad r = \frac{b}{N_H}$$

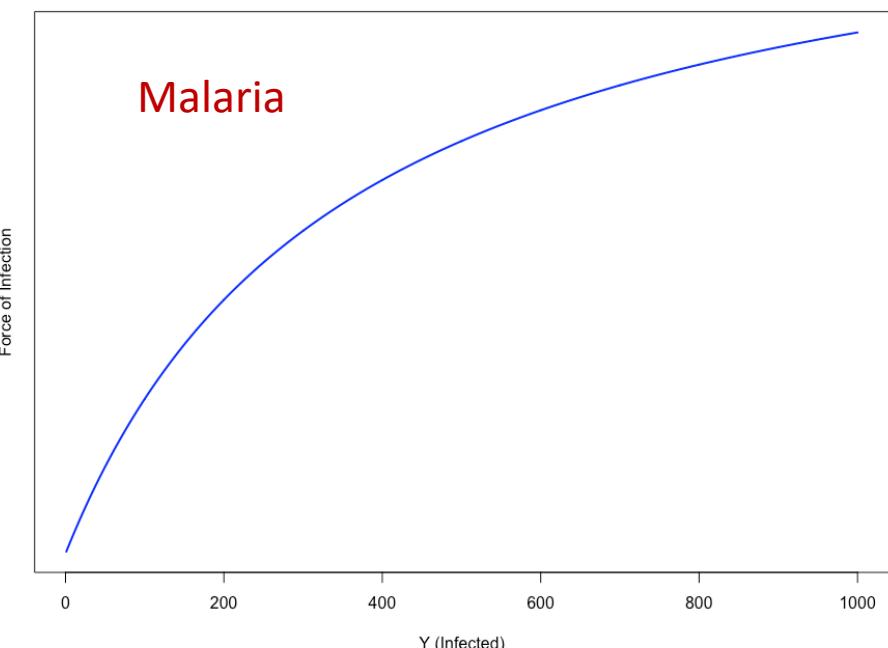
$$b T_{HM} \frac{b T_{MH} Y_H v_M}{(b T_{MH} Y_H + \mu_M N_H) \mu_M N_H} X_H$$

$$\text{Force of Infection} = \lambda = b T_{HM} \frac{b T_{MH} Y_H v_M}{(b T_{MH} Y_H + \mu_M N_H) \mu_M N_H}$$

For SIR model = $\lambda = \beta I$ (freq dependent) or βY (density dependent)

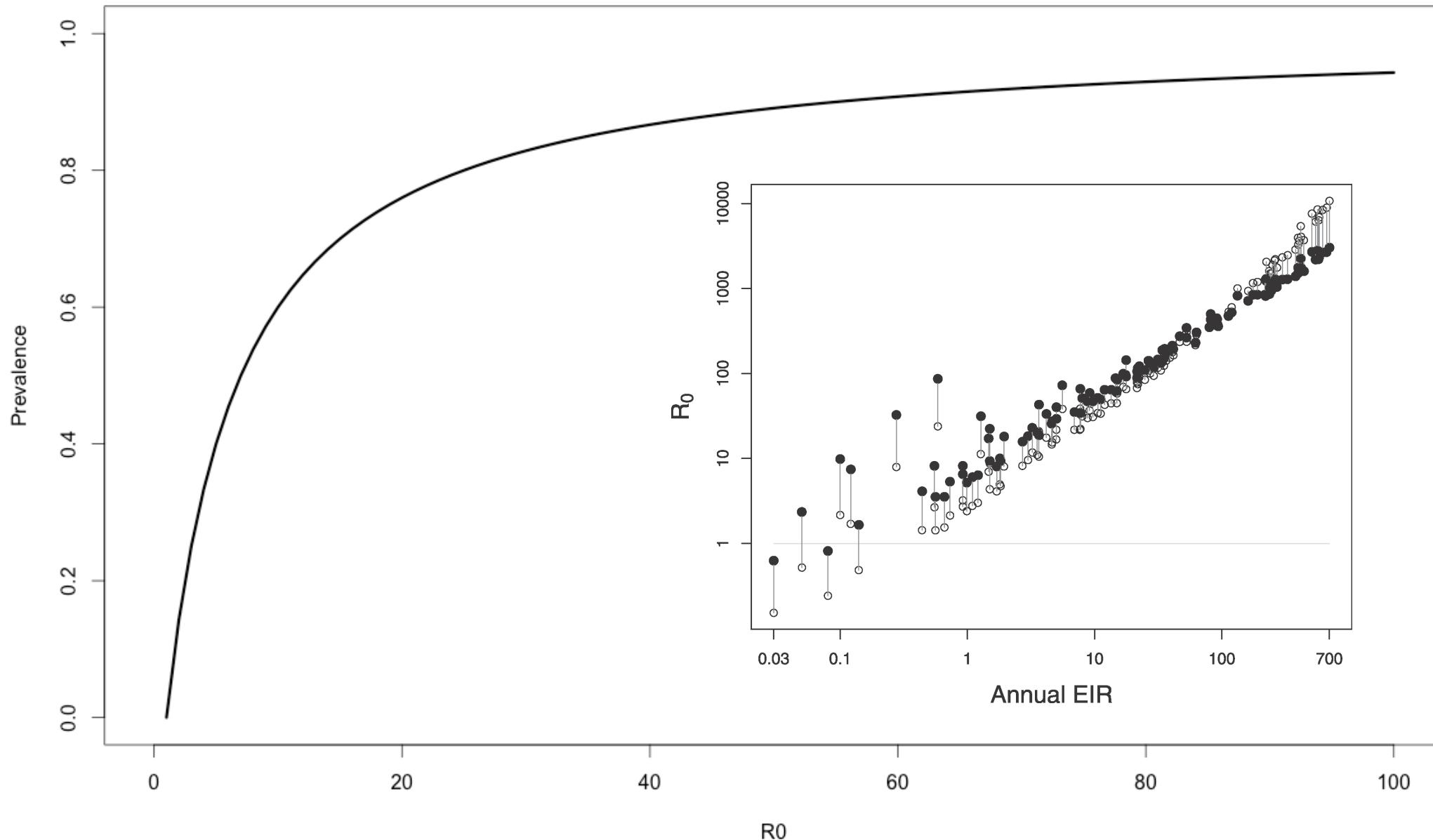


SIR



Malaria

R_0 and Prevalence for Malaria



Mosquitos and Climate

Mordecai et al, 2013

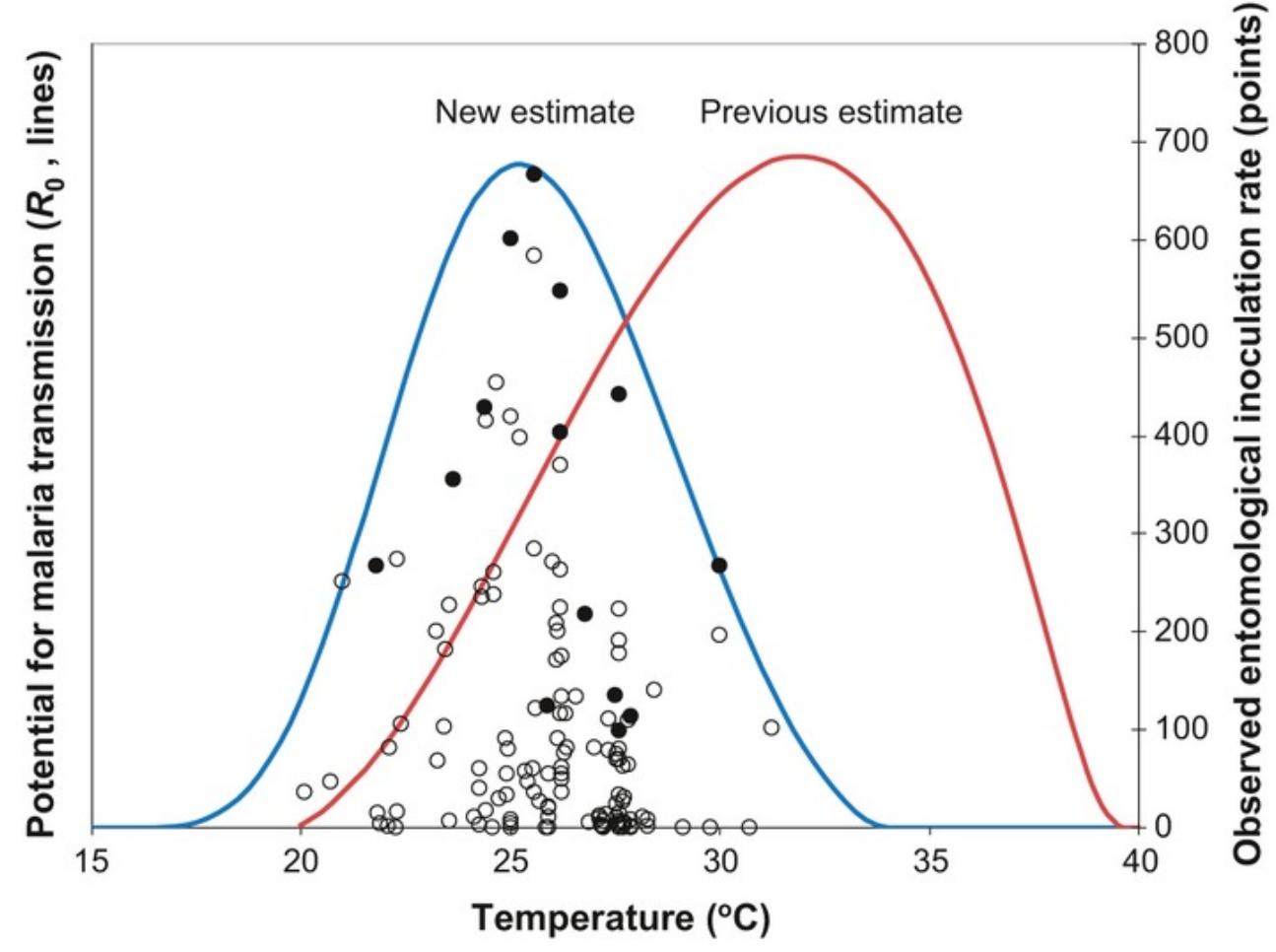
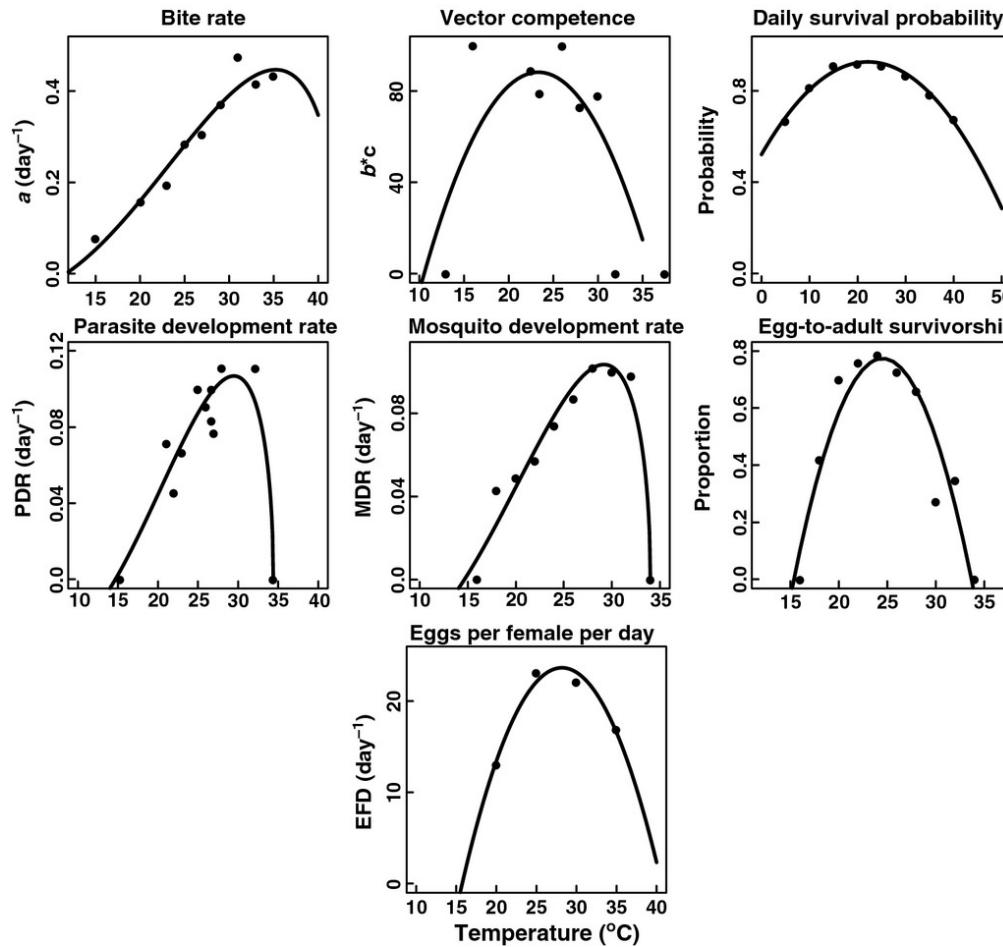
ECOLOGY LETTERS

Ecology Letters, (2013) 16: 22–30

doi: 10.1111/ele.12015

LETTER

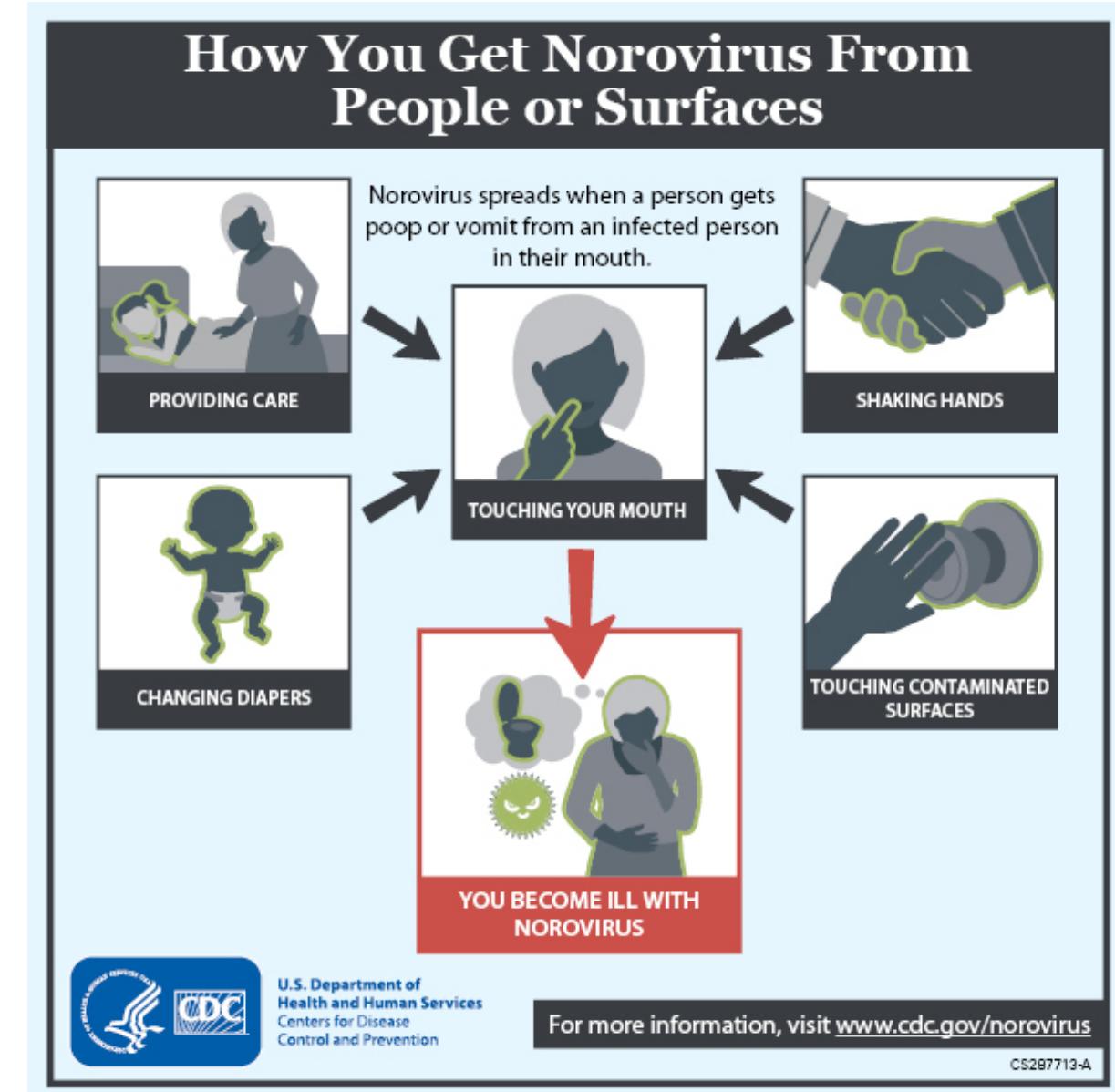
Optimal temperature for malaria transmission is dramatically lower than previously predicted



Environmentally Mediated Transmission

Exercise

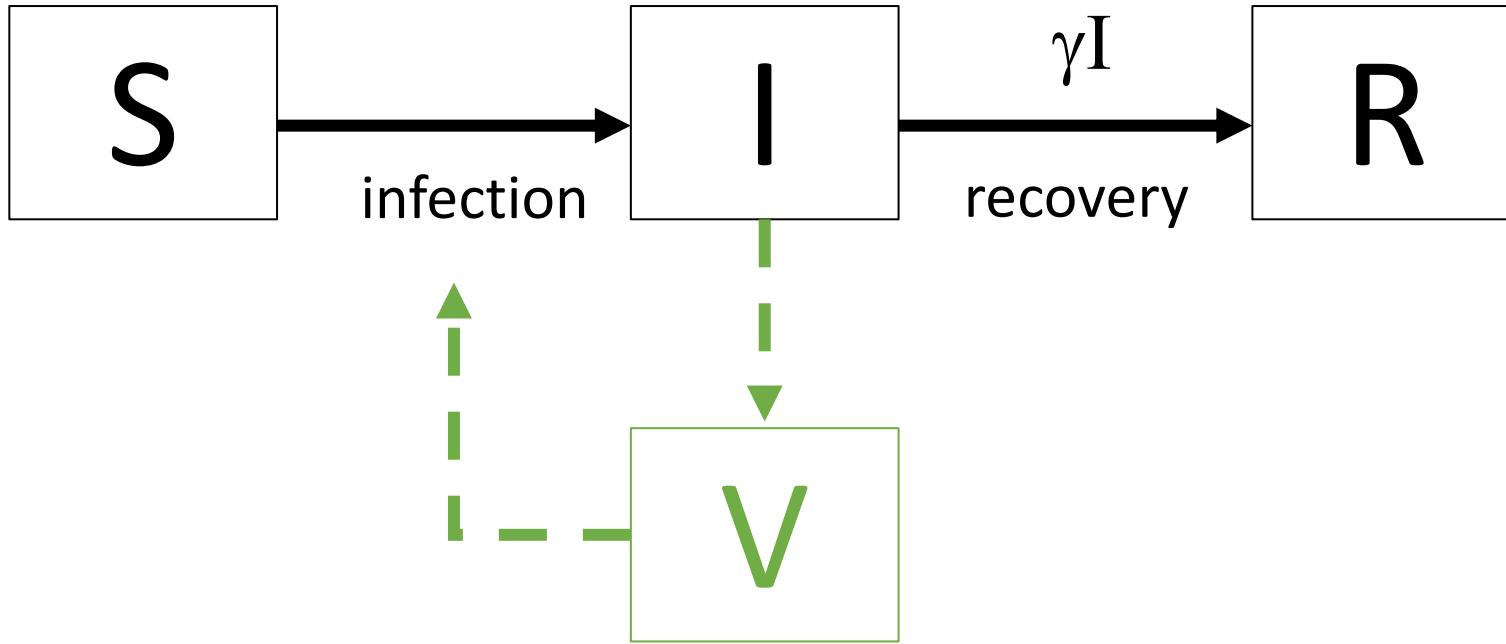
Norovirus is a gastrointestinal viral infection, which causes around 20 million illnesses per year in the United States. It has caused large outbreaks on cruise ships (for example, nearly 700 cases on *Explorer of the Seas* in 2014), though most cases occur on land. Transmission is believed to through ingestion of aerosolized vomit or touching surfaces contaminated with feces/vomit and then one's mouth.



Exercise

Assume that transmission occurs exclusively through environmental contact. You may ignore demography on short time scale and assume recovery leads to immunity.

1. Create a compartmental model of norovirus transmission in a home
2. Write down a series of equations describing it
3. What do the parameters mean? Are they measurable?
4. What are limitations?



α = rate of vomiting virus into the environment

ϕ = per capita rate of ingesting
infectious dose of virus from environment

$1/\pi$ = survival of virus in the environment

ε = rate of removing (cleaning) vomit/virus

$$\frac{dS}{dt} = -\phi VI$$

$$\frac{dI}{dt} = \phi VI - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$

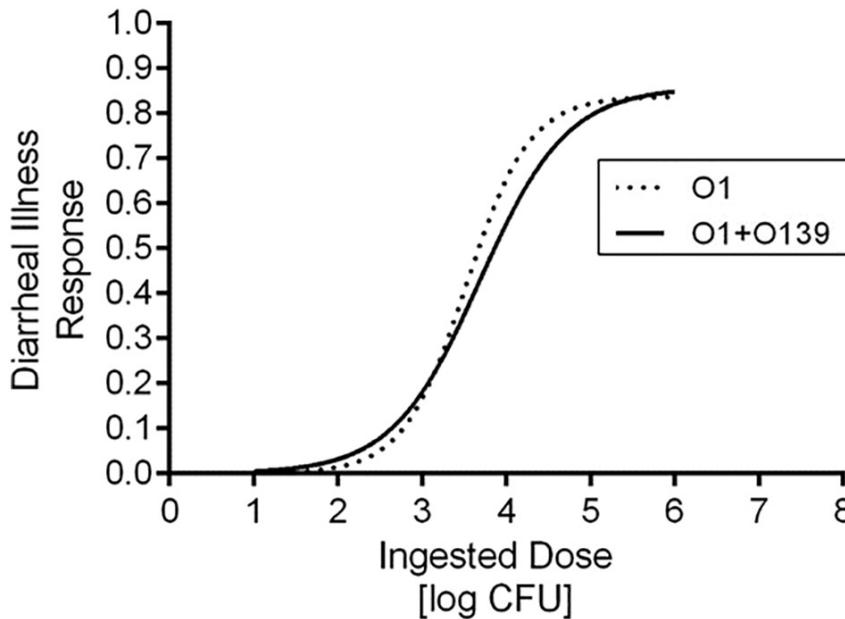
$$\frac{dV}{dt} = \alpha I - \pi V - \varepsilon V$$

Cholera



Cholera

Human Subject Dose Response Model
Vibrio cholerae O1 and O1+O139 Serogroups



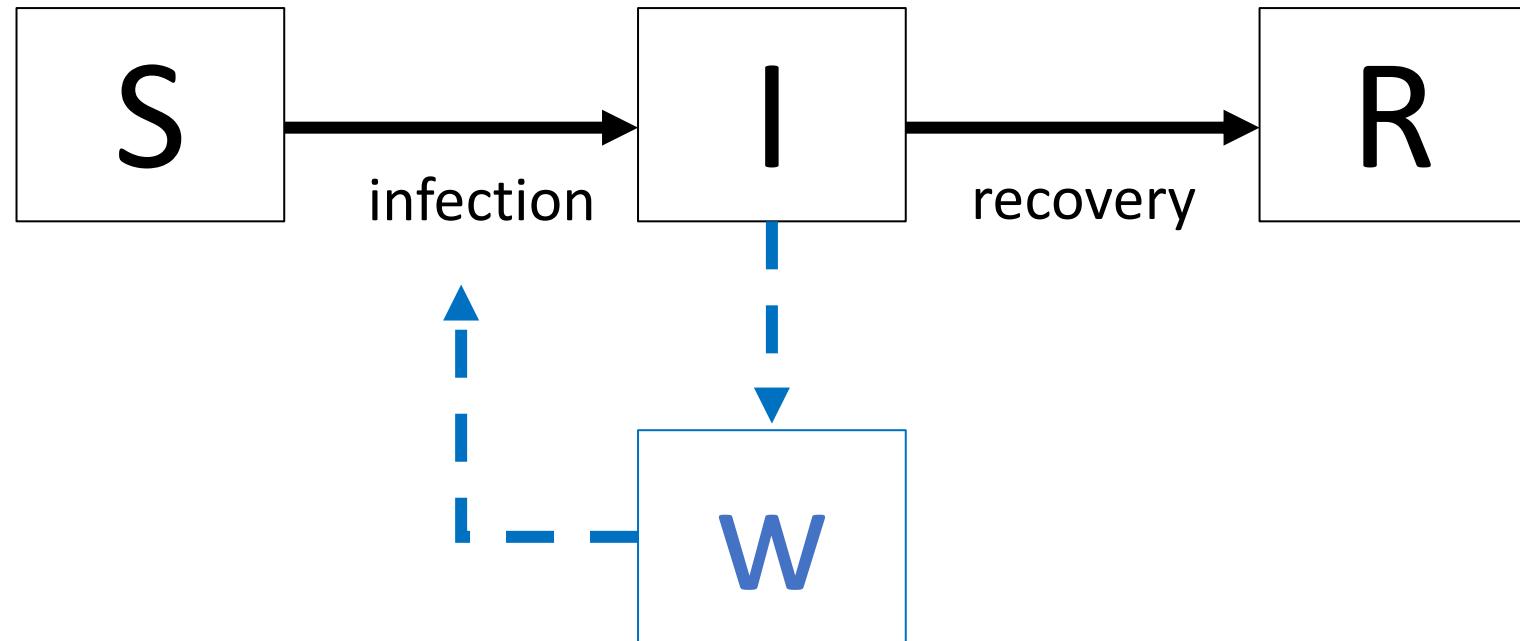
THE JOURNAL OF INFECTIOUS DISEASES • VOL. 130, NO. 4 • OCTOBER 1974
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MAJOR ARTICLES

Response of Man to Infection with *Vibrio cholerae*. II. Protection from Illness Afforded by Previous Disease and Vaccine

R. A. Cash, S. I. Music,* J. P. Libonati, J. P. Craig,
N. F. Pierce, and R. B. Hornick

From the Division of Infectious Diseases, University of Maryland School of Medicine, and the Division of Infectious Diseases, Baltimore City Hospital, Baltimore, Maryland; and the Department of Microbiology and Immunology, Downstate Medical Center, Brooklyn, New York



W = concentration in environment
 K = concentration at which 50% infected (ID_{50})

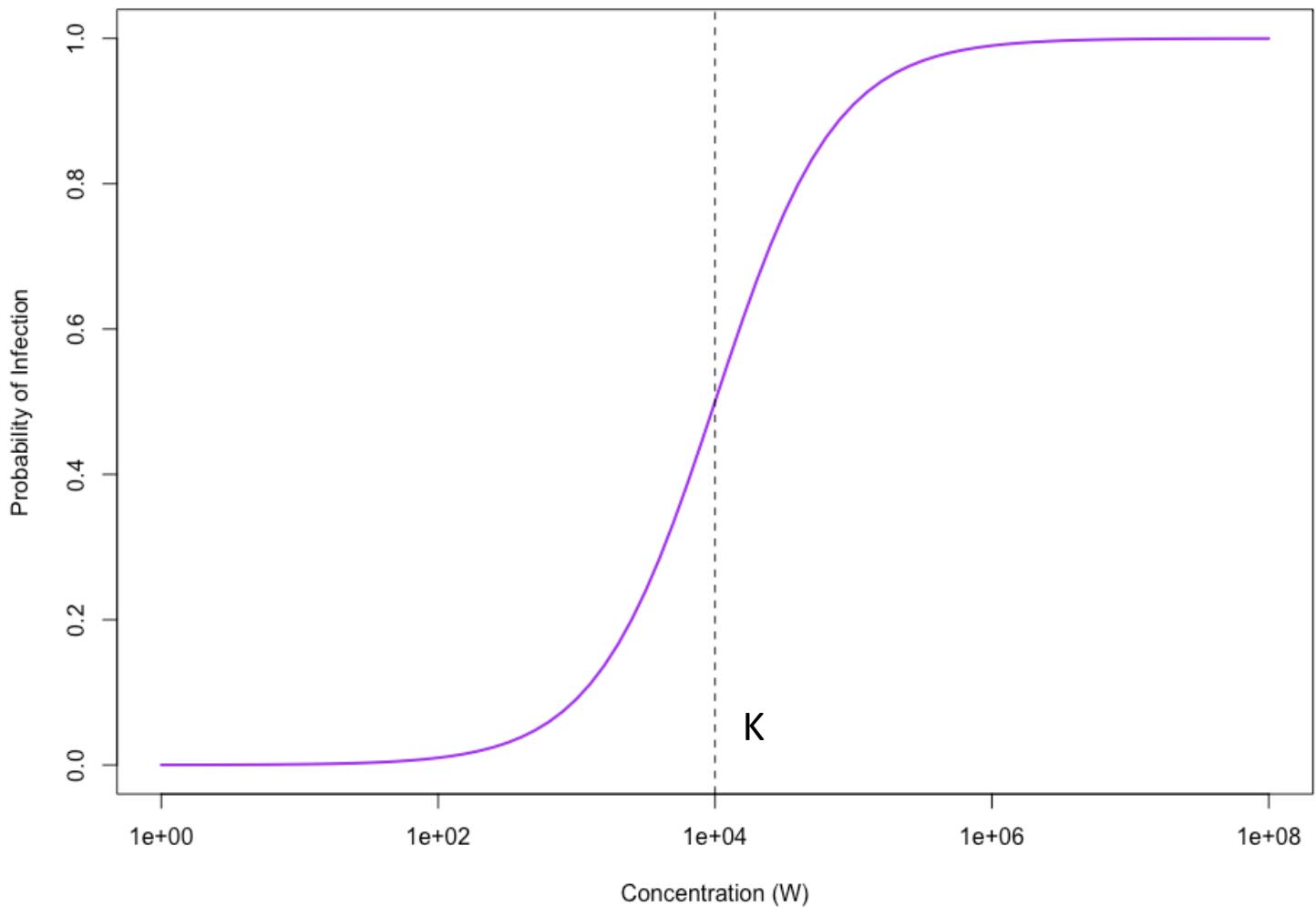
$$\lambda(W) = \frac{W}{K + W}$$

Cholera Infectious Dose

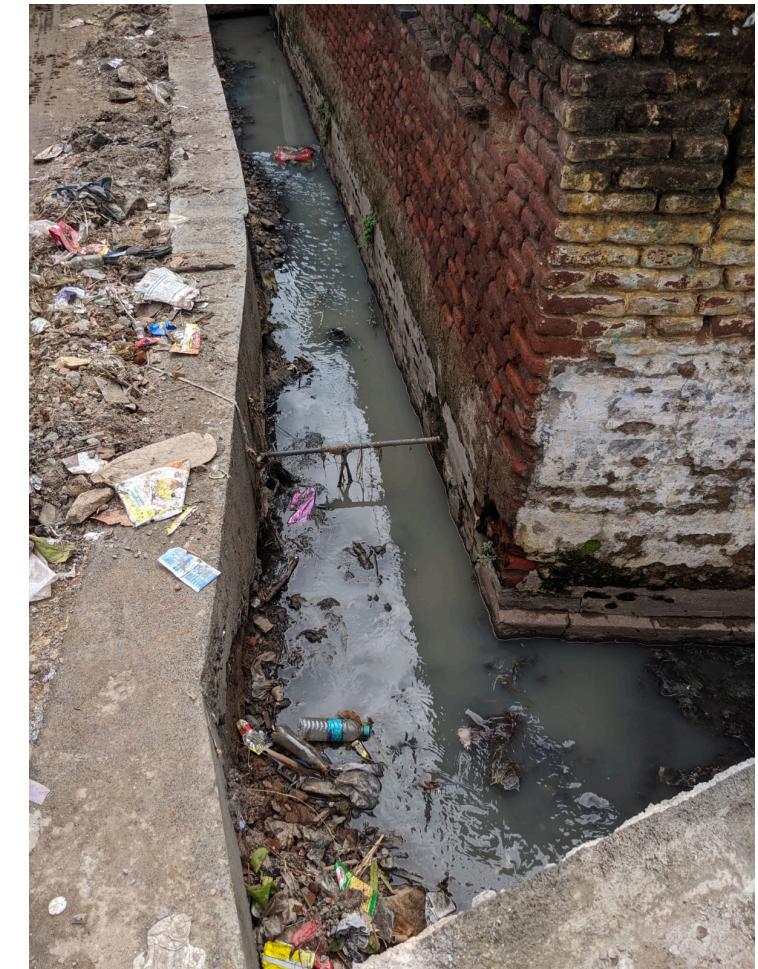
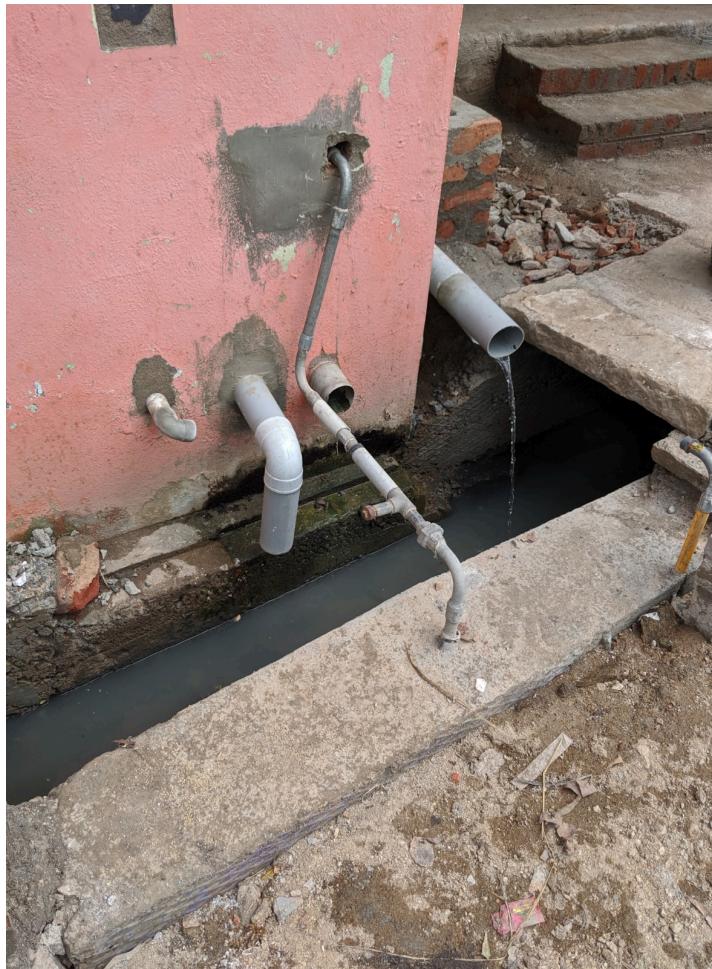
W = concentration in environment

K = concentration at which 50% infected (ID_{50})

$$\lambda(W) = \frac{W}{K + W}$$



Mixing of Sewage and Water



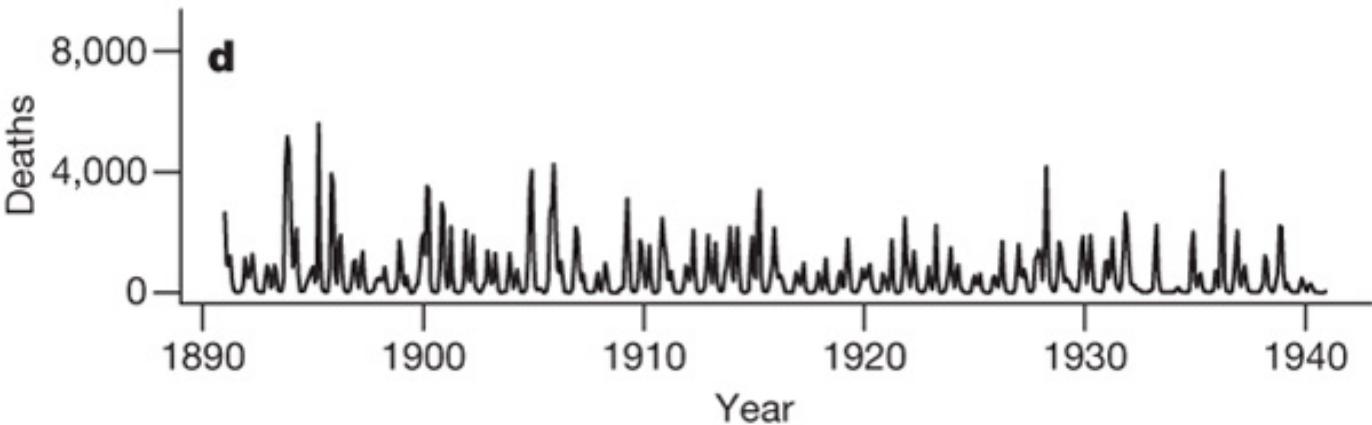
What would one need to know to specify a detailed/ realistic model of cholera transmission through environmental reservoir?

- Size of reservoir
- Proportion of fecal waste entering it
- Extent of mixing of sewage with water
- Proportion of people using this sewage/water for consumption
- How much is consumed
- Survival of *V. cholerae* in environment
- Whether treatment of water is performed and how effective it is

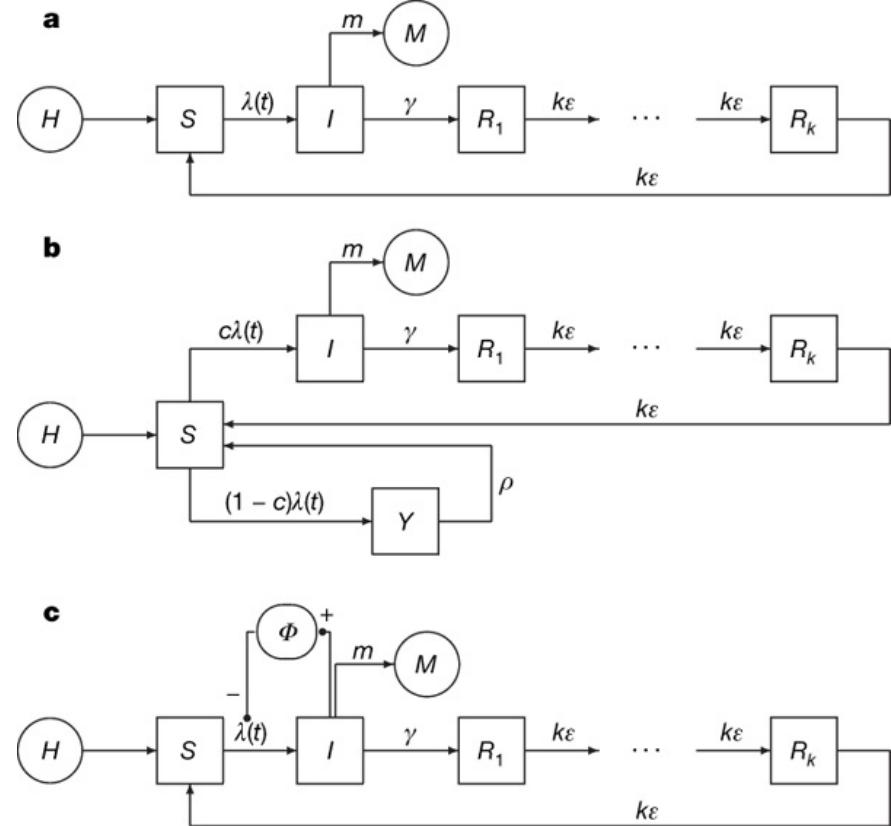
Many ways to model cholera

Inapparent infections and cholera dynamics

Aaron A. King^{1,2}, Edward L. Ionides³, Mercedes Pascual^{1,4} & Menno J. Bouma⁵



- What model provides the best fit, balancing for complexity?
- How much does the environment contribute to transmission?
- What proportion of cases are symptomatic?
- What is the duration of immunity after infection?



Summary

- Many pathogens have transmission routes that are not directly human to human, and can involve vectors and the environment
- The force of infection in these models is often non-linearly related to disease prevalence. We can observe saturation or threshold-type effects
- There are often many ways to describe natural history and transmission of the same pathogen, and it can challenging to select model parameters that are measurable or models that are identifiable