



What's your favorite animal so far?



16%

0%

68%

5%

11%

Fundamentals of Ecology

Week 8, Ecology Lecture 7

Cara Brook

February 27, 2025

**Office hours: On ZOOM
Friday, Feb 28, 2025
4-5pm
*I will email out a link!***

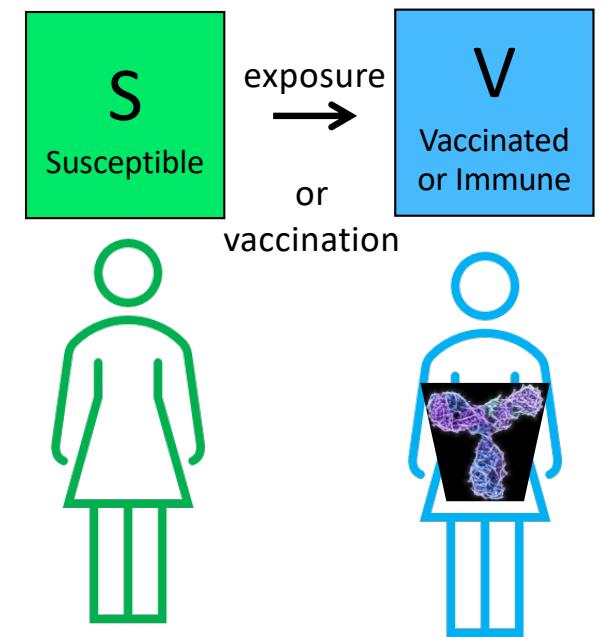
Learning objectives from Lecture 6

You should be able to:

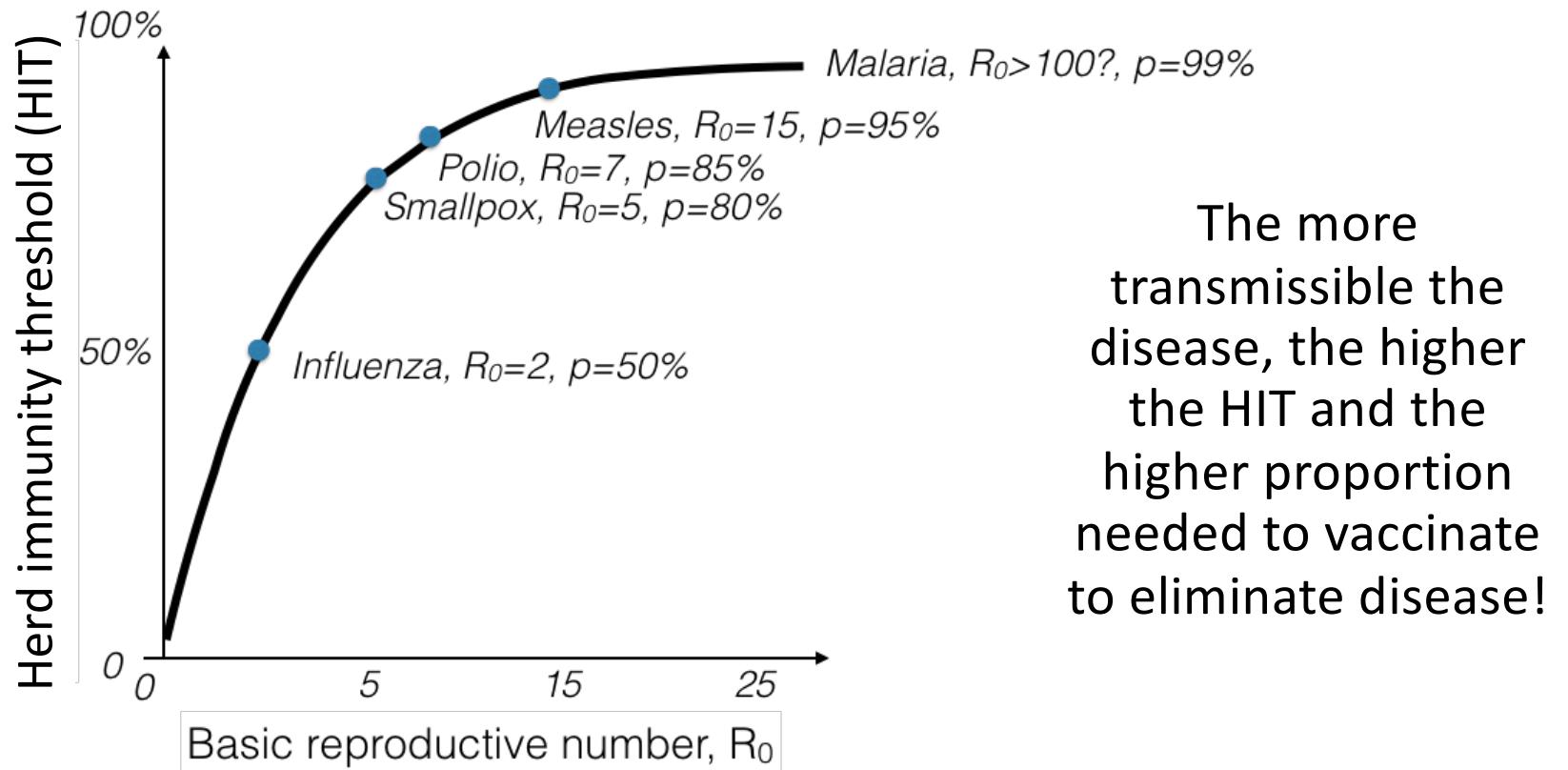
- Recognize that coexistence is rare without spatial structuring or niche partitioning (from competition/coexistence lessons)
- Know the history of disease impacts on human population growth and evolution
- Understand different classes of parasite or pathogen and how they manifest as disease
- Understand the SIR equation and be able to convert between diagrams and equations. Know the processes that connect the different boxes
- Understand the herd immunity concept (also the proportion needed to vaccinate to eradicate disease) and identify on a phase plane graph (from lab)
- Understand the direction of time in a disease epidemic from a phase plane graph (from lab)
- Understand the relationship between R_0 and R_t/RE

Mathematics of Vaccination

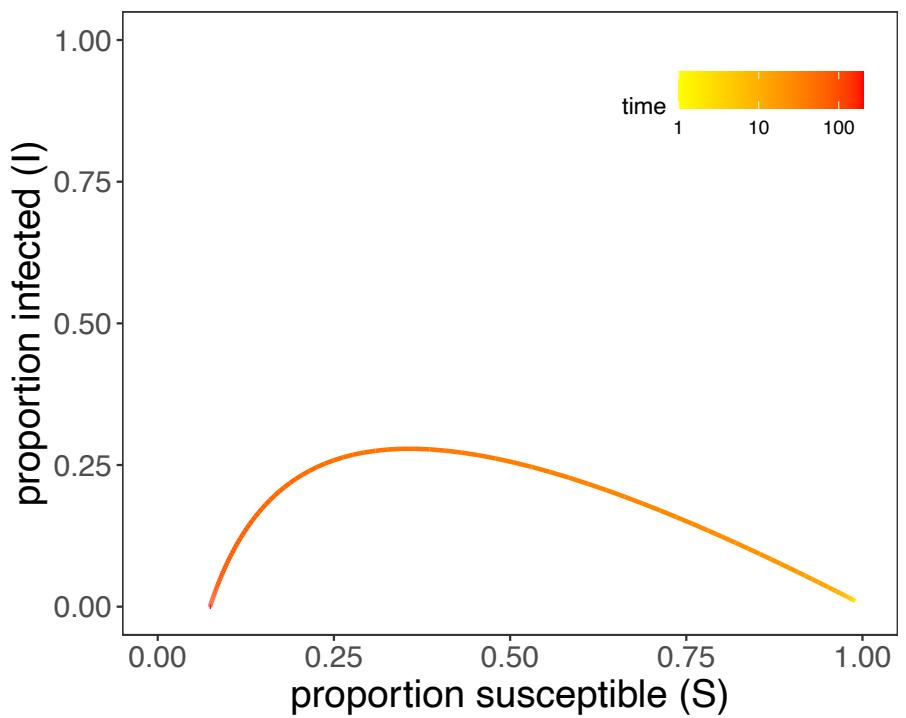
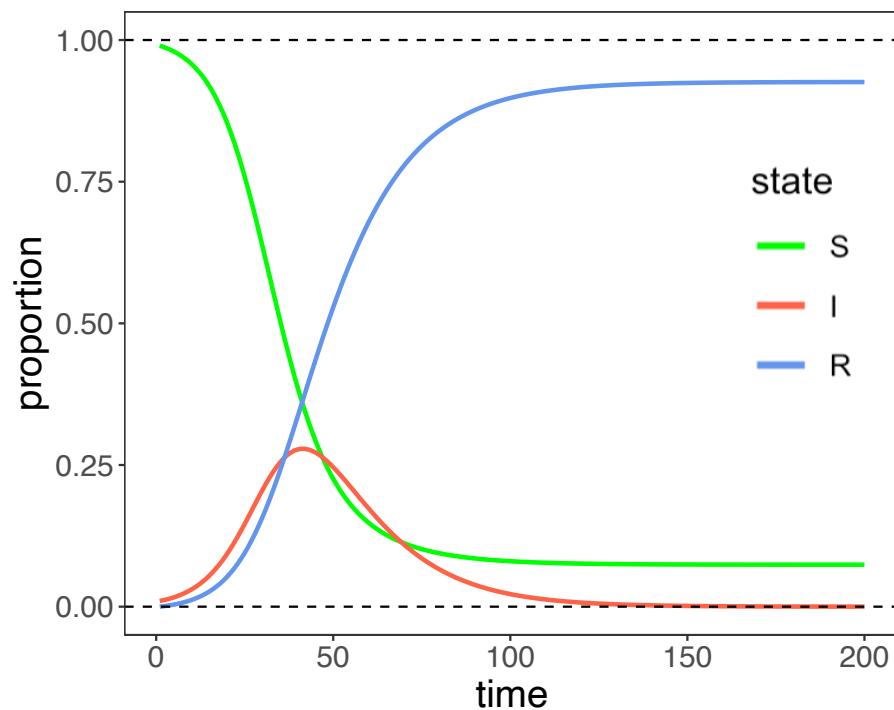
- Goal: **Reduce $R_E < 1$** by removing individuals from the susceptible population.
- Because infectious periods tend to be short-lived (*depending on the pathogen!*), we can theoretically divide the population into two classes: S (susceptible) and V (vaccinated, or immune)
- If $S + V = N$, then
Prop. Susceptible + Prop. Vaccinated = 1.
- Remember, $R_E = R_0 P_S$ or $R_E = R_0(1 - P_V)$
- $R_E < 1 \approx (1 - P_V)R_0 < 1$
- Rearranging, $P_V > 1 - \frac{1}{R_0}$
- **This is the herd immunity threshold.**
- **Even susceptibles will not become infected because the disease will not spread ($R_E < 1$).**



R_0 and the Herd Immunity Threshold

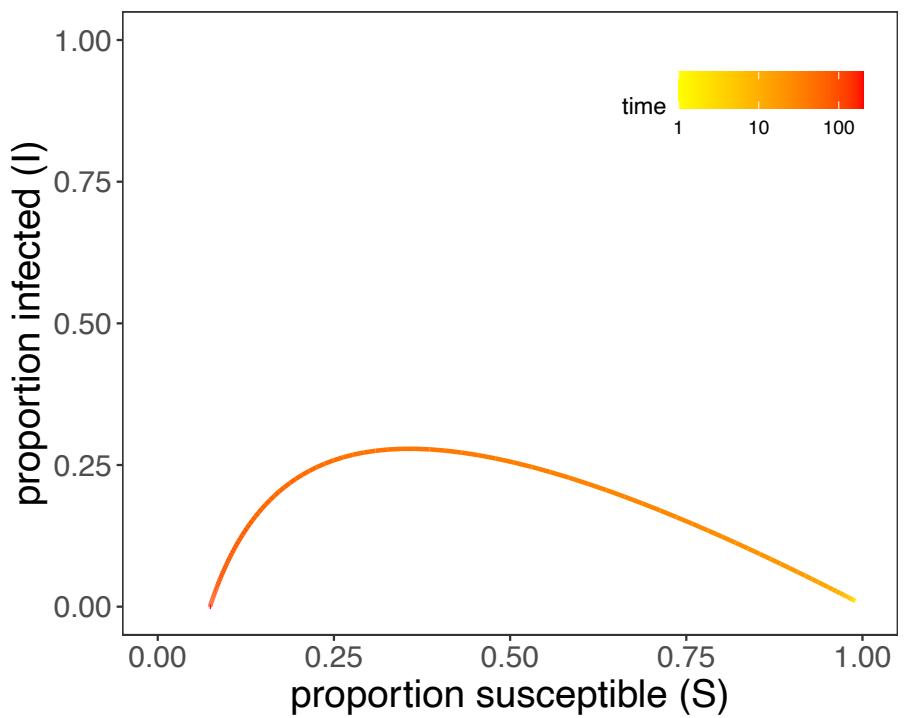
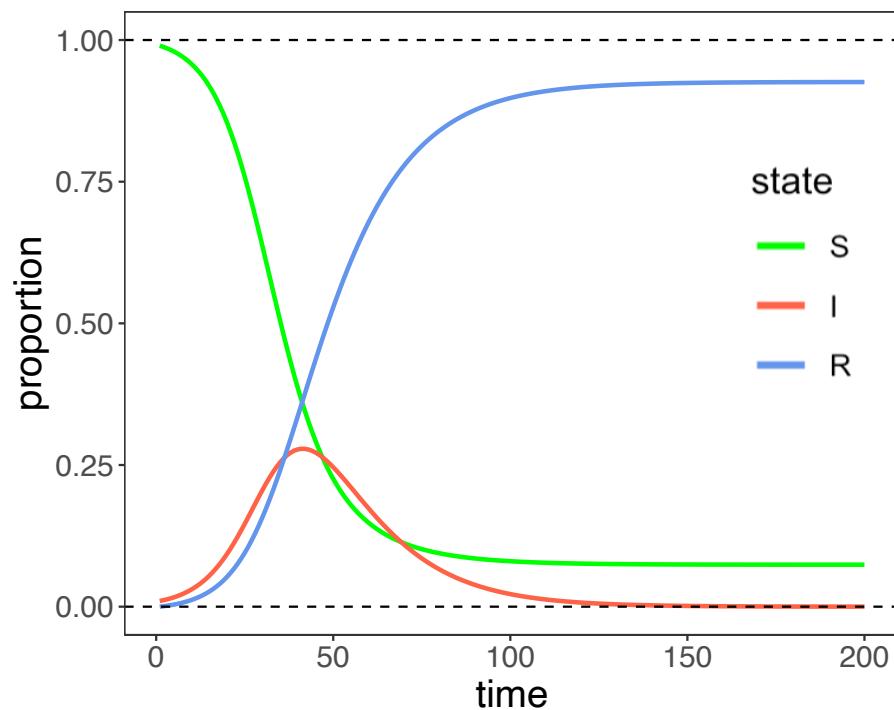


R_0 and the Herd Immunity Threshold



$$R_0 = 2.8$$

R_0 and the Herd Immunity Threshold

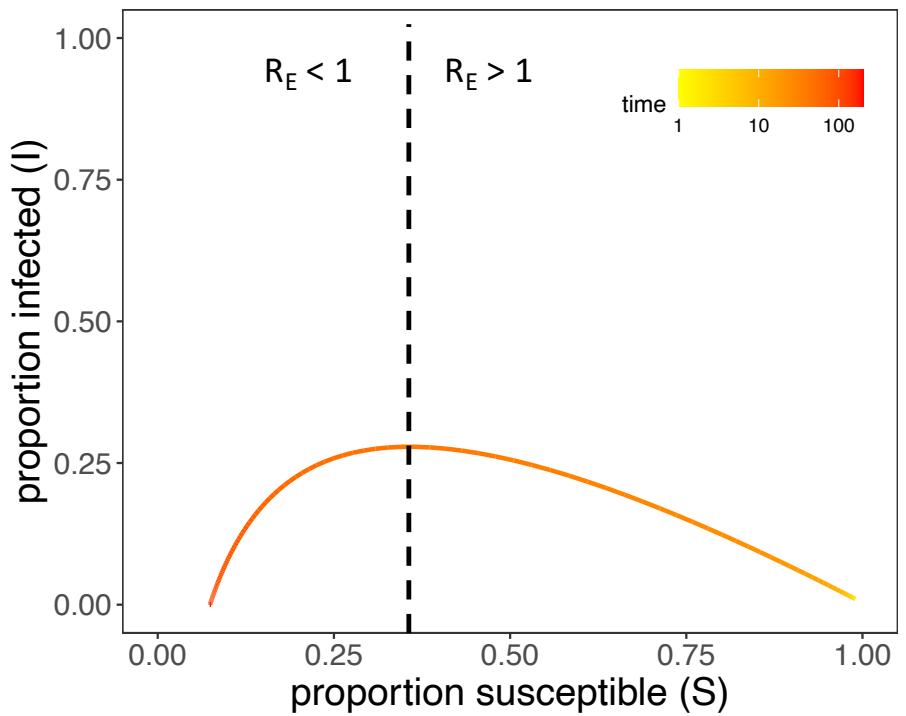
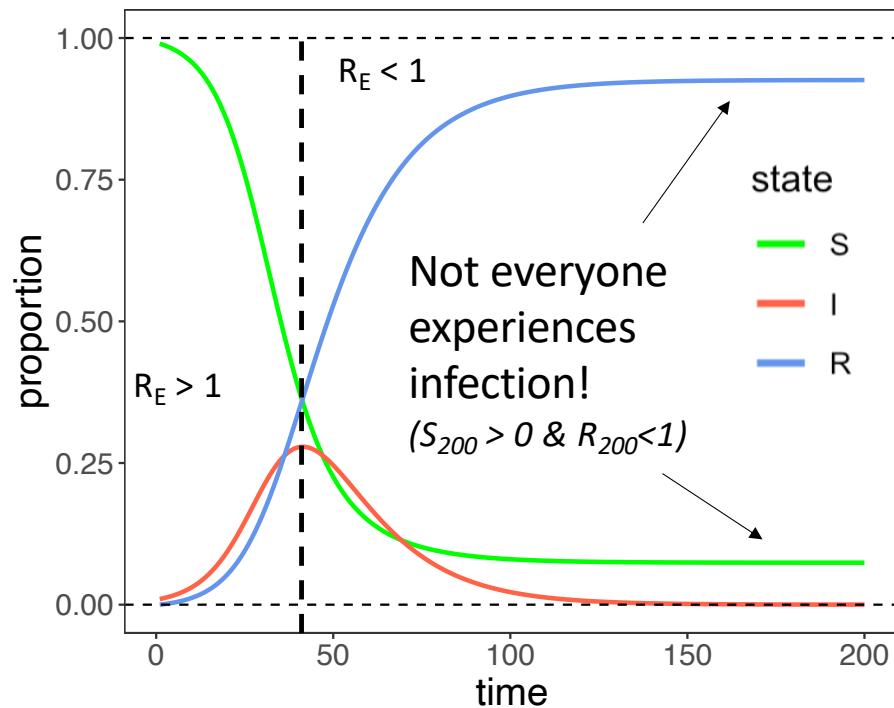


$$R_0 = 2.8$$

$$P_v = 1 - 1/R_0 = 1 - (1/2.8) = 0.64$$

64% need to be immune to stop the disease from spreading.
That means only 36% remaining susceptibles are permitted!

R_0 and the Herd Immunity Threshold

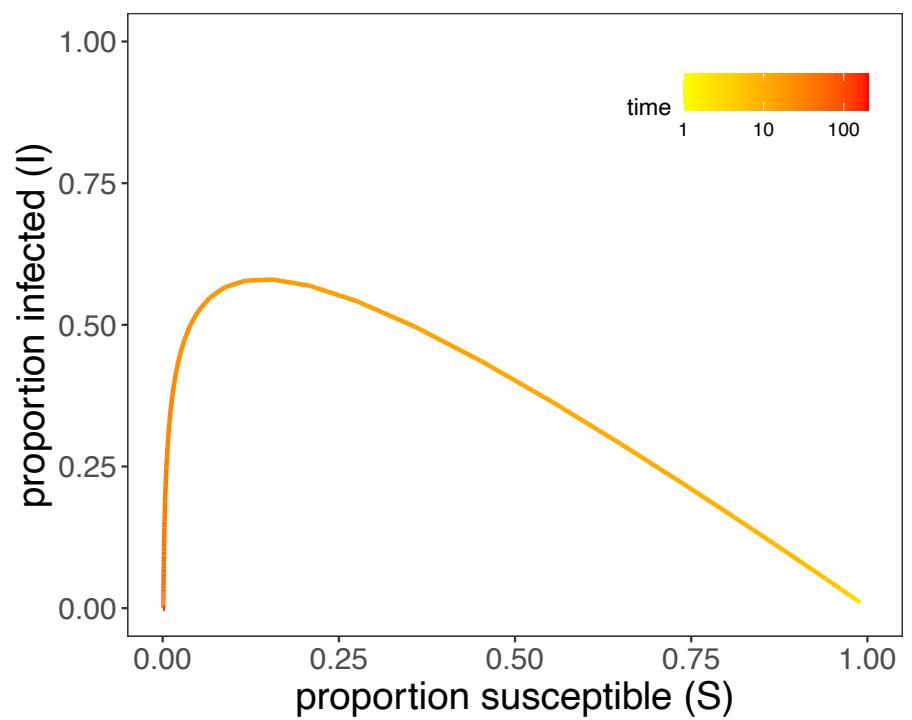
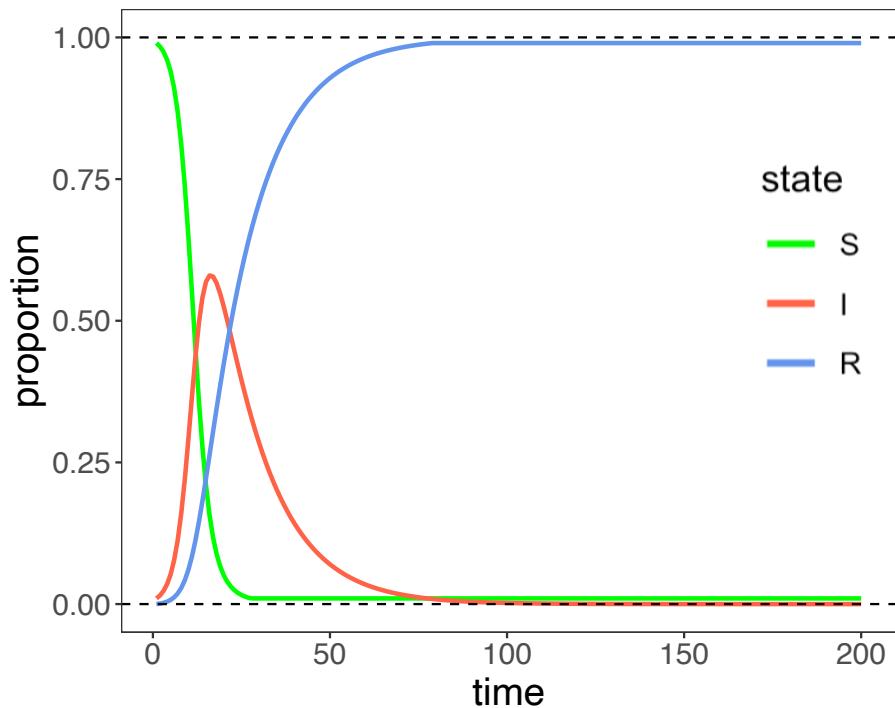


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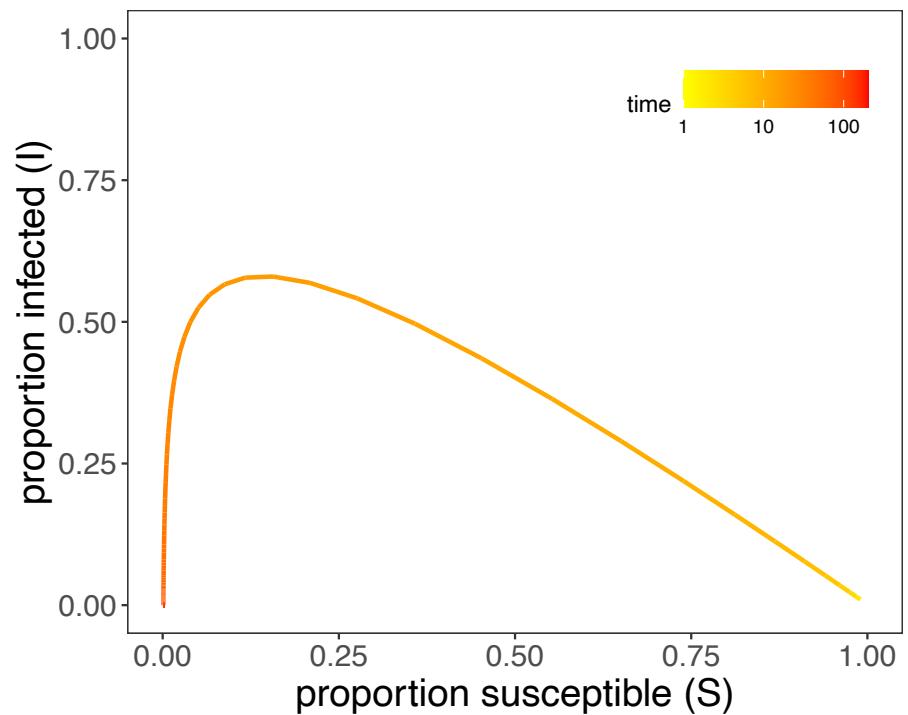
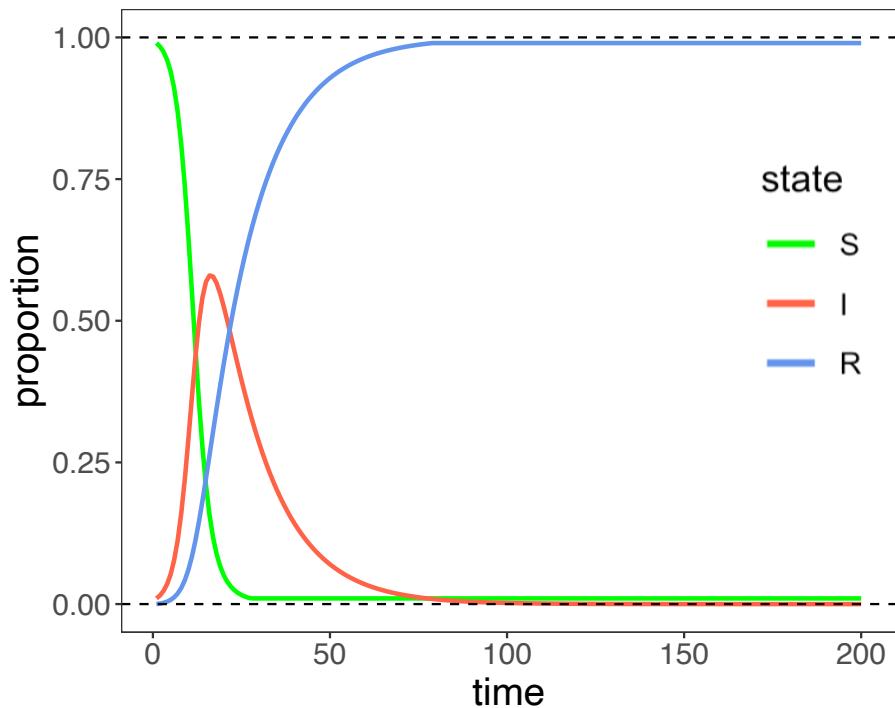
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R_0 and the Herd Immunity Threshold



$$R_0 = 7$$

R_0 and the Herd Immunity Threshold

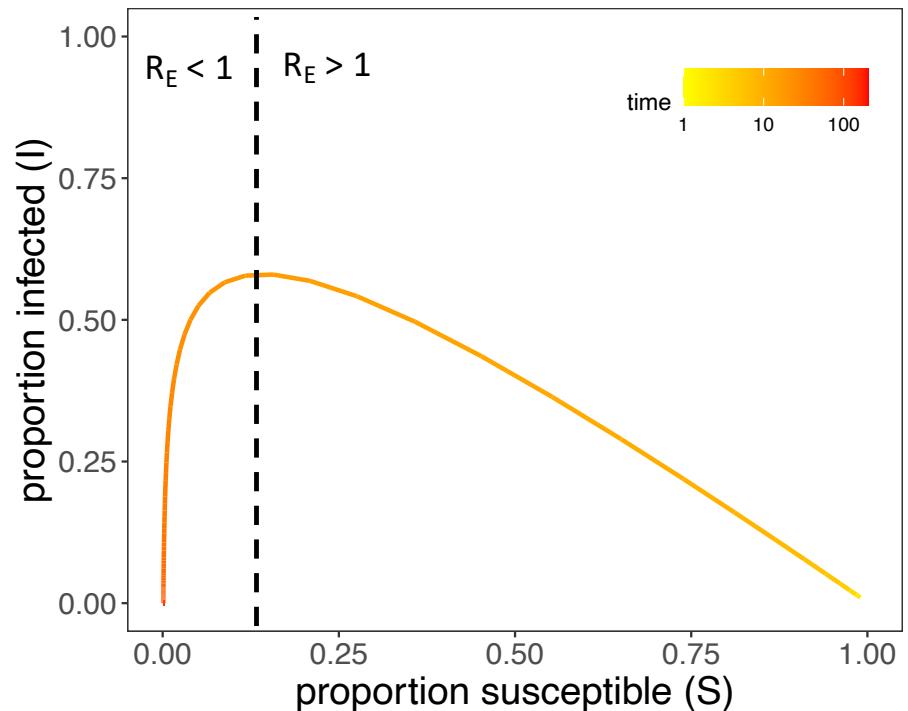
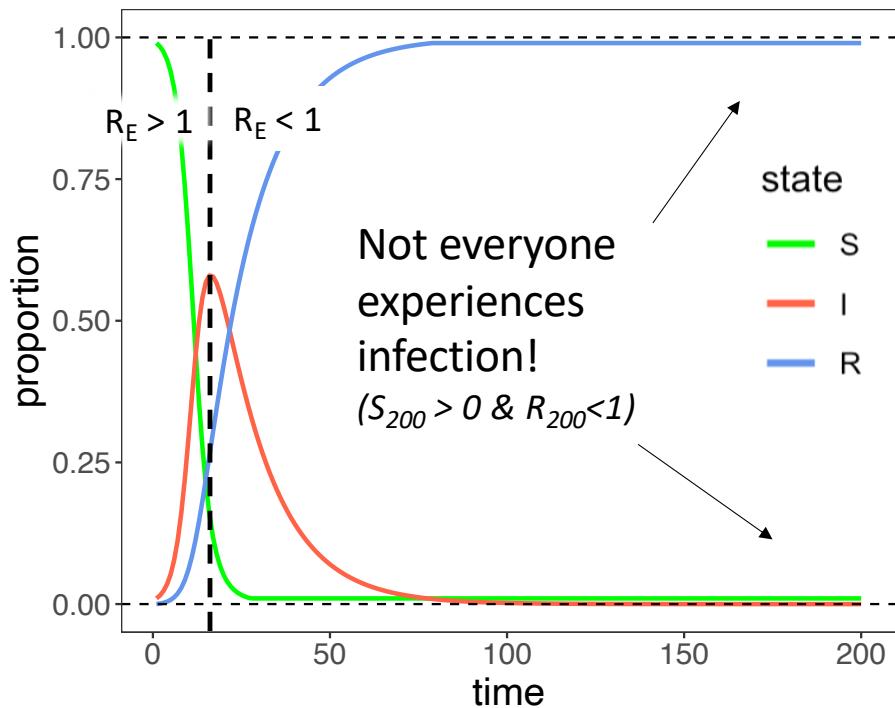


$$R_0 = 7$$

$$P_v = 1 - 1/R_0 = 1 - (1/7) = 0.86$$

86% need to be immune to stop the disease from spreading.
That means only 14% remaining susceptibles are permitted!

R_0 and the Herd Immunity Threshold



$$R_0 = 7$$

$$P_v = 1 - 1/R_0 = 1 - (1/7) = 0.86$$

86% need to be immune to stop the disease from spreading.
That means only 14% remaining susceptibles are permitted!



What is R_E ? It is

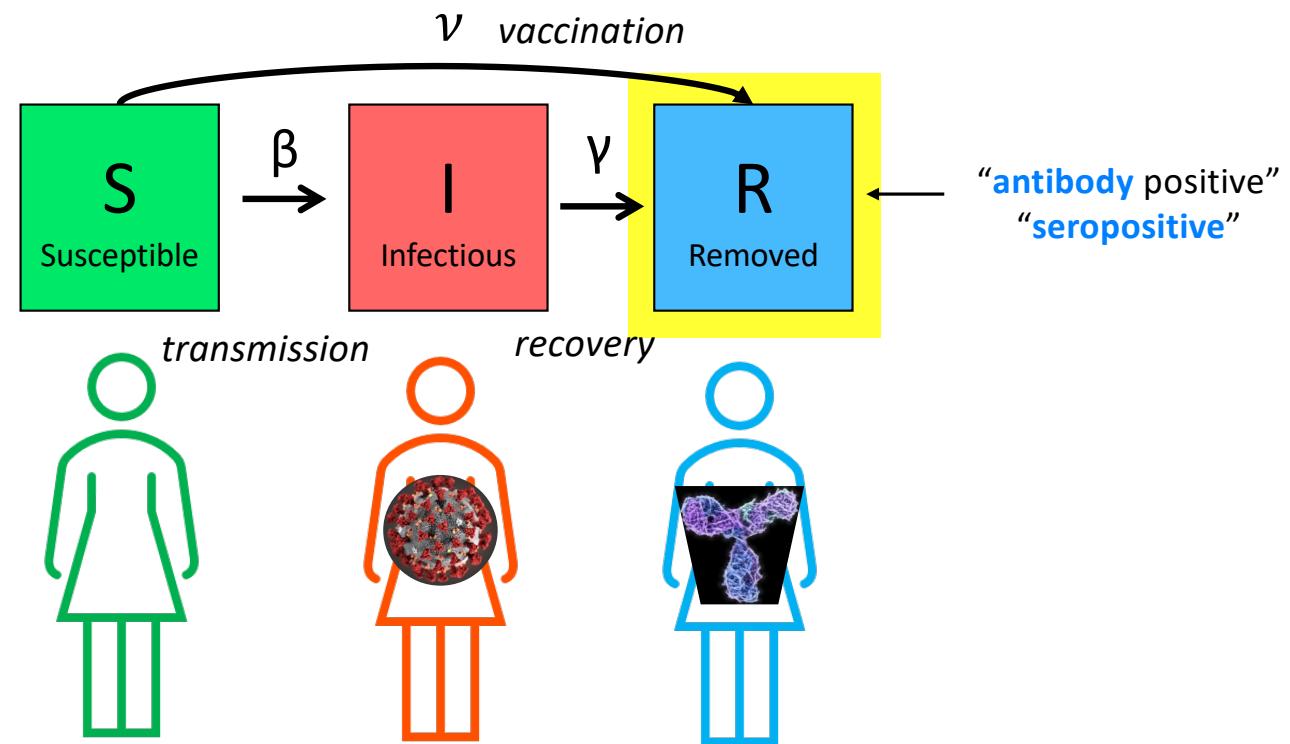
- A. the herd immunity threshold during an epidemic



- B. the rate of change of a disease in a completely susceptible population

SEE MORE

Vaccination stems from a long history



Vaccination stems from a long history

- Variolation: Early attempts to provide protection against smallpox (*Variola*) via inoculation with scab material from a recent patient infected with *Variola minor*



Vaccination stems from a long history

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 - First described in China in the 10th century
 - Caused 1% mortality!



Vaccination stems from a long history

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- 1789 Edward Jenner used cowpox vesicles to inoculate an 8-year-old boy
 - Later inoculated with smallpox and boy was unaffected
 - The first vaccine, taken from *vacca*, cow in Latin



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- Smallpox was globally eradicated in 1977, following a massive international campaign
- Today, we are seeing enhanced transmission of monkeypox partly resulting from a lack of circulating immunity to closely related smallpox



Only two global vaccination success stories



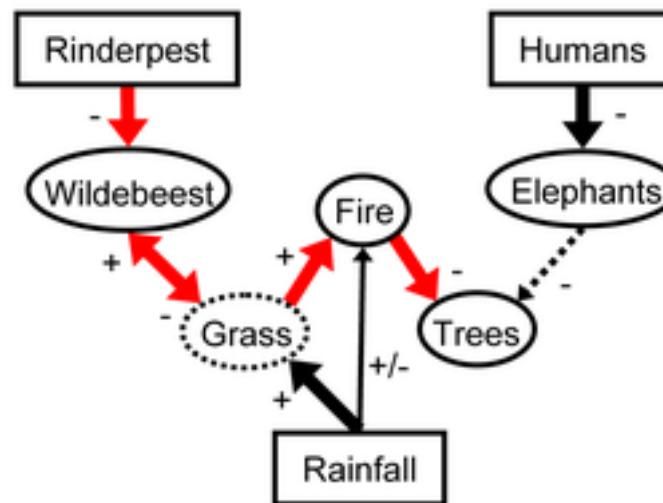
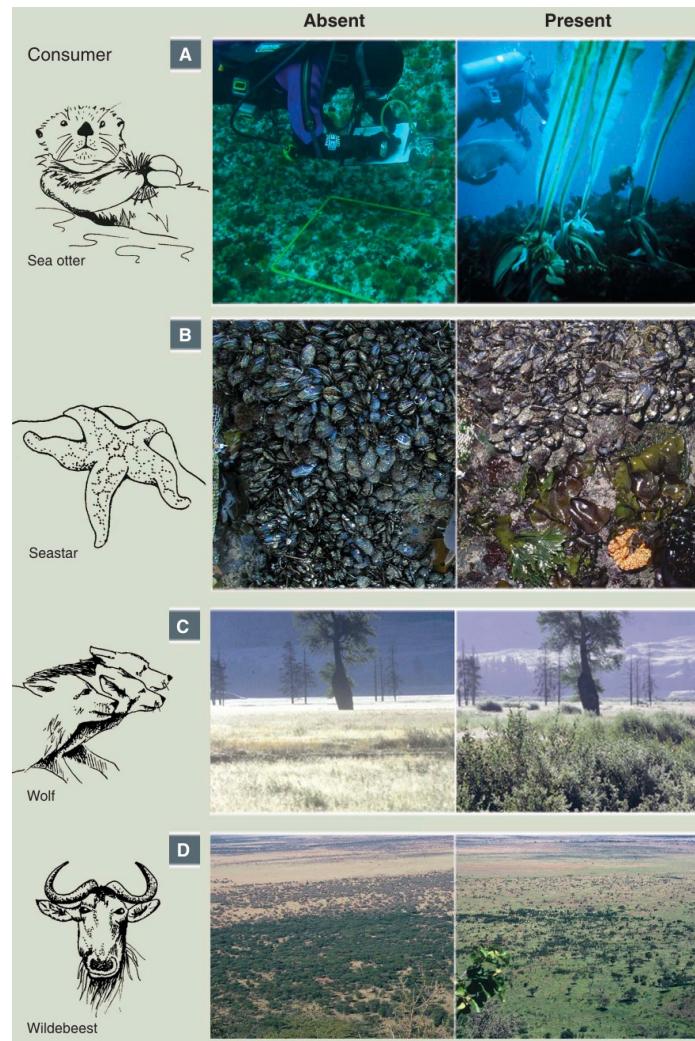
Only two global vaccination success stories



Rinderpest was globally eradicated in 2011, though inoculation efforts date back to the 1700s!

Remember those **trophic cascades**...

Estes et al. 2011. *Science*.



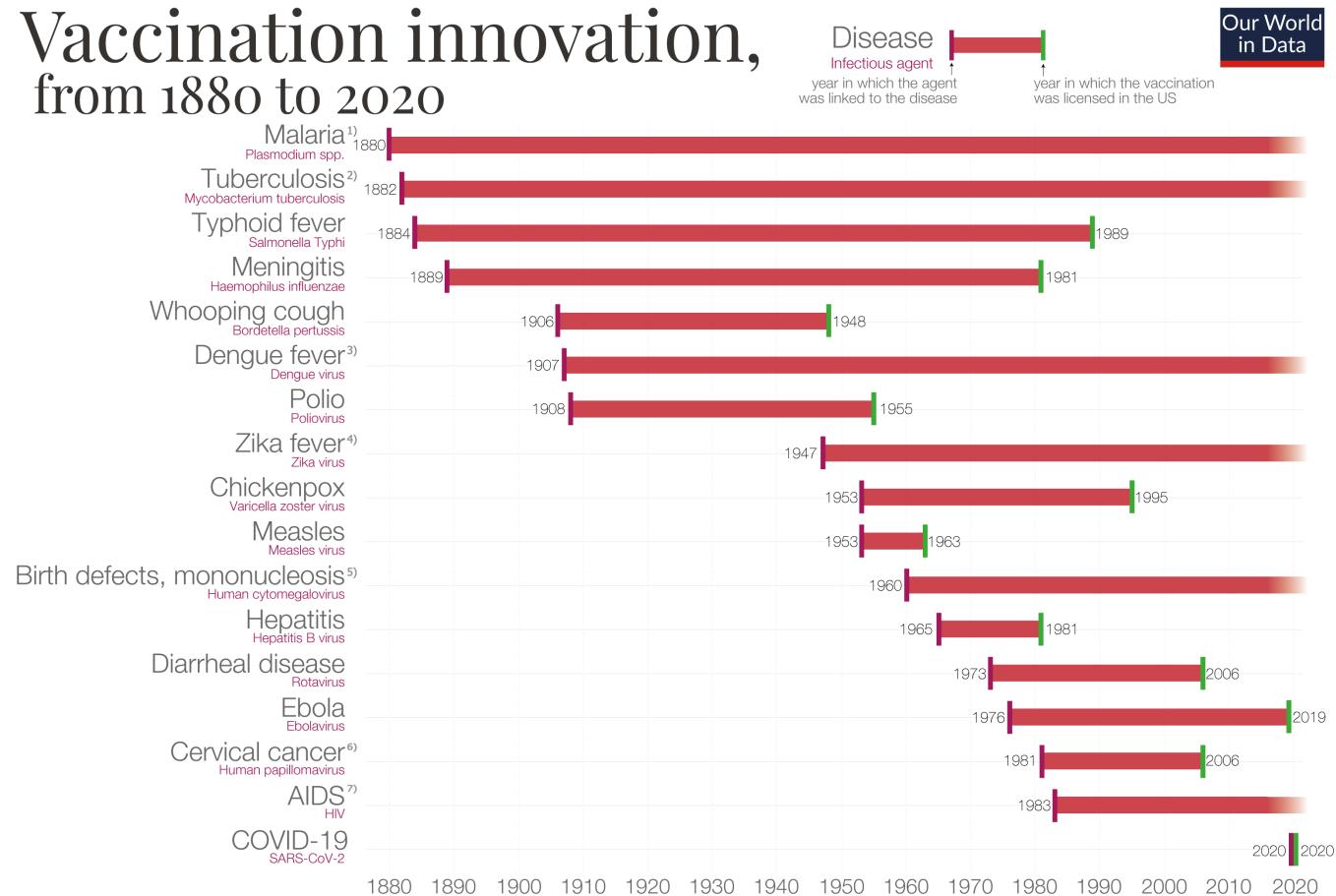
1. ↓ rinderpest
2. ↑ wildebeest
3. ↓ grass
4. ↓ fire
5. ↑ trees

Rinderpest eradication releases wildebeest populations that control savanna, limit fire, and promote tree regrowth

Holdo et al. 2009. *PLoS Biology*

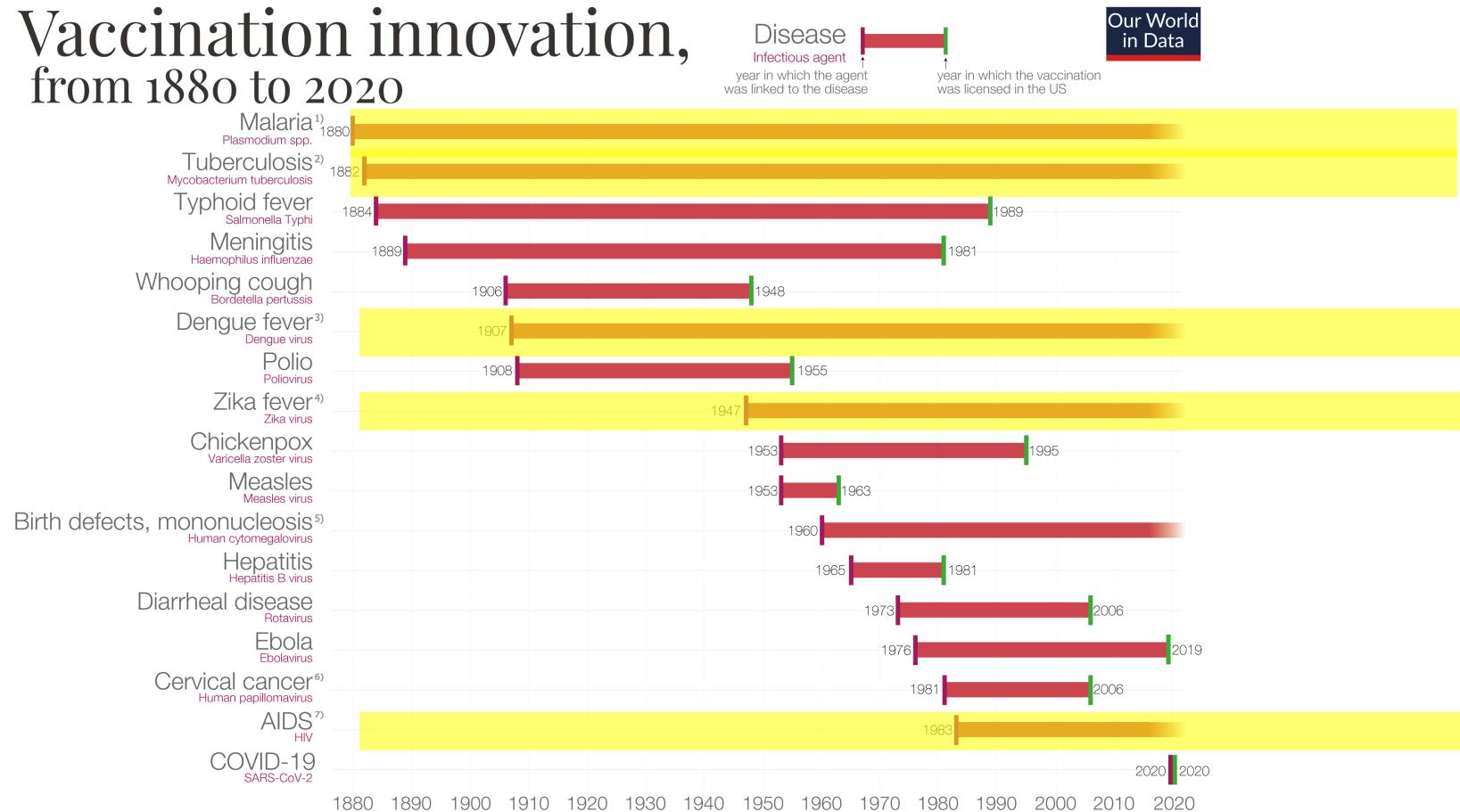
The pace of vaccine development has accelerated drastically

Vaccination innovation, from 1880 to 2020



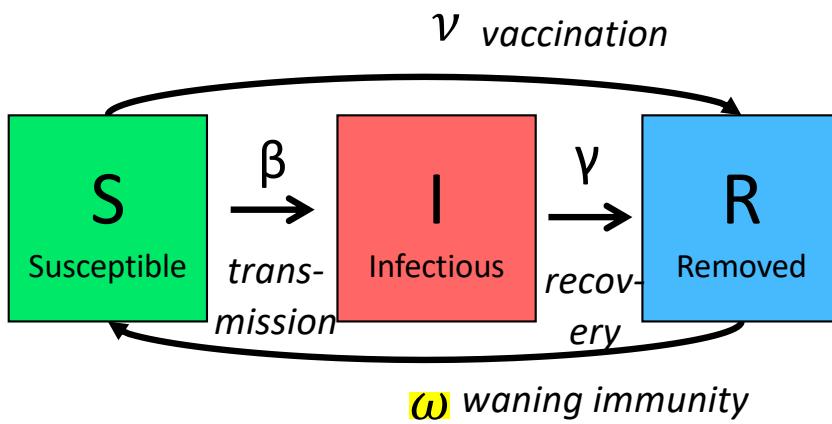
But we still lack vaccines for several important diseases.

Vaccination innovation, from 1880 to 2020



Challenges to Vaccination

- Imperfect immunity, especially with non-viral pathogens

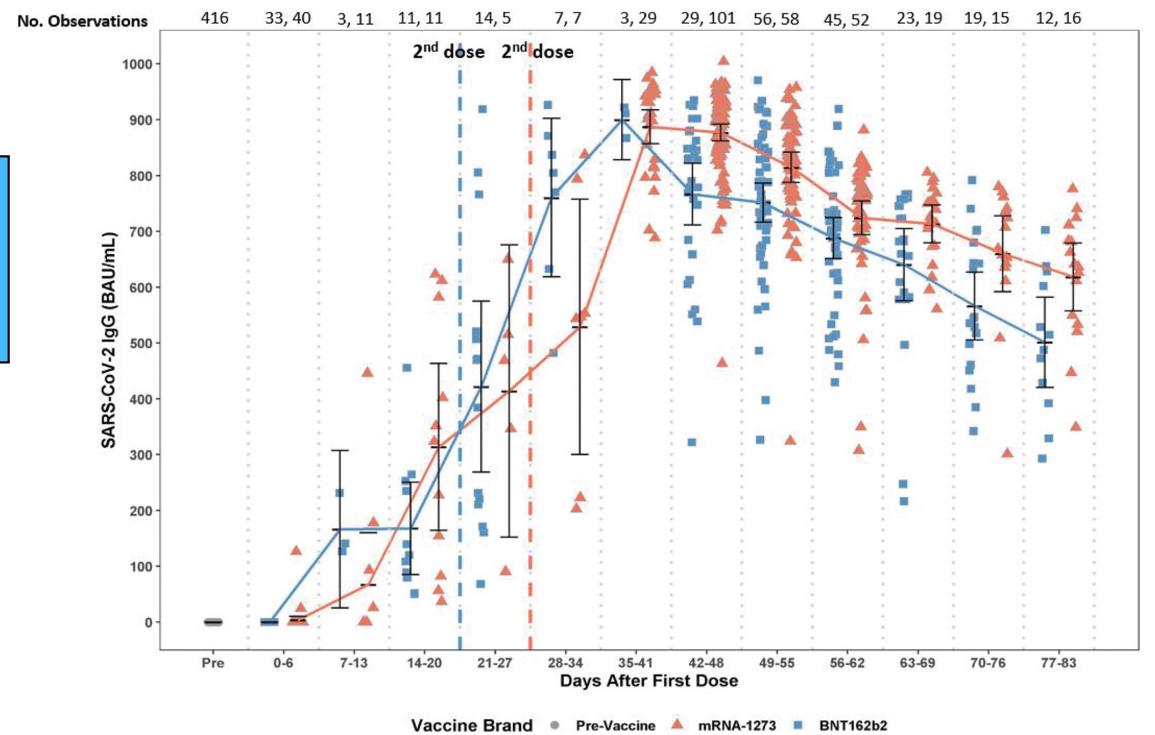


β = transmission rate

γ = recovery rate

ν = vaccination rate

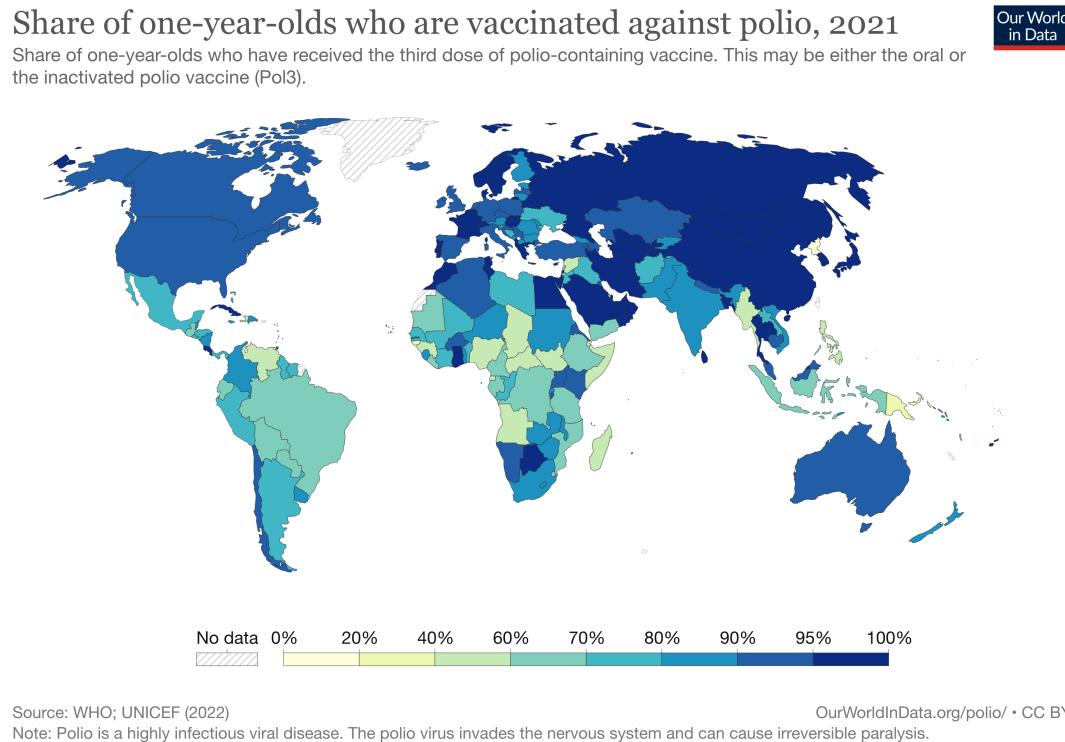
ω = rate waning immunity



Montoya et al. 2021 *Microbiology Spectrum*

Challenges to Vaccination

- Imperfect immunity, especially with non-viral pathogens
- Geographic differences in public health policy and access



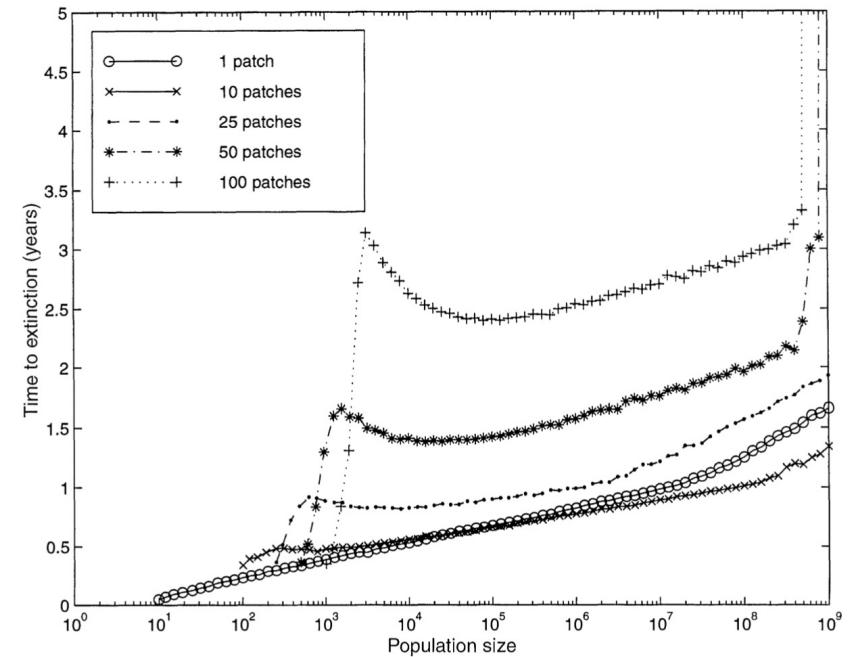
Challenges to Vaccination

- Imperfect immunity, especially with non-viral pathogens
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- Continuous births
- Animal reservoirs



Challenges to Vaccination

- Imperfect immunity, especially with non-viral pathogens
- Geographic differences in public health policy and access
- Continuous births
- Animal reservoirs
- Spatial structure (metapopulation rescue)



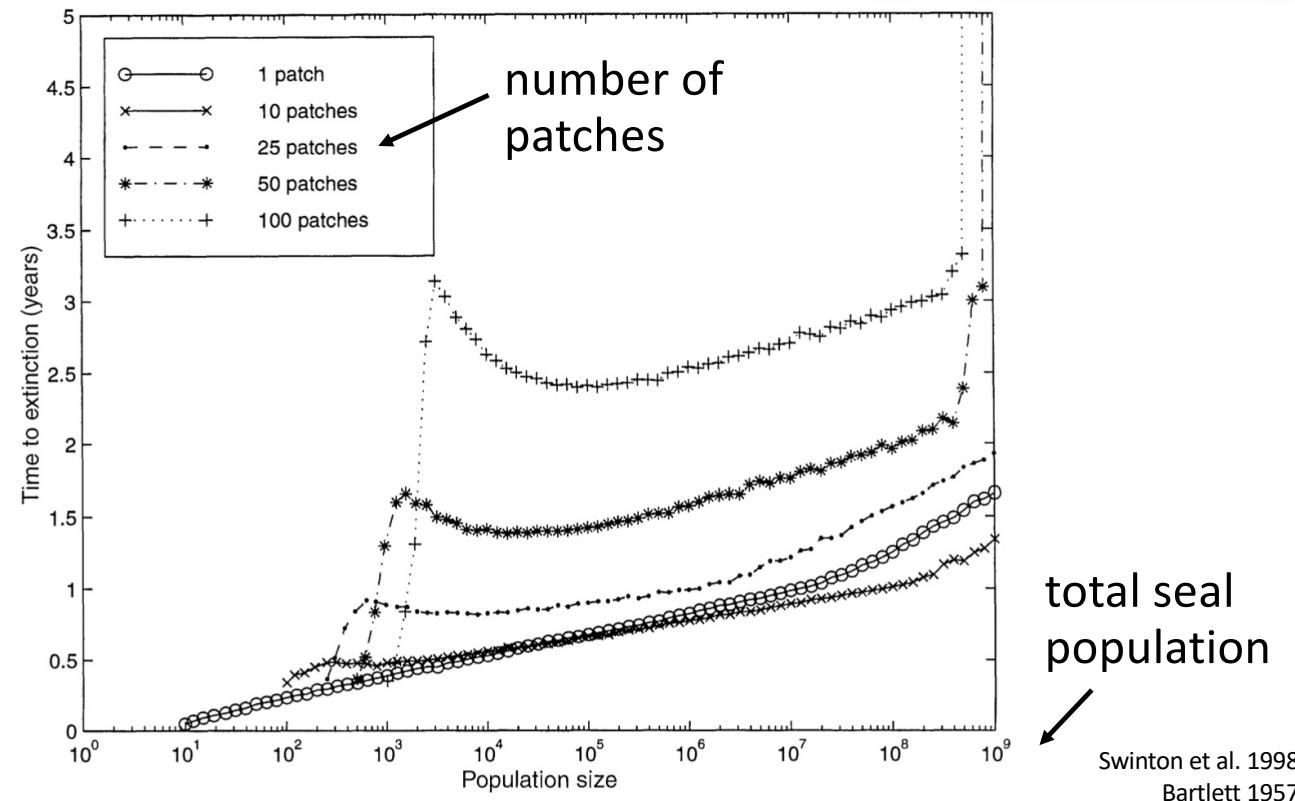
Swinton et al. 1998
Bartlett 1957

Challenges to Vaccination

- Spatial structure (metapopulation rescue)



time until all patches
go extinct (remember
metapopulations!)



Challenges to Vaccination

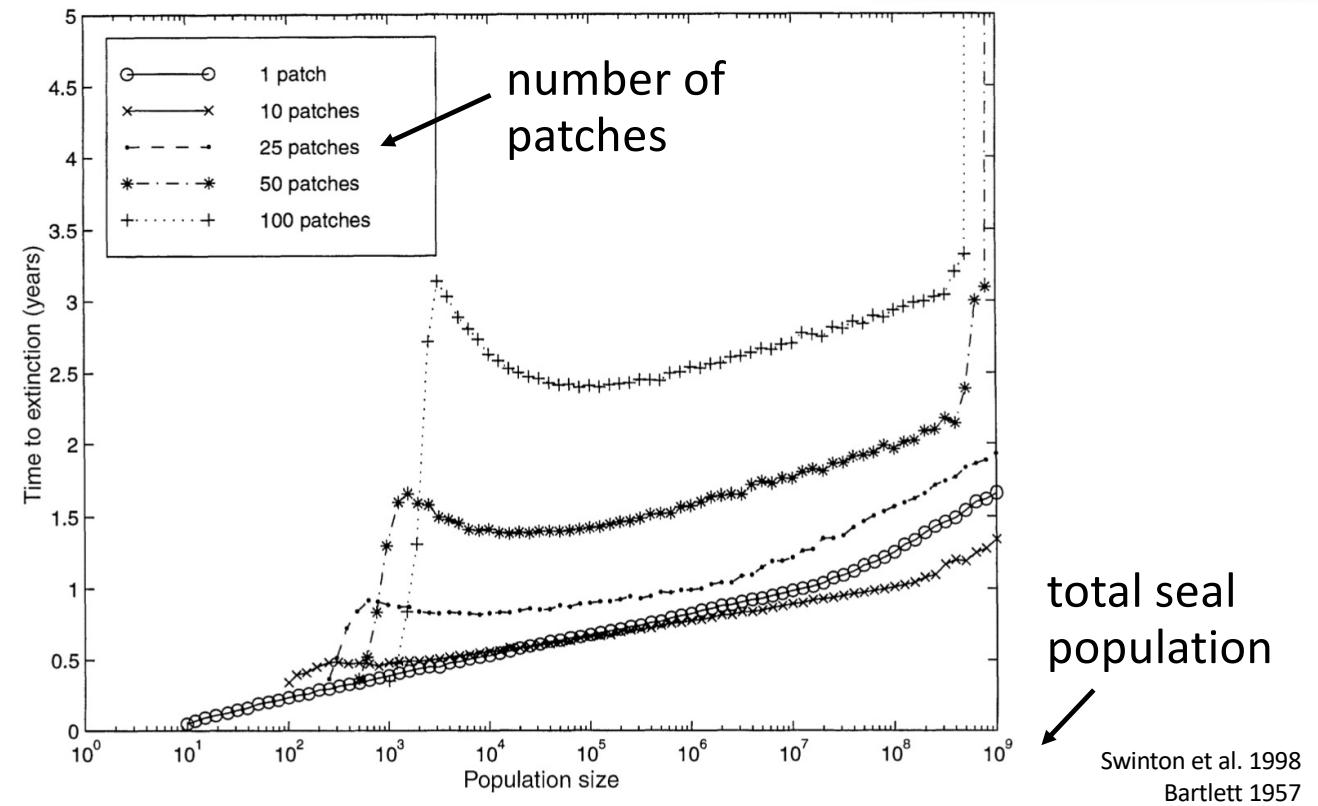
- Spatial structure (**metapopulation rescue**)



time until all patches go extinct (remember metapopulations!)

All else equal, **increasing the number of patches** will slow the time to extinction.

...though remember **source-sink** dynamics!





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Visual settings



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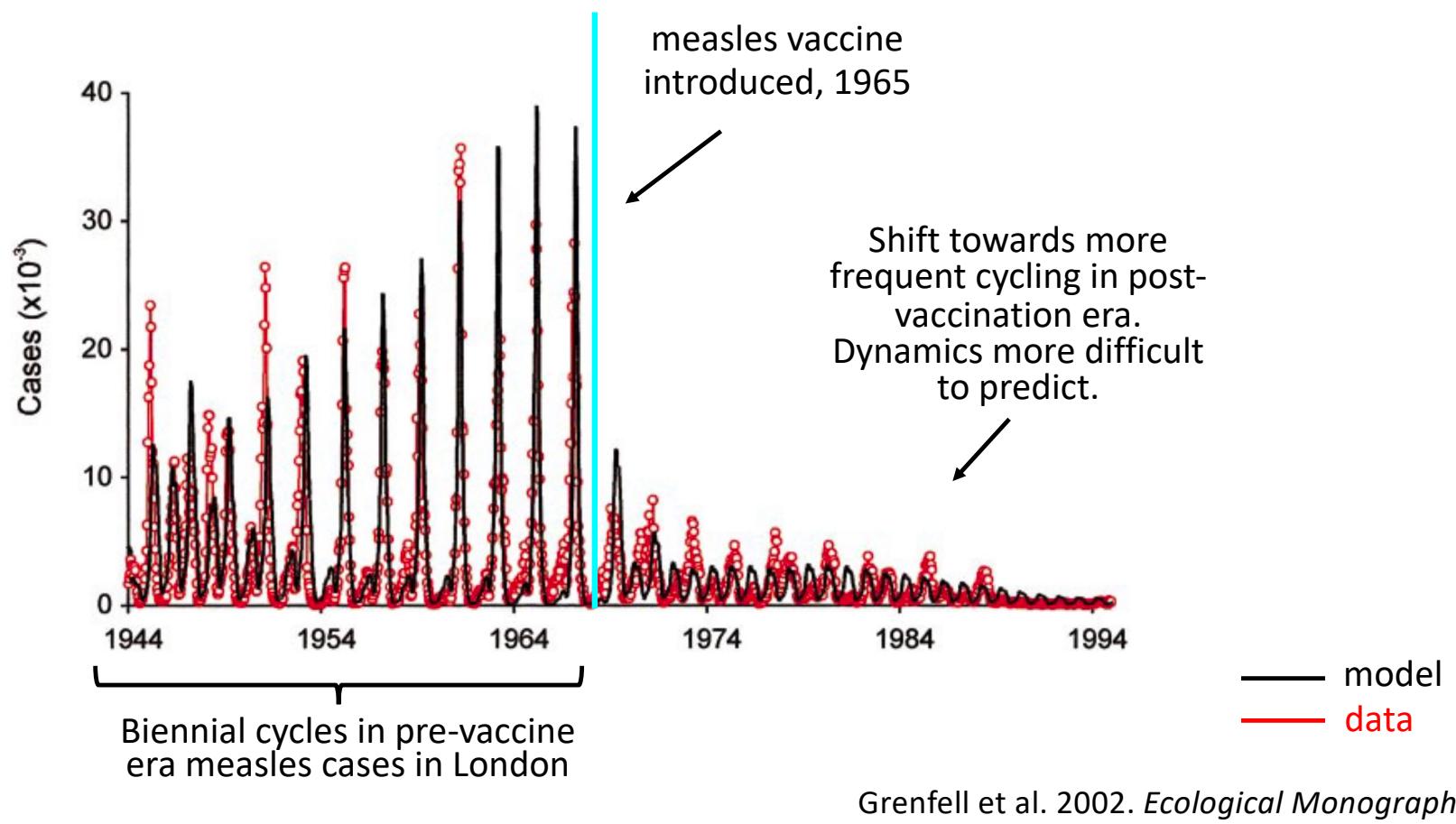


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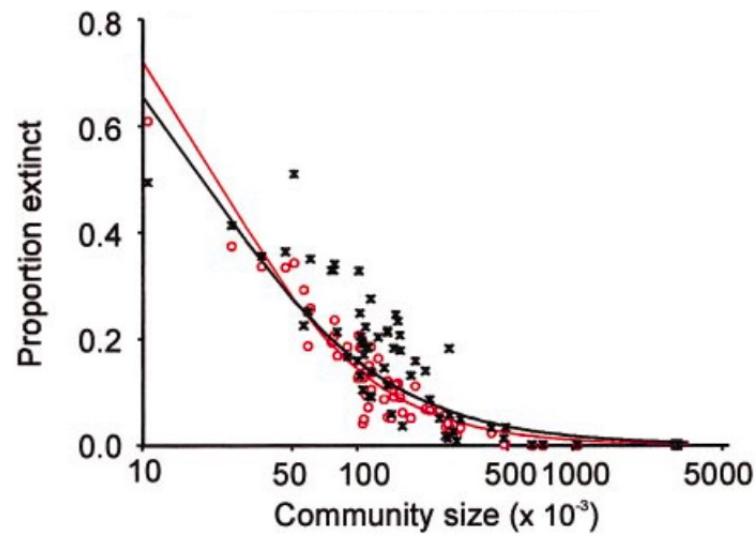
Challenges to Vaccination

- Imperfect immunity, especially with non-viral pathogens
- Geographic differences in public health policy and access
- Continuous births
- Animal reservoirs
- Spatial structure (metapopulation rescue)
- More complex pathogens!

Much of the mathematical theory underlying vaccination was first developed for measles

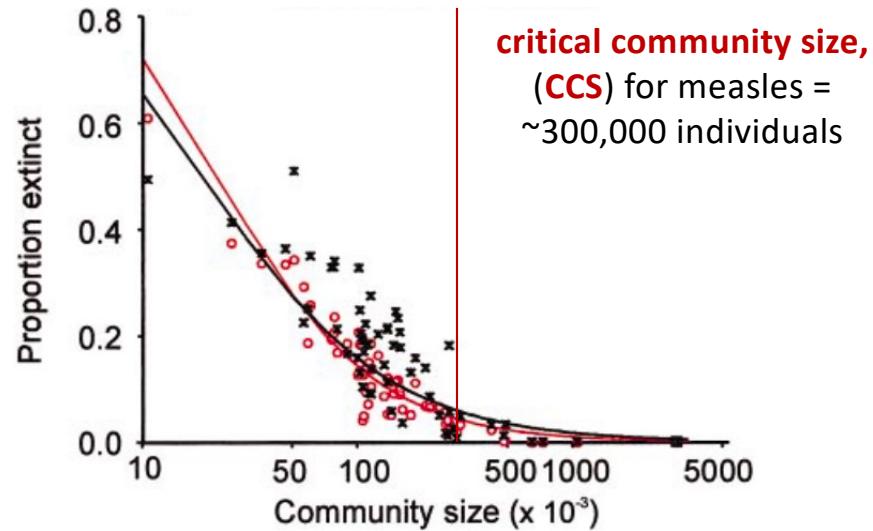


Even for measles, stochastic dynamics mean that predictions become more challenging at smaller population sizes.



Grenfell et al. 2002. *Ecological Monographs*

CCS is the **minimum number of hosts** needed to sustain **endemic transmission** of a pathogen indefinitely into the future.



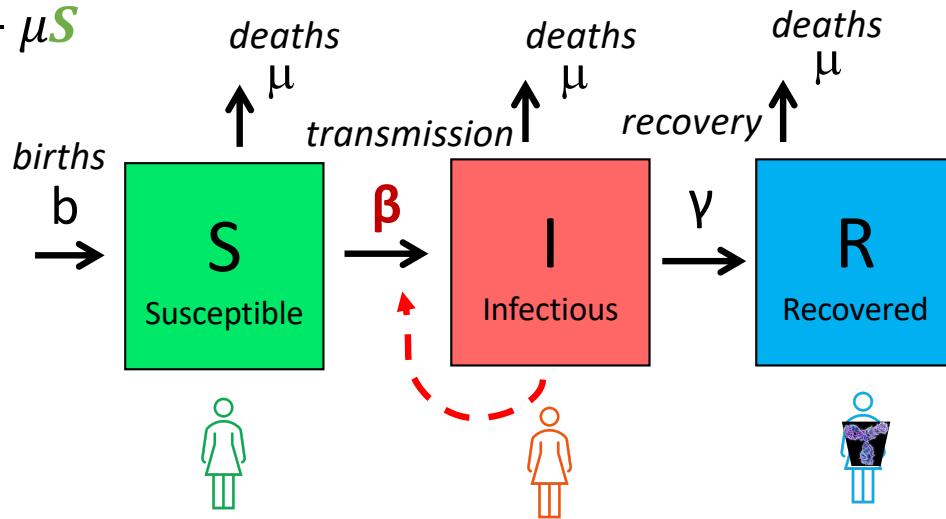
Bartlett 1957. *J of Roy Stat Soc.*
Grenfell et al. 2002. *Ecological Monographs*.
Haydon et al. 2002. *Emerging Infectious Diseases*.

We can adapt the simple SIR model to better match our pathogen of interest and our corresponding data.

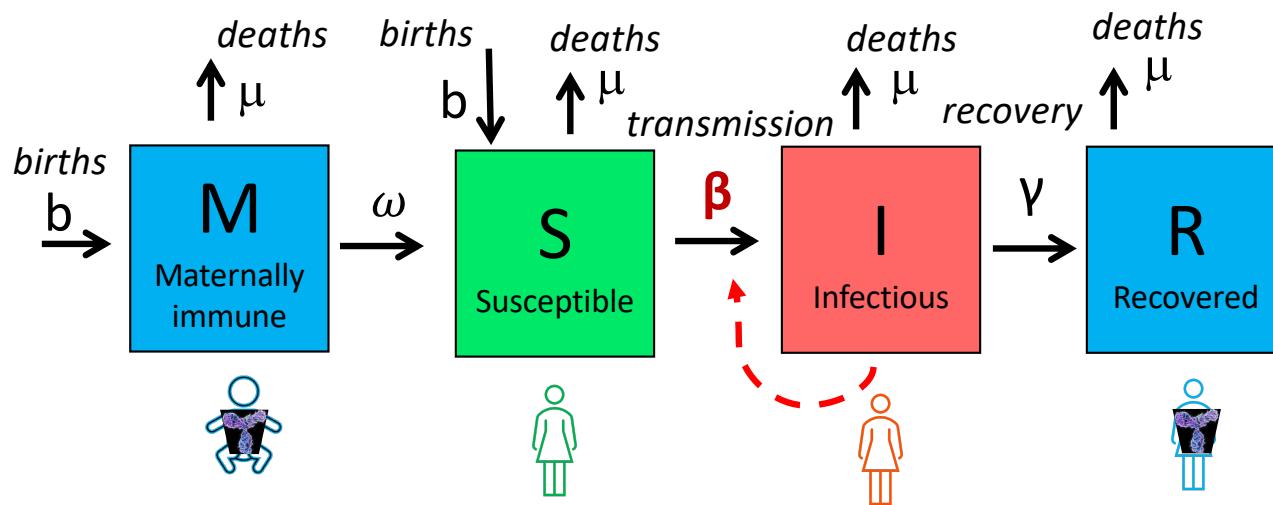
$$\frac{dS}{dt} = b(S + I + R) - \beta SI - \mu S$$

$$\frac{dI}{dt} = \beta SI - \gamma I - \mu I$$

$$\frac{dR}{dt} = \gamma I - \mu R$$



Incorporating Maternal Immunity



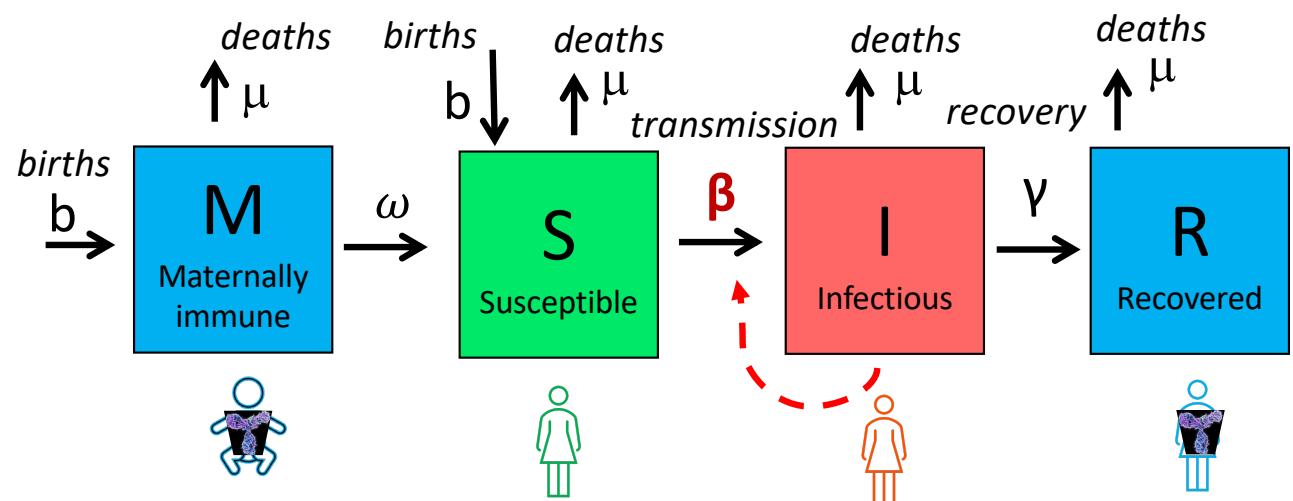
Incorporating Maternal Immunity

$$\frac{dS}{dt} = bS - \beta SI - \mu S$$

$$\frac{dI}{dt} = \beta SI - \gamma I - \mu I$$

$$\frac{dR}{dt} = \gamma I - \mu R$$

What does our new equation look like?



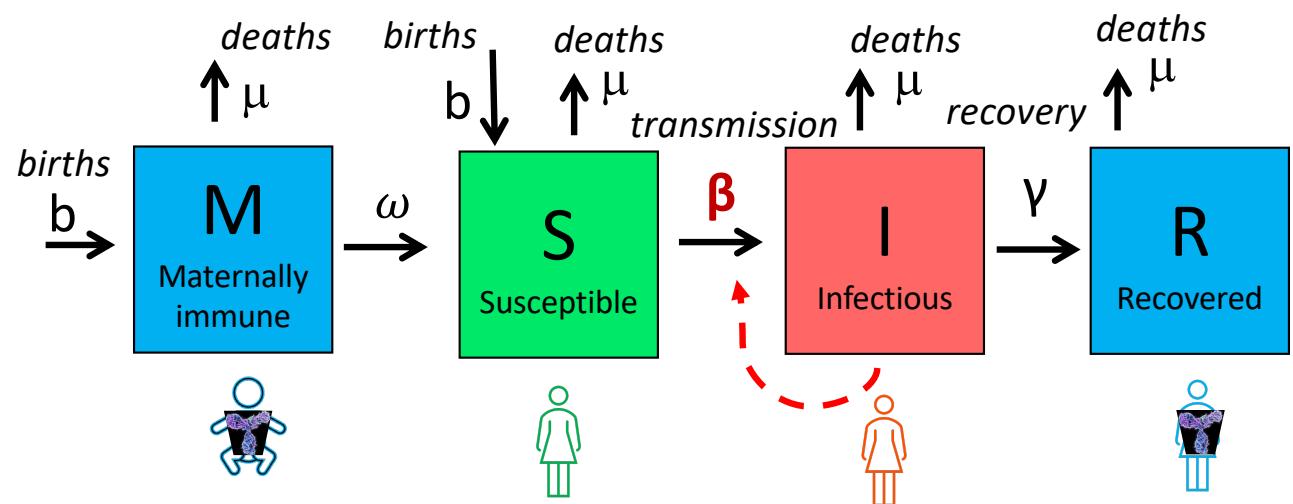
Incorporating Maternal Immunity

$$\frac{dM}{dt} = b(I + R) - \omega M - \mu M$$

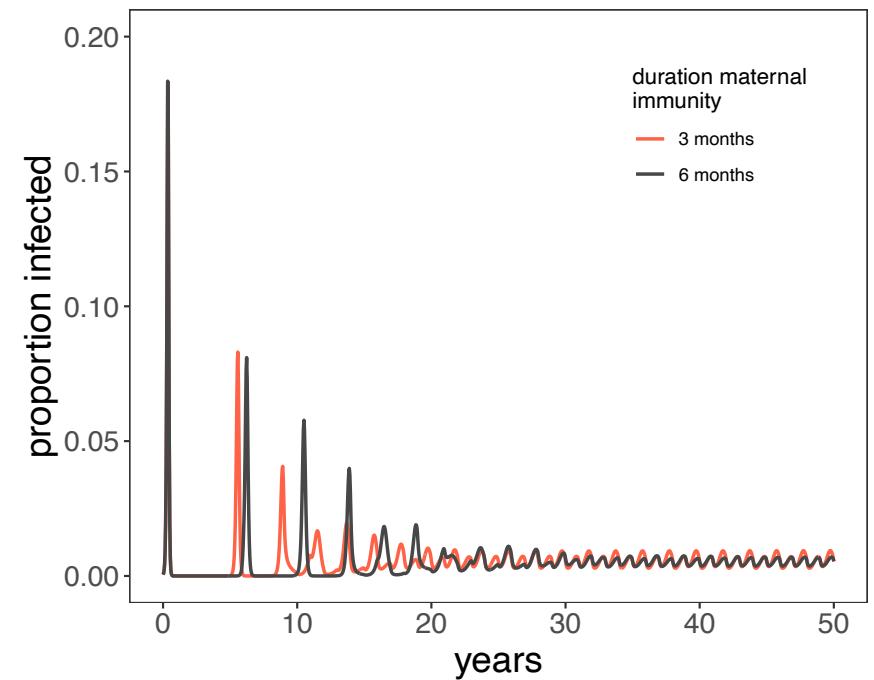
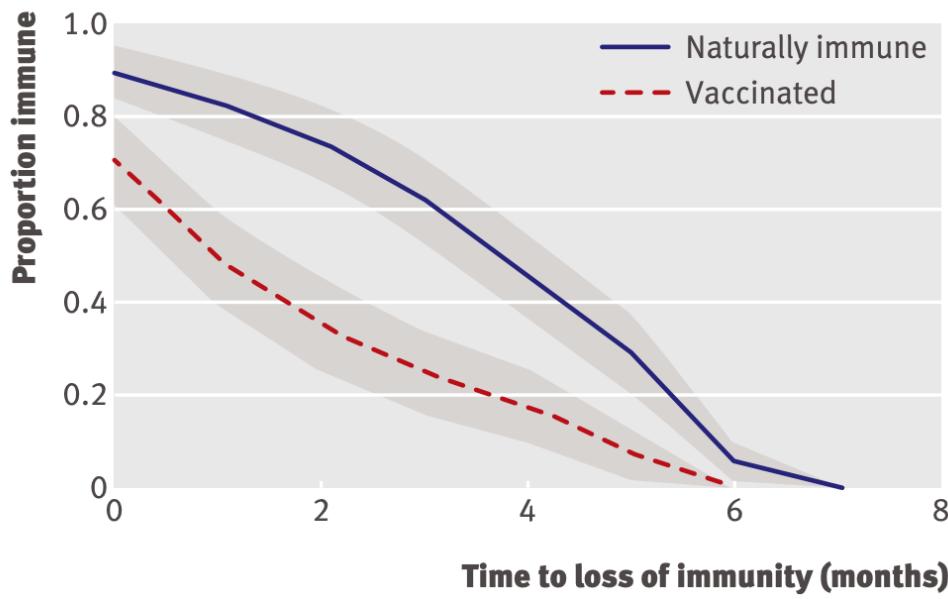
$$\frac{dS}{dt} = \omega M + bS - \beta SI - \mu S$$

$$\frac{dI}{dt} = \beta SI - \gamma I - \mu I$$

$$\frac{dR}{dt} = \gamma I - \mu R$$



Duration of maternal immunity for measles for naturally infected vs. vaccinated mothers → will impact dynamical predictions!

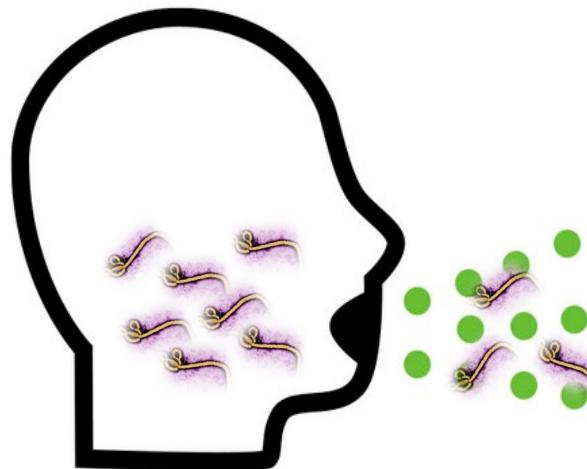
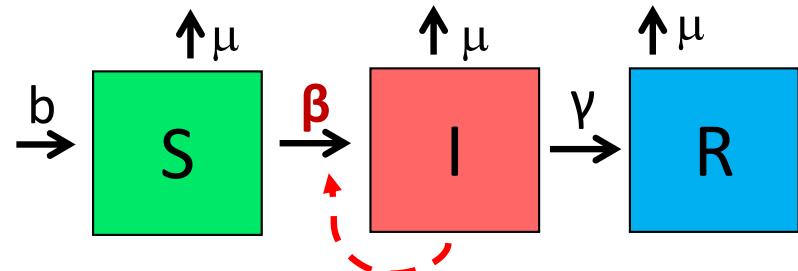


Leuridan et al. 2010. *BMJ*.

incorporating maternal immunity

Pathogens exhibit **diverse transmission mechanisms** that require **tailored modeling structures**

- **Directly-transmitted** diseases are transmitted via exchange of bodily fluids
 - Droplet (> 5 microns) spread or direct contact
 - Includes sexually-transmitted pathogens, though often modeled with a more complex contact network
 - Smallpox (*Variola* spp.), HIV, Mononucleosis (*Epstein Barr virus*)
- **Indirectly-transmitted** diseases are transmitted via droplets retained in air
 - Droplets < 5 microns in diameter
 - Measles, COVID (*SARS-CoV-2*)



**Modeled
using the
classic SIR
structure!**

Pathogens exhibit **diverse transmission mechanisms** that require **tailored modeling structures**

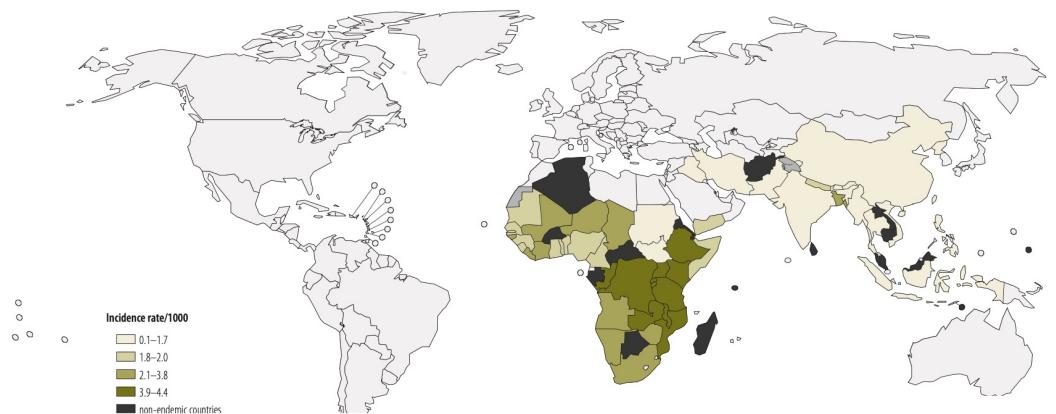
- **Environmentally-transmitted** pathogens are transmitted outside of the host (e.g. water-borne, food-borne)
 - Examples: Cholera (*Vibrio cholerae*), Salmonellosis (*Salmonella* spp. bacteria), White-Nosed Syndrome (*Pseudogymnoascus destructans*)

**Modeled with the
environmental
reservoir as a
distinct state
variable!**

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Global Burden of Cholera, 2012



Ali et al. 2012. WHO Bulletin.

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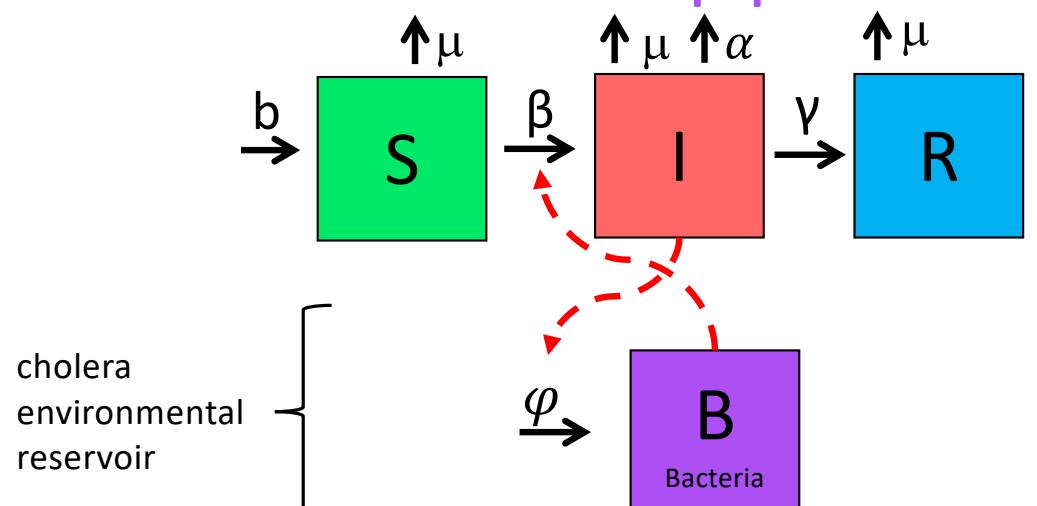
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 - Examples: Cholera (*Vibrio cholerae*), Salmonellosis (*Salmonella* spp. bacteria), White-Nosed Syndrome (*Pseudogymnoascus destructans*)
 - **Here, the environmental reservoir is often modeled as its own population**

$$\frac{dB}{dt} = \varphi \mathbf{IB}$$

$$\frac{dS}{dt} = b(S + I + R) - \beta SB - \mu S$$

$$\frac{dI}{dt} = \beta SB - \gamma I - \mu I - \alpha I$$

$$\frac{dR}{dt} = \gamma I - \mu R$$



Codeço 2001. *BMC Infectious Diseases*.

Pathogens exhibit **diverse transmission mechanisms** that require **tailored modeling structures**

- **Vertically-transmitted** pathogens are transmitted mother-to-child *in utero*
 - Examples: HIV, *Herpes simplex virus*, *Cytomegalovirus*, Rubella, Zika



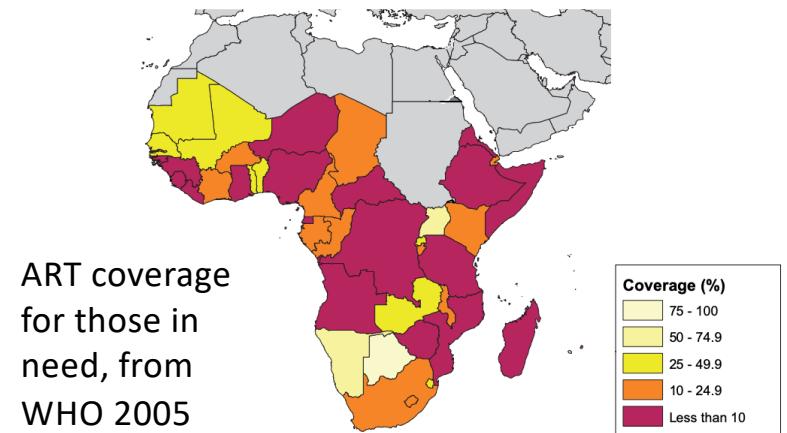
Modeled with
inherited infection
rather than
through contact!

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- In untreated HIV+ mothers, rate of vertical transmission for HIV = 15-45%
- Reduced to <1% for those on ART, though global access to ART is geographically heterogeneous





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Visual settings



Edit



Loading...

Pathogens exhibit **diverse transmission mechanisms** that require **tailored modeling structures**

- **Vector-borne** diseases (a type of indirect transmission) are transmitted via blood-feeding arthropod (mosquitoes, ticks, fleas)

Typically
modeled with
the vector as a
distinct state
variable!

Pathogens exhibit **diverse transmission mechanisms** that require **tailored modeling structures**

- **Vector-borne** diseases (a type of indirect transmission) are transmitted via blood-feeding arthropod (mosquitoes, ticks, fleas)

- Euclidean **vector**: a quantity with a magnitude and direction



- Epidemiological **vector**: an agent that carries and transmits an infectious patient into another living organism



**Typically
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Pathogens exhibit **diverse transmission mechanisms** that require **tailored modeling structures**

- **Vector-borne** diseases (a type of indirect transmission) are transmitted via blood-feeding arthropod (mosquitoes, ticks, fleas)
 - Malaria: Mosquito-borne protozoan *Plasmodium spp.*
 - “Arboviruses”: Mosquito-borne viruses, including Dengue, Zika, Yellow fever virus, West Nile virus, Chikungunya virus
 - Sleeping sickness, also known as African trypanosomiasis: tsetse fly vector and protozoan pathogen (trypanosome)
 - Chagas disease: kissing bug vector and trypanosome pathogen
 - Plague: flea vector and bacterial pathogen (*Yersinia pestis*)

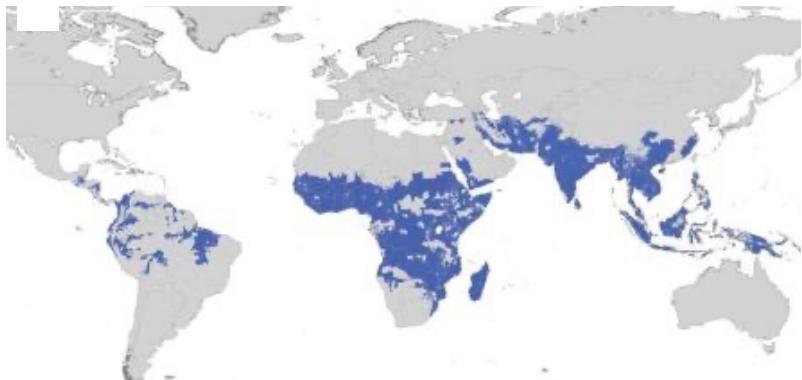
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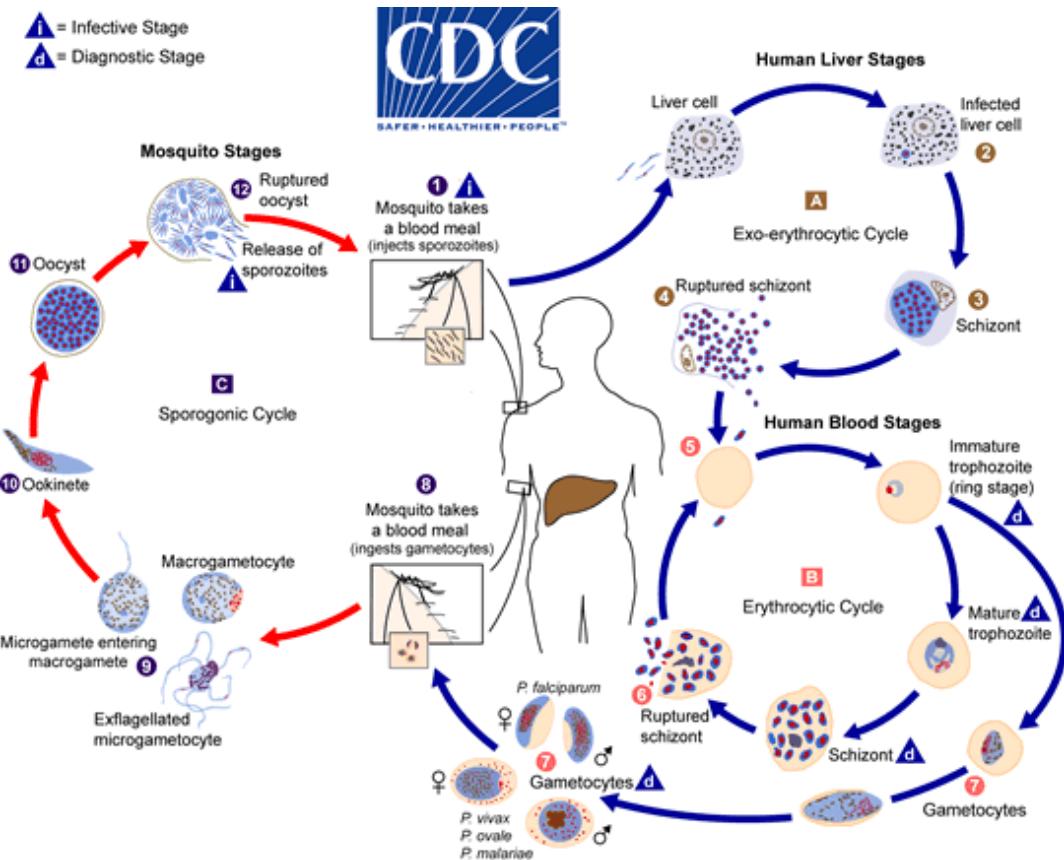
Malaria

- 4 main human ***Plasmodium* parasites** (*falciparum*, *vivax*, *malariae*, *ovalae*).
- Over 200 *Plasmodium* spp. globally, infecting birds, reptiles, and other mammals (rodents, bats, primates)

Distribution *Plasmodium falciparum*



Distribution *Plasmodium vivax*



Guerra et al. 2006. *Trends in Parasitology*

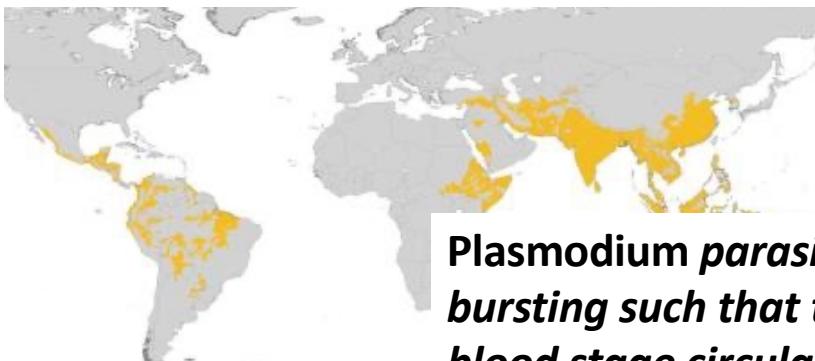
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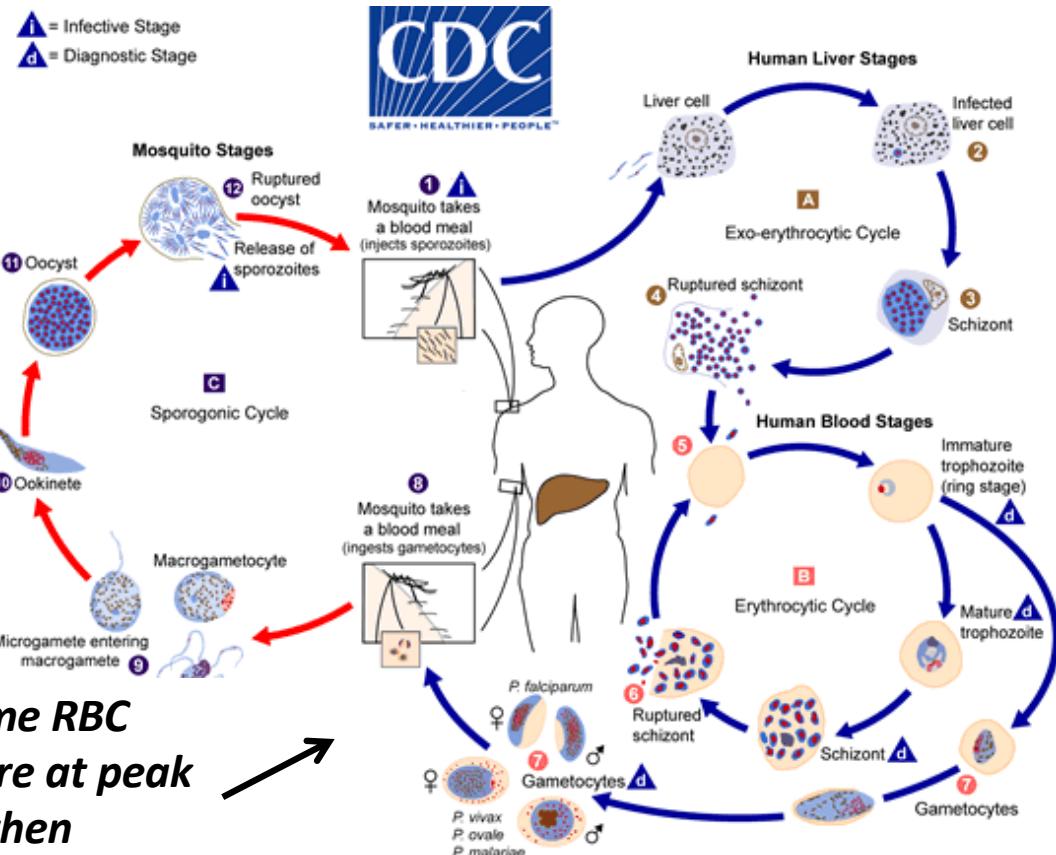
Distribution *Plasmodium falciparum*



Distribution *Plasmodium vivax*



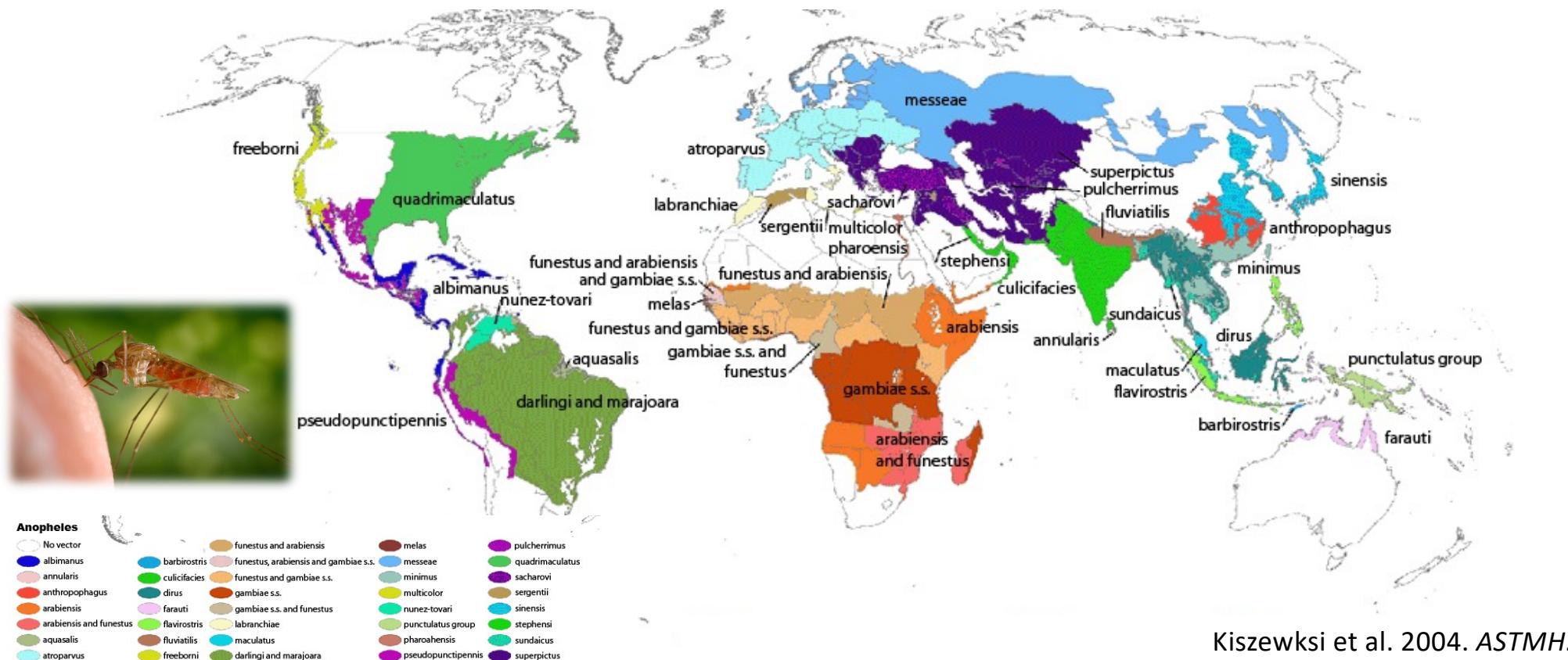
Plasmodium parasites time RBC bursting such that they are at peak blood stage circulation when mosquito vectors are feeding at dusk!



Guerra et al. 2006. Trends in, mosquito vectors are feeding at dusk!

Malaria

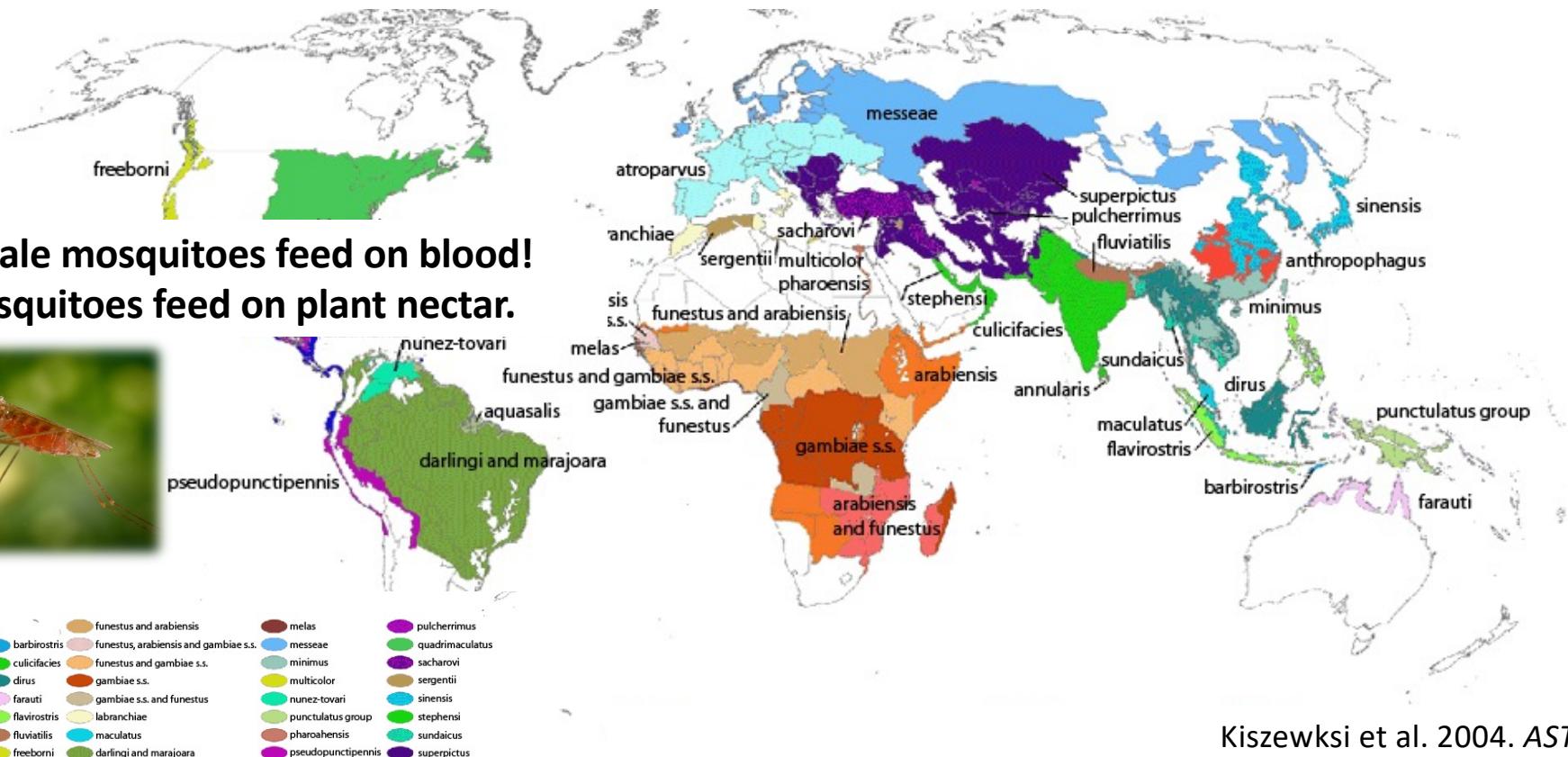
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- Over 200 *Plasmodium* spp. globally, infecting birds, reptiles, and other mammals (rodents, bats, primates)
- >400 global species of ***Anopheles* mosquito**, >100 that can transmit human malaria
- ~30-40 *Anopheles* spp. most commonly implicated in human malaria transmission!



Kiszewksi et al. 2004. *ASTMH*.

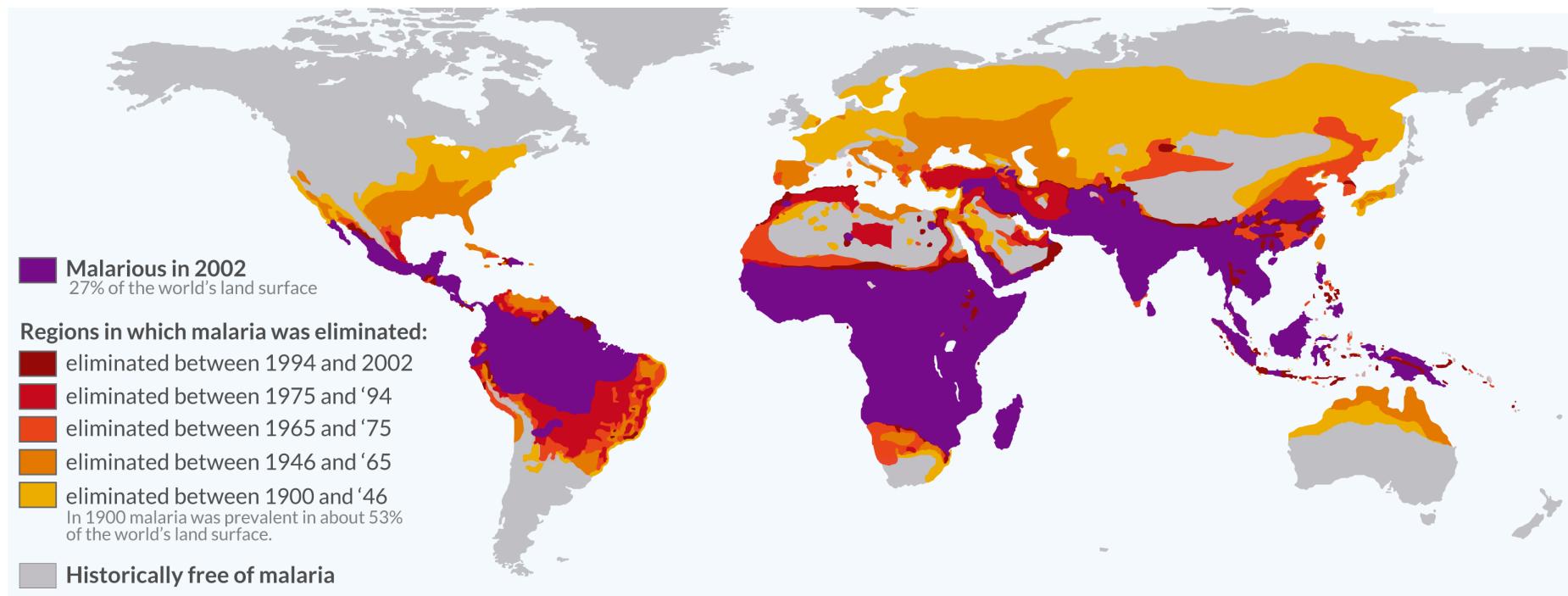
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- Over 200 *Plasmodium* spp. globally, infecting birds, reptiles, and other mammals (rodents, bats, primates)
- >400 global species of ***Anopheles* mosquito**, >100 that can transmit human malaria
- ~30-40 *Anopheles* spp. most commonly implicated in human malaria transmission!



Kiszewksi et al. 2004. *ASTMH*.

Malaria has been eliminated from many regions where it was previously endemic, including the US.



Still one of the leading causes of child mortality globally – responsible for about half a million childhood deaths a year, 80% in Africa.

OurWorldinData.org

Malaria models have played a critical role in public health policy for over a century.

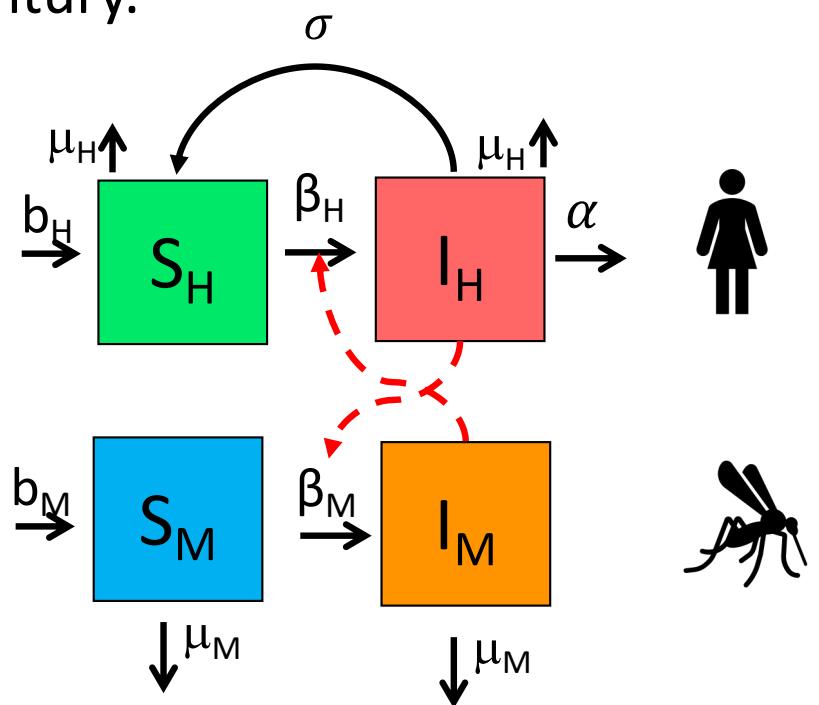
- 1911: British medical Dr. Sir Ronald Ross developed the first model of malaria while working in the Indian Medical Service.
 - He had already won the 1902 Nobel prize in physiology and medicine for discovering the life cycle of avian malaria

$$\frac{dS_H}{dt} = b_H(S_H + I_H) + \sigma I_H - \beta_H S_H I_M - \mu_H S_H$$

$$\frac{dI_H}{dt} = \beta_H S_H I_M - \sigma I_H - \mu_H I_H - \alpha I_H$$

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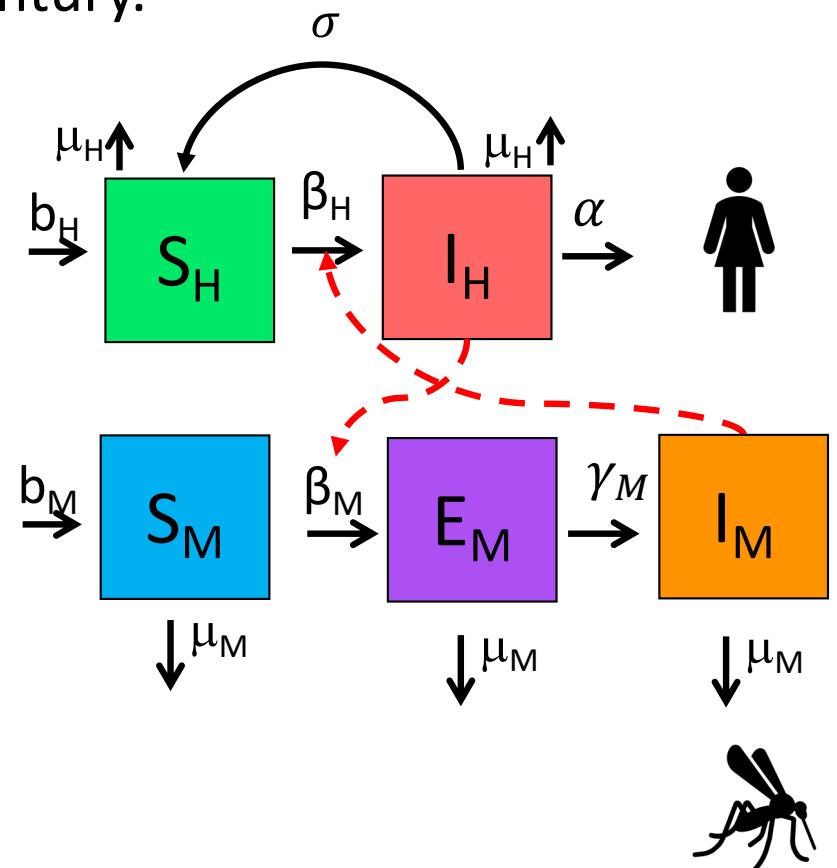
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- 1957: MacDonald modified this model to include the latent period of the parasite developing in the mosquito.
 - He implicated the survivorship of the female mosquito as the weakest link in the life cycle!

$$\frac{dS_M}{dt} = b_M(S_M + E_M + I_M) - \beta_M S_M I_H - \mu_M S_M$$

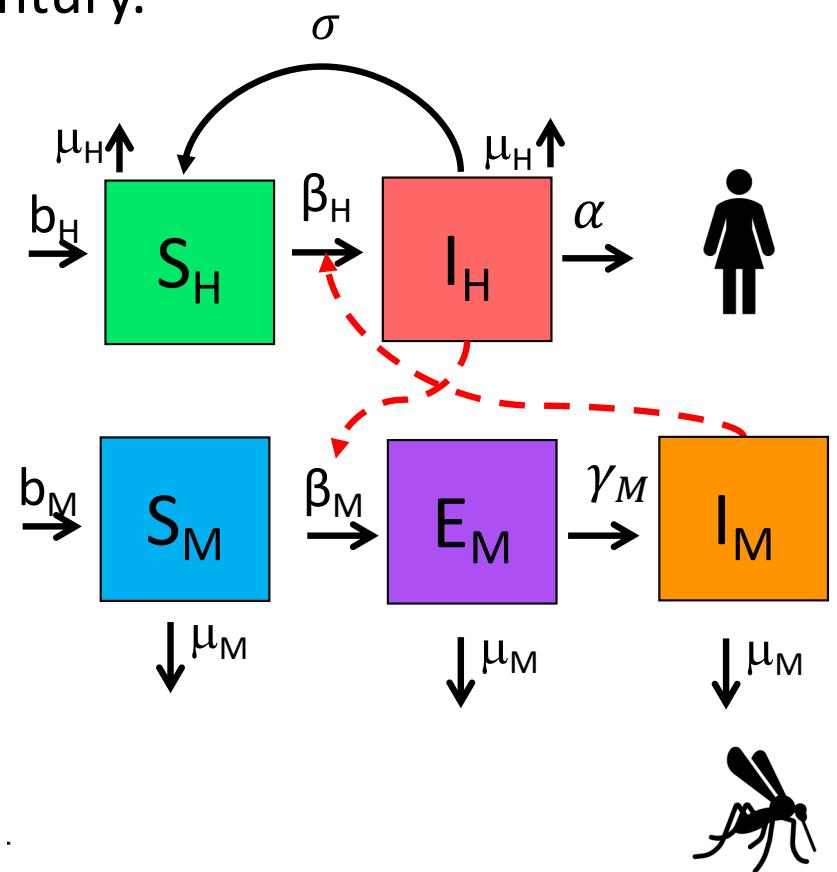
$$\frac{dE_M}{dt} = \beta_M S_M I_H - \mu_M E_M - \gamma_M E_M$$

$$\frac{dI_M}{dt} = \gamma_M E_M - \mu_M I_M$$



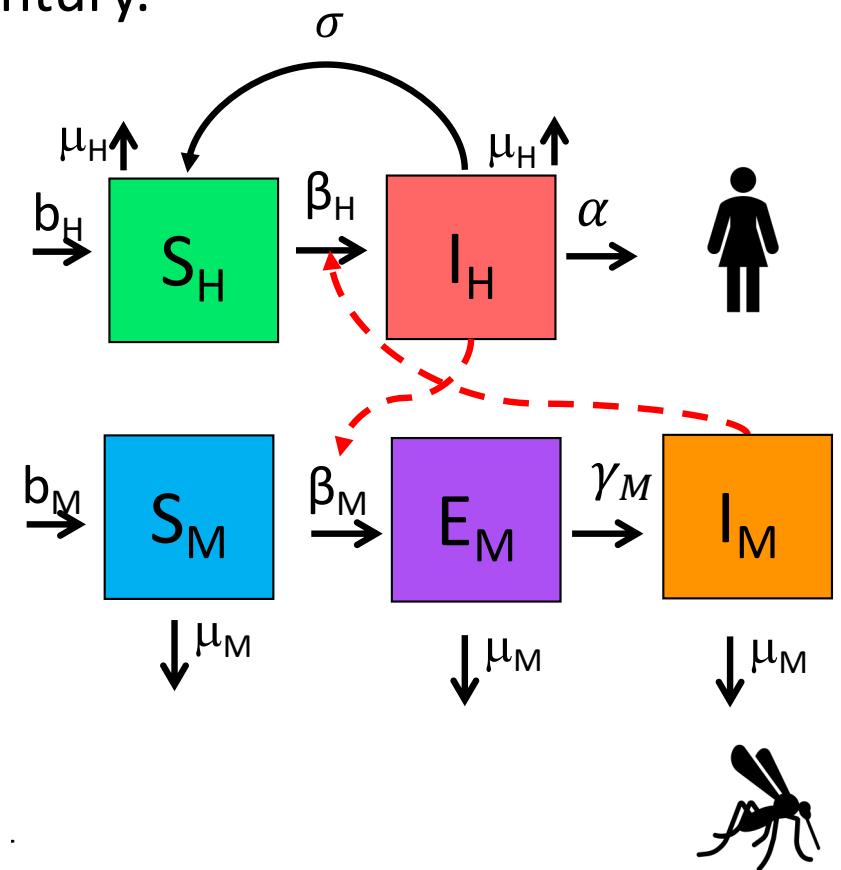
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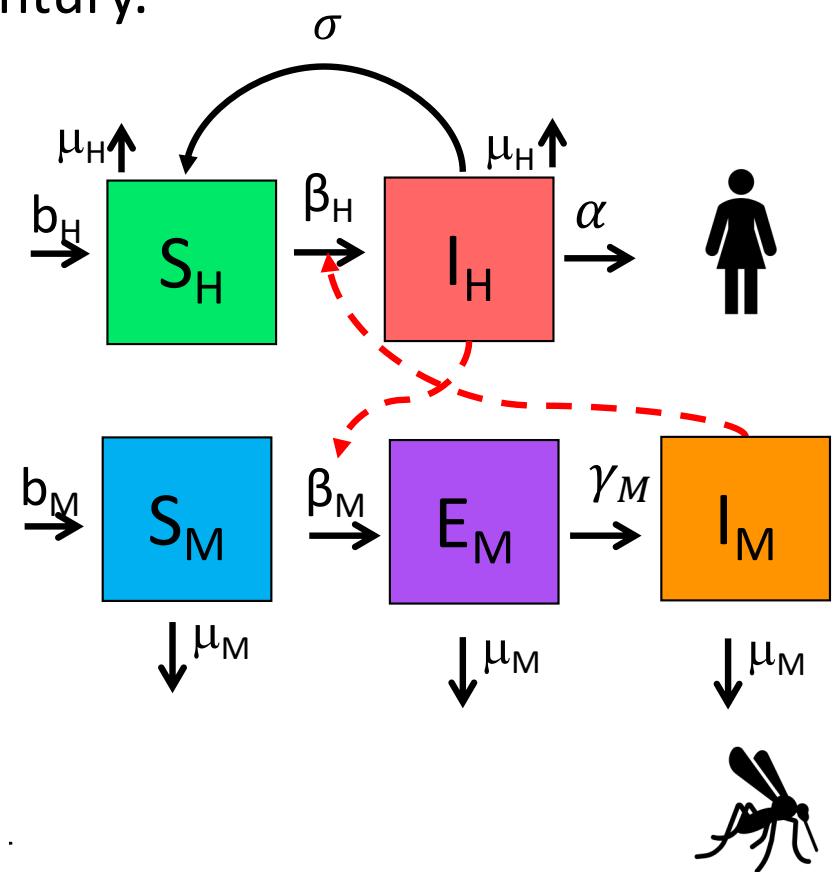
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 - DDT **bioaccumulates** and is carcinogenic – led to development of an environmental backlash in the US, culminating in Rachel Carson's 1962 book *Silent Spring*

Bioaccumulation:

the gradual accumulation of substances in an organism through time; particularly dangerous for **high trophic level consumers**



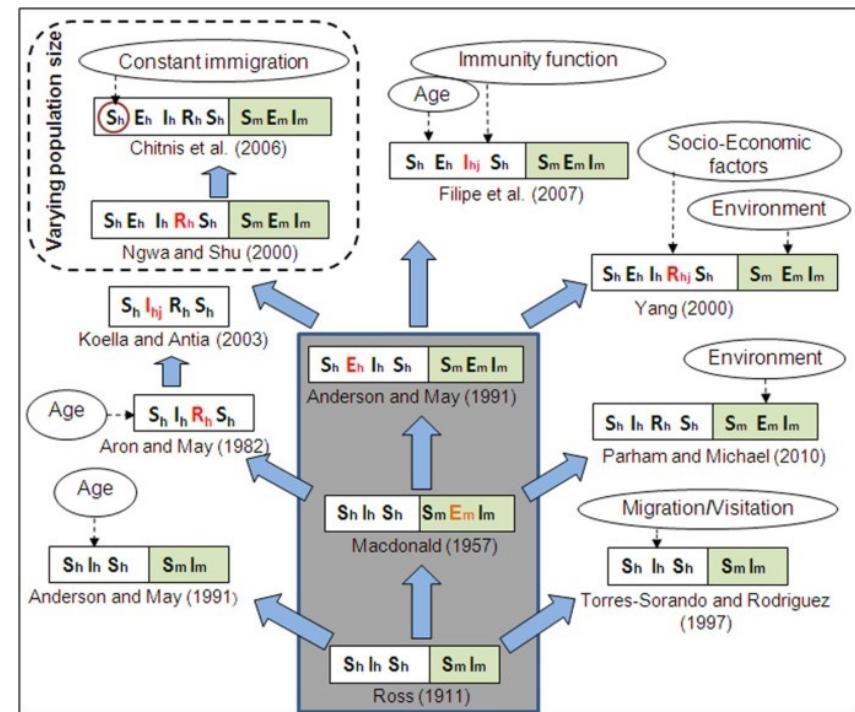
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 - DDT banned globally in 2004, excepting in cases of WHO-recommended indoor residual spraying (IRS) for vector control in malaria-endemic regions



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- 1991: Anderson and May extended model to show latency in the human population.



Mandal et al. 2011. *Malaria Journal*.

Ended here



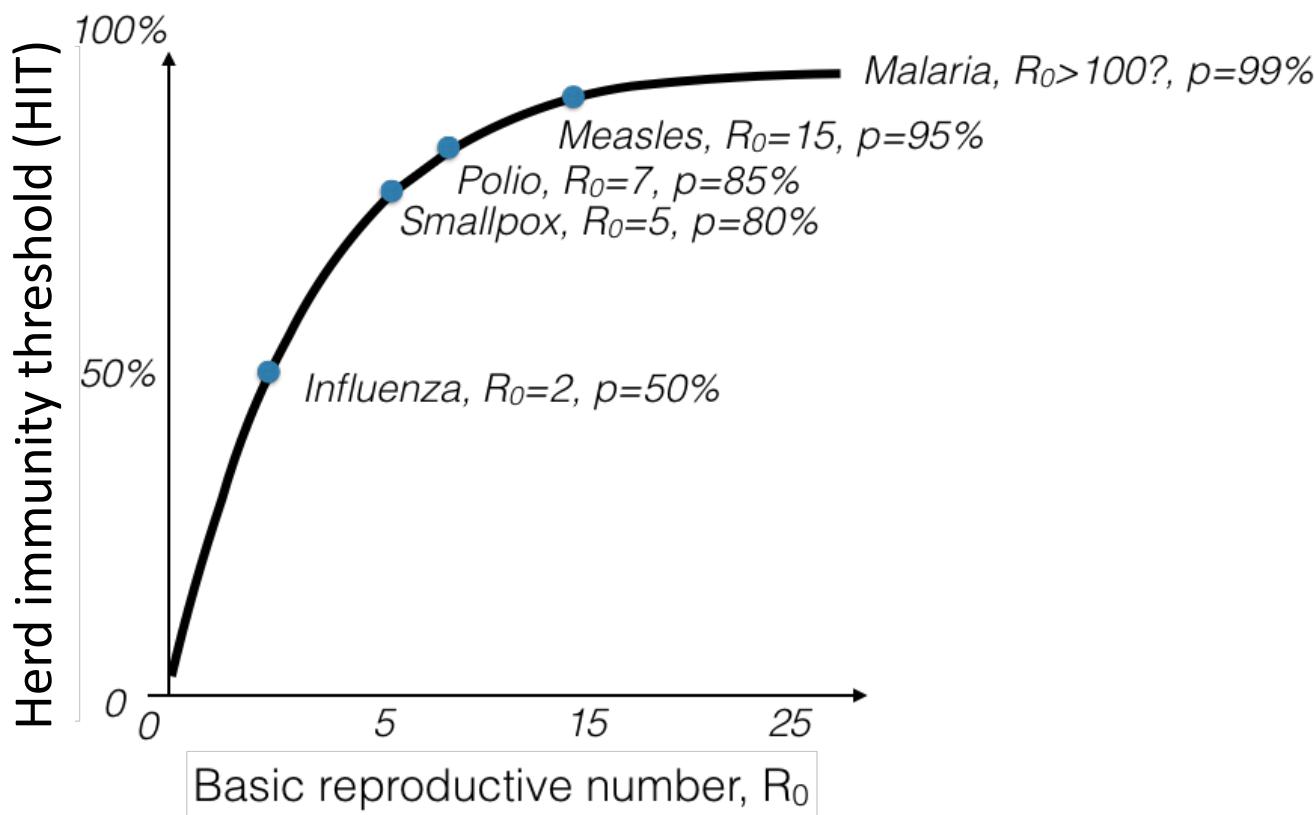
Which statement about malaria models is accurate?

(A) A Ross-McDonald malaria models demonstrate mosquito recovery from infection.

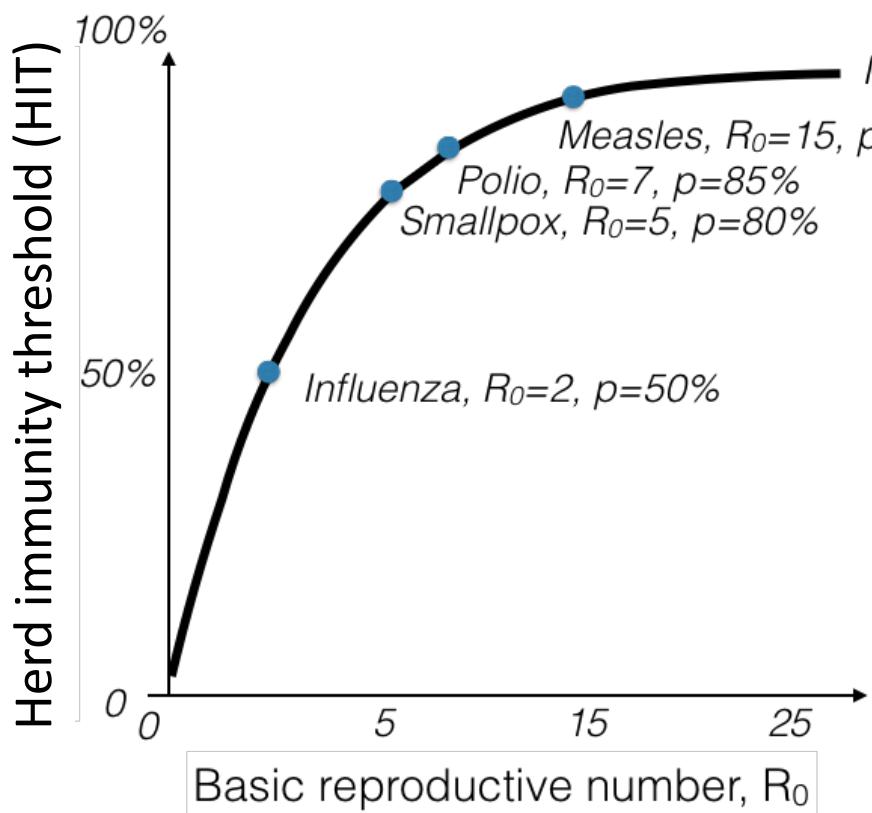
0%

(B) B The Ronald Ross malaria models influenced public health policy through SEE MORE of an exposed...

Challenges to malaria elimination

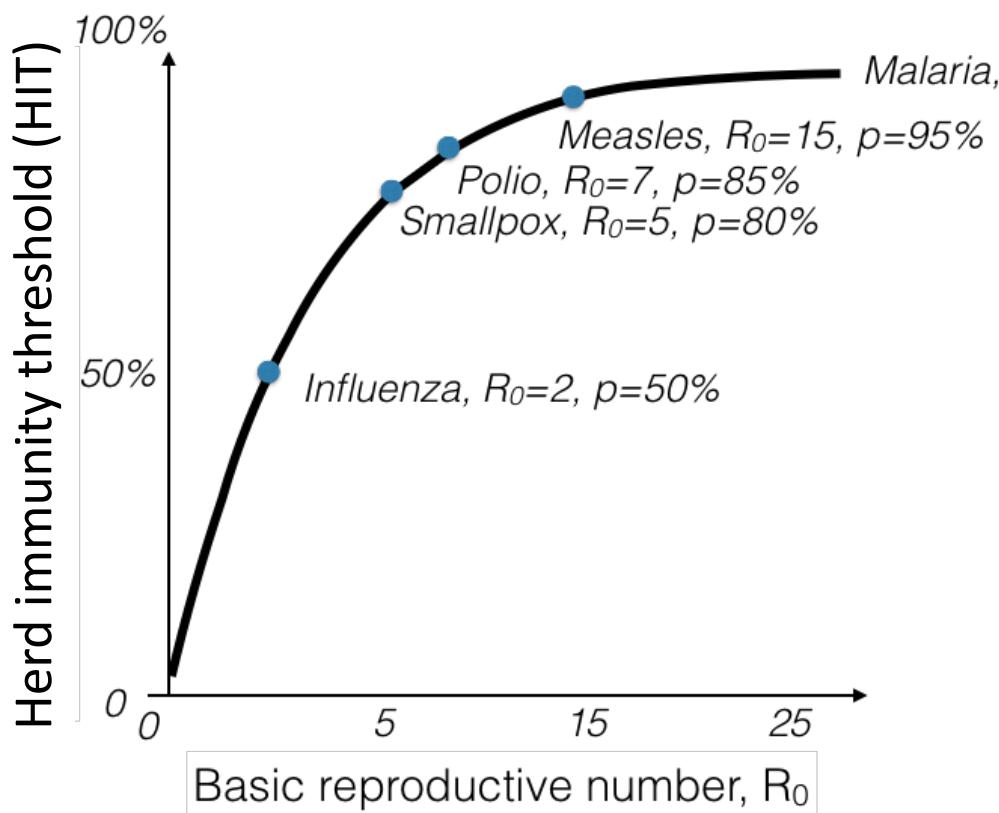


Challenges to malaria elimination



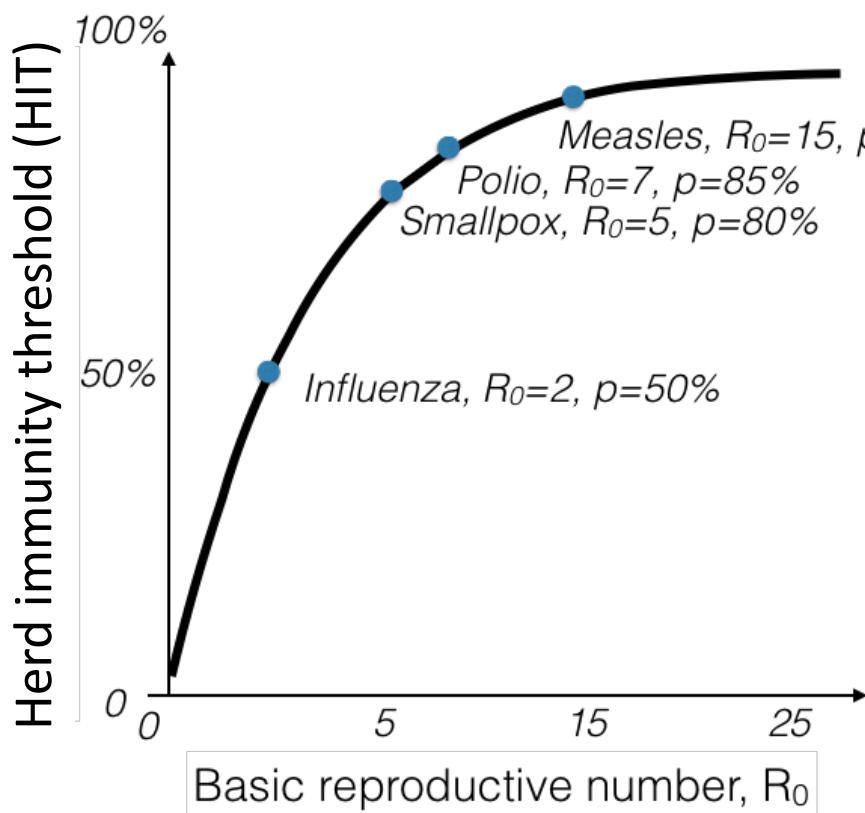
- High parasite diversity: sexual reproduction in 4+ *Plasmodium* species
 - Fast evolution of resistance (e.g. to drugs)

Challenges to malaria elimination



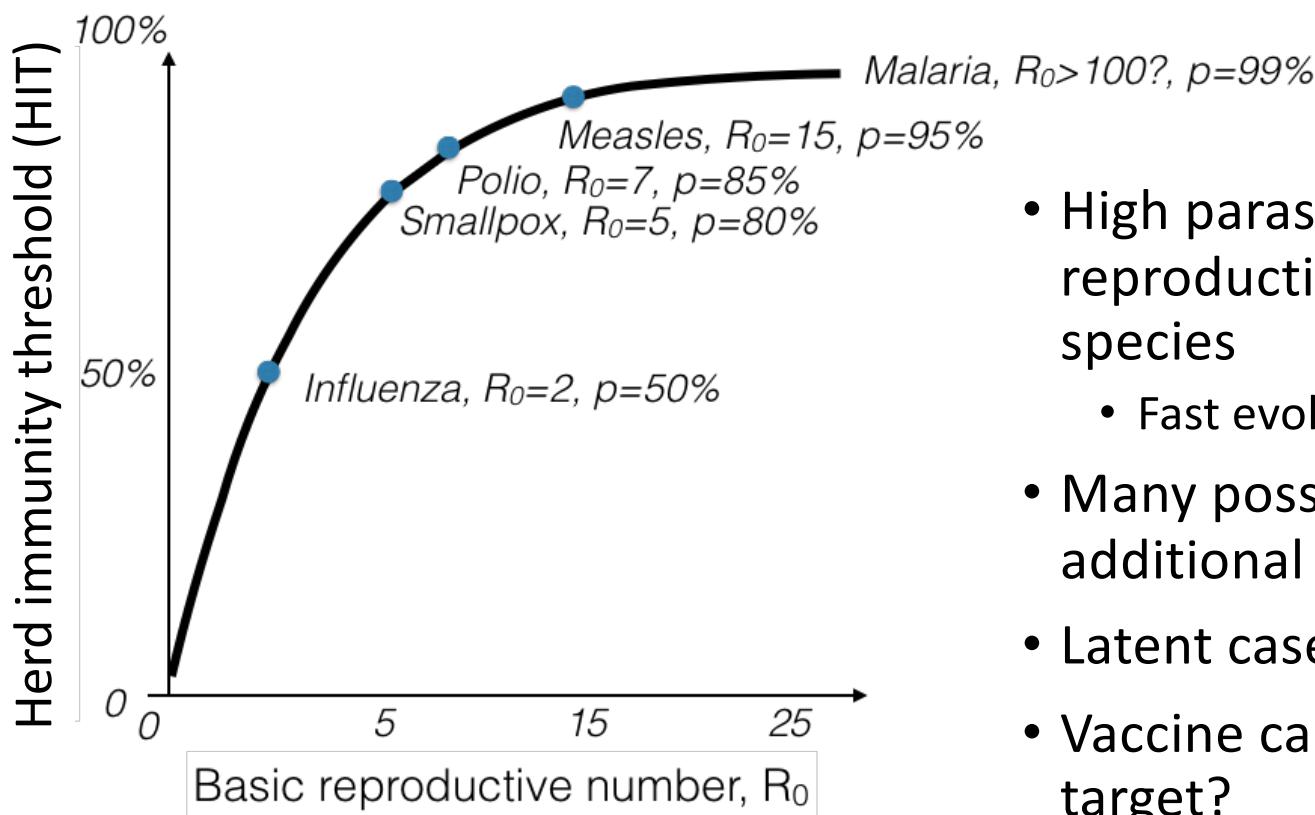
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Challenges to malaria elimination



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 - Fast evolution of resistance (e.g. to drugs)
- Many possible vectors! Potentially additional possible reservoirs!
- Latent cases as burden is reduced
- Vaccine candidates: what life stage to target?

Pathogens exhibit **diverse transmission mechanisms** that require tailored modeling structures

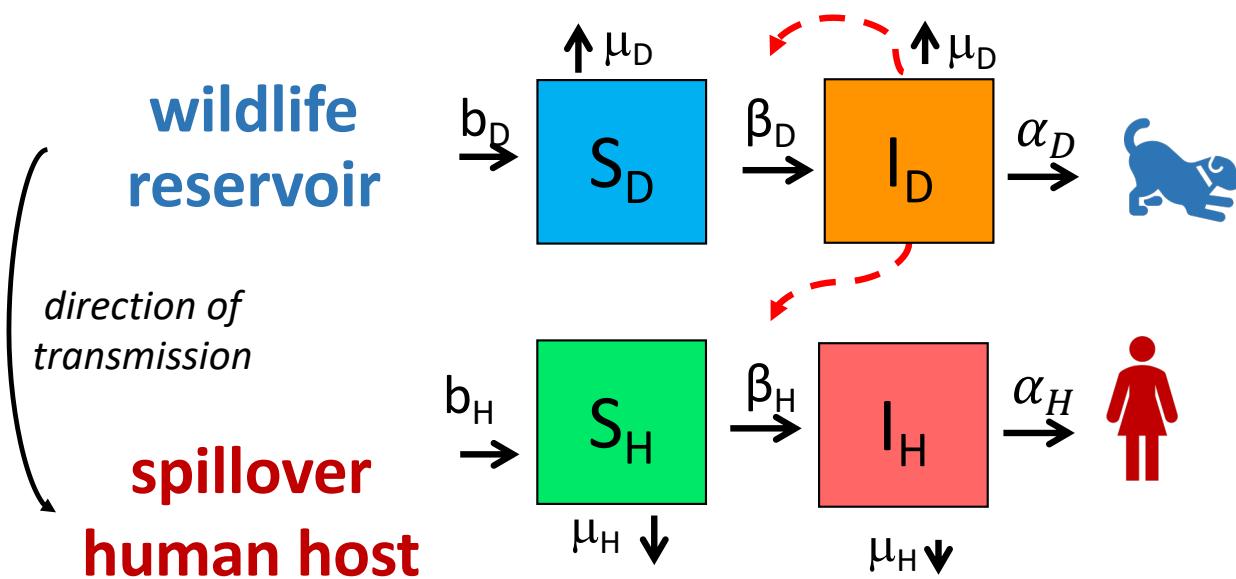
- **Vector-borne** diseases (a type of indirect transmission) are transmitted via blood-feeding arthropod (mosquitoes, ticks, fleas)
 - Malaria: Mosquito-borne protozoan *Plasmodium spp.*
 - “Arboviruses”: Mosquito-borne viruses, including Dengue, Zika, Yellow fever virus, West Nile virus, Chikungunya virus
 - Sleeping sickness, also known as African trypanosomiasis: tsetse fly vector and protozoan pathogen (trypanosome)
 - Chagas disease: kissing bug vector and trypanosome pathogen
 - **Plague**: flea vector and bacterial pathogen (*Yersinia pestis*)

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Plague is BOTH vector-borne and zoonotic!

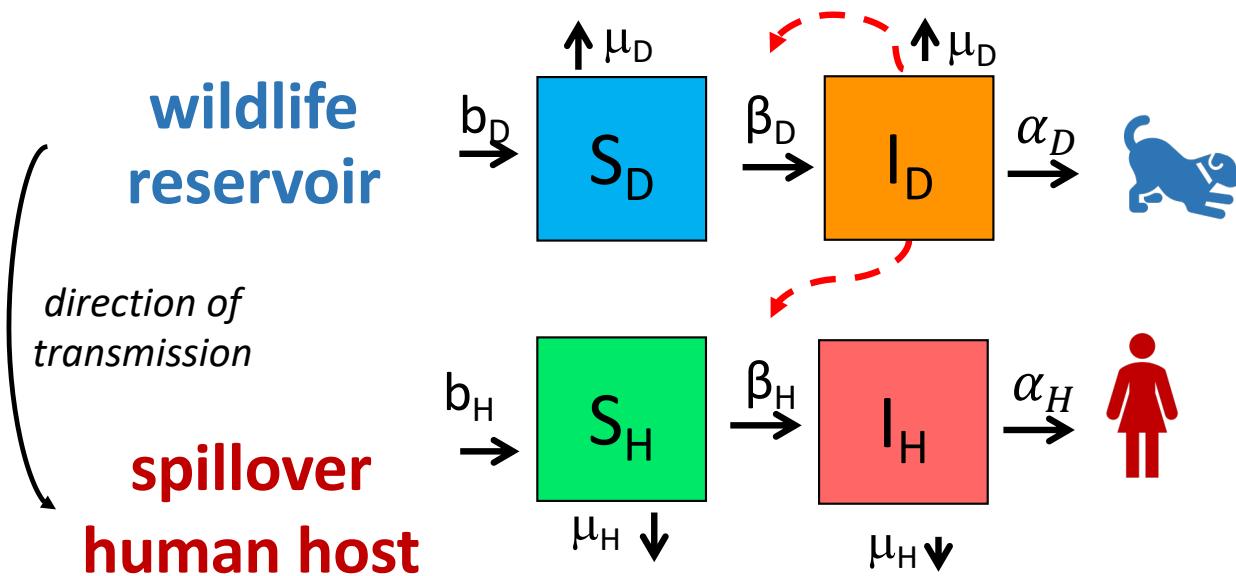
Zoonoses are pathogens transmitted from a **wildlife reservoir** to a **spillover human host**.



ex: rabies

Haydon et al. 2002. *Emerging Infectious Diseases*.

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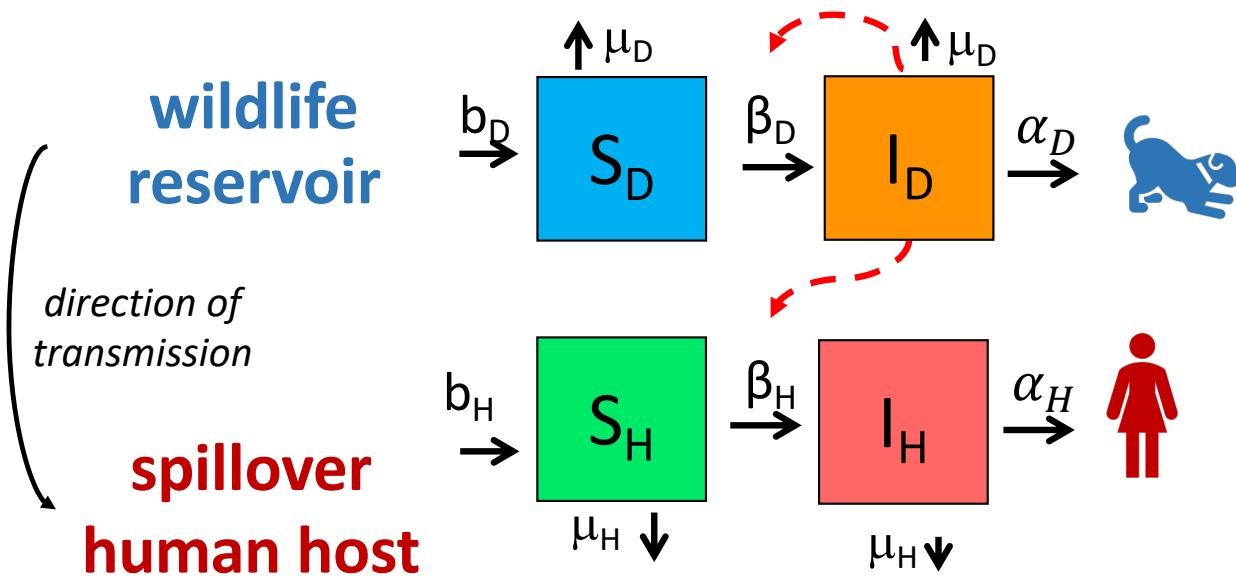


Typically modeled with the reservoir as a distinct state variable!

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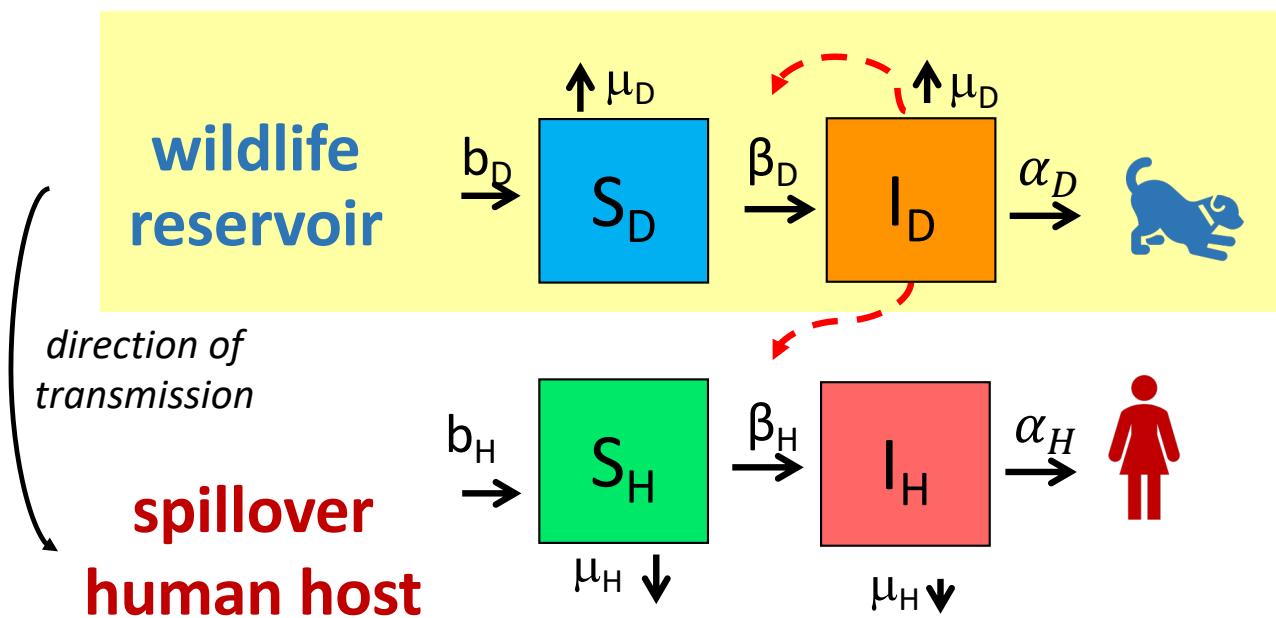


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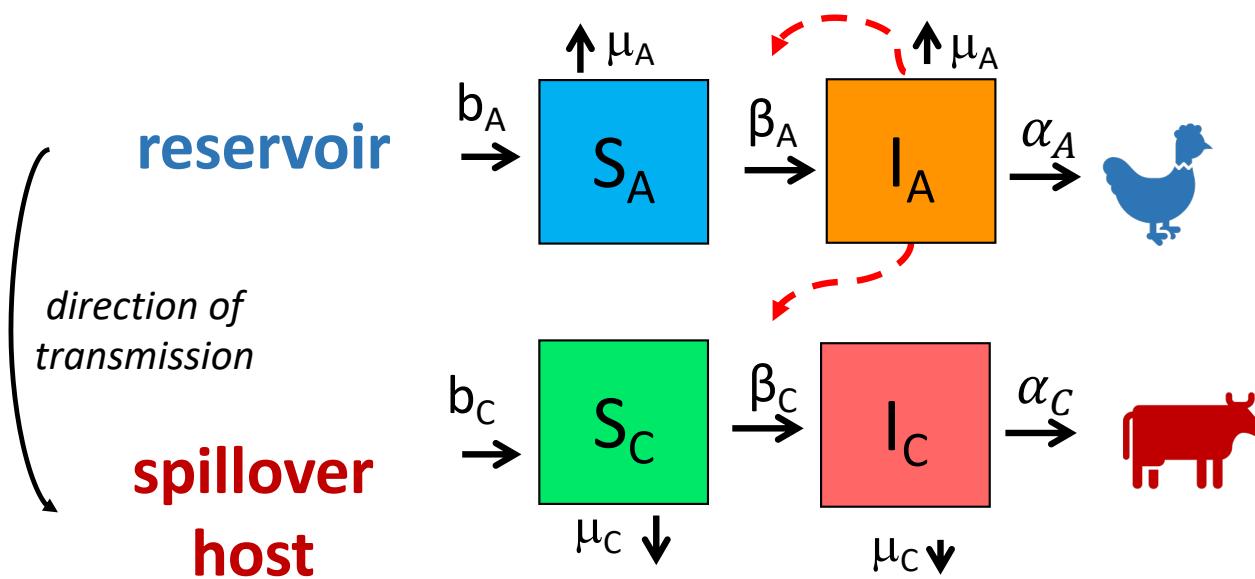
The **reservoir** host must be able to independently maintain the pathogen, with **population size > CCS!**

Animal hosts are not vectors!

ex: rabies

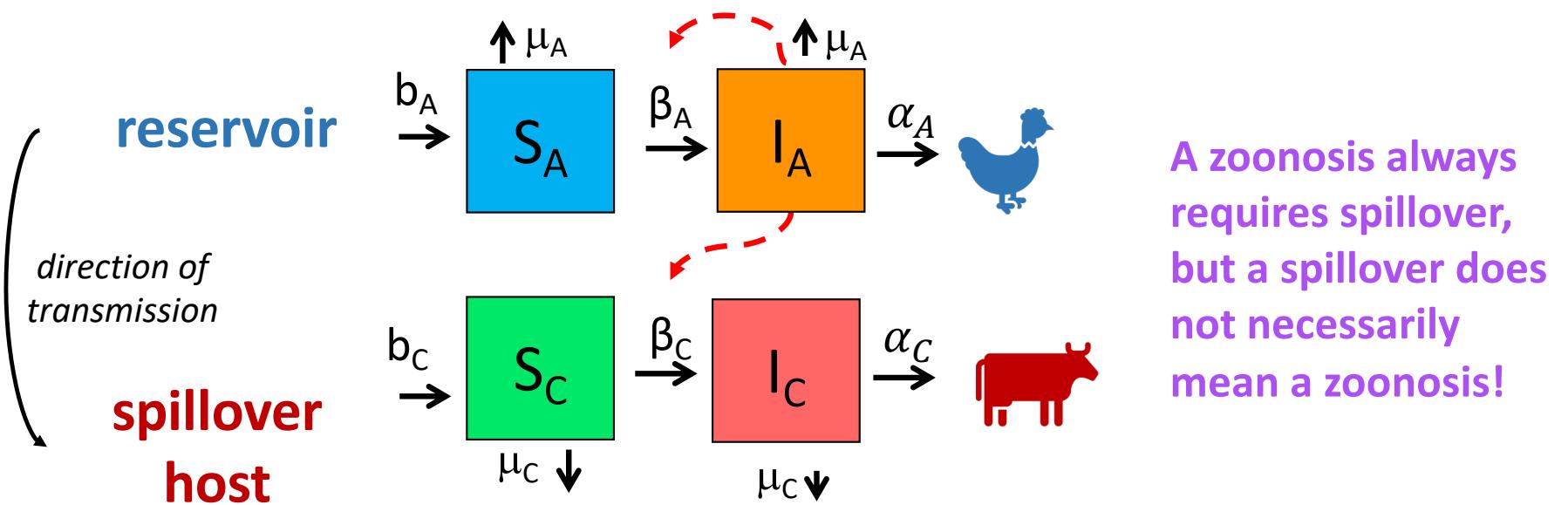
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Spillover is the term used to describe pathogen transmission between any two different species.



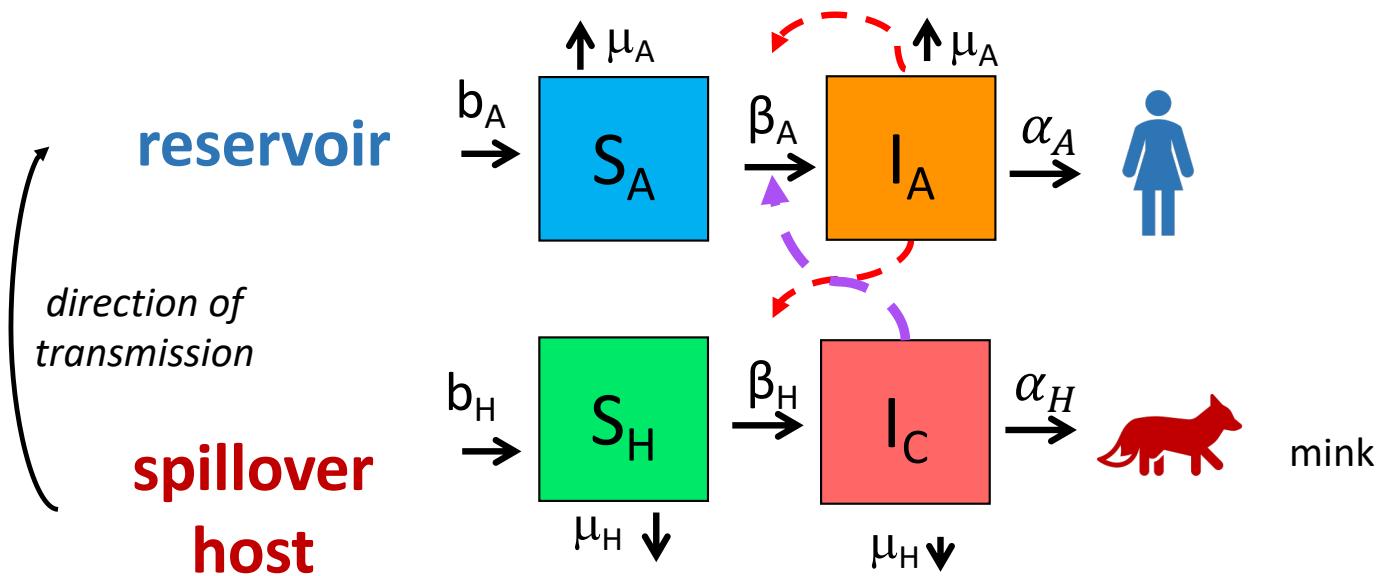
ex: avian flu

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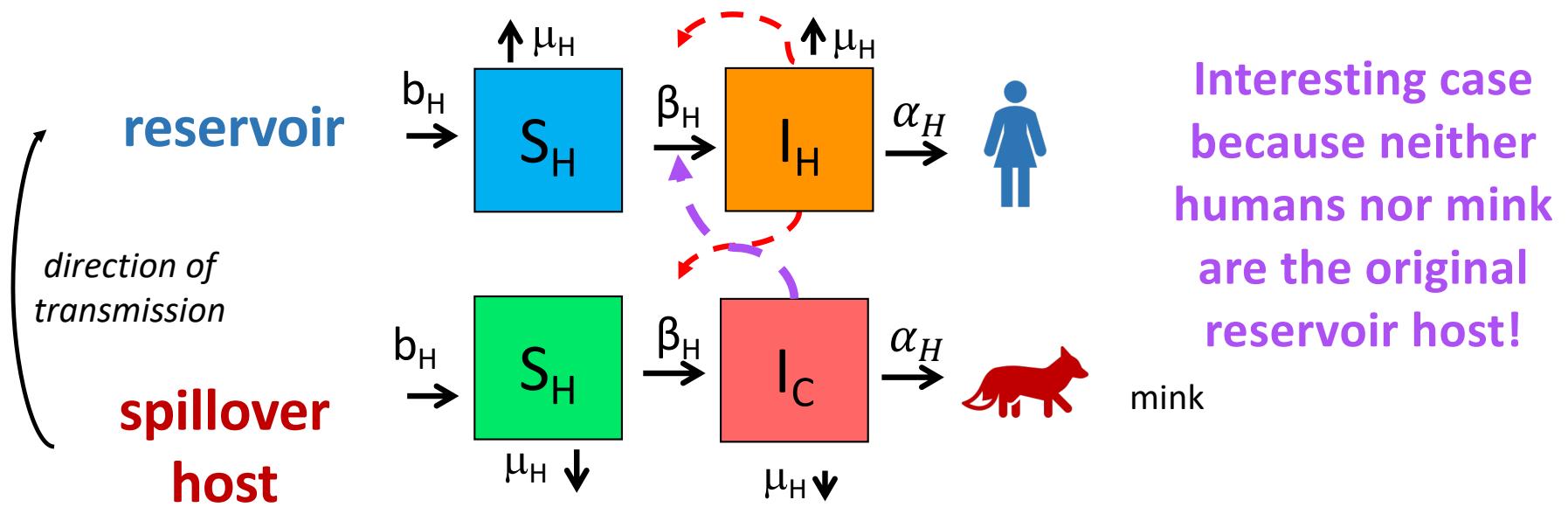
ex: avian flu

Spillback is the term used to describe pathogen transmission back to a **reservoir host** from a **spillover host**.



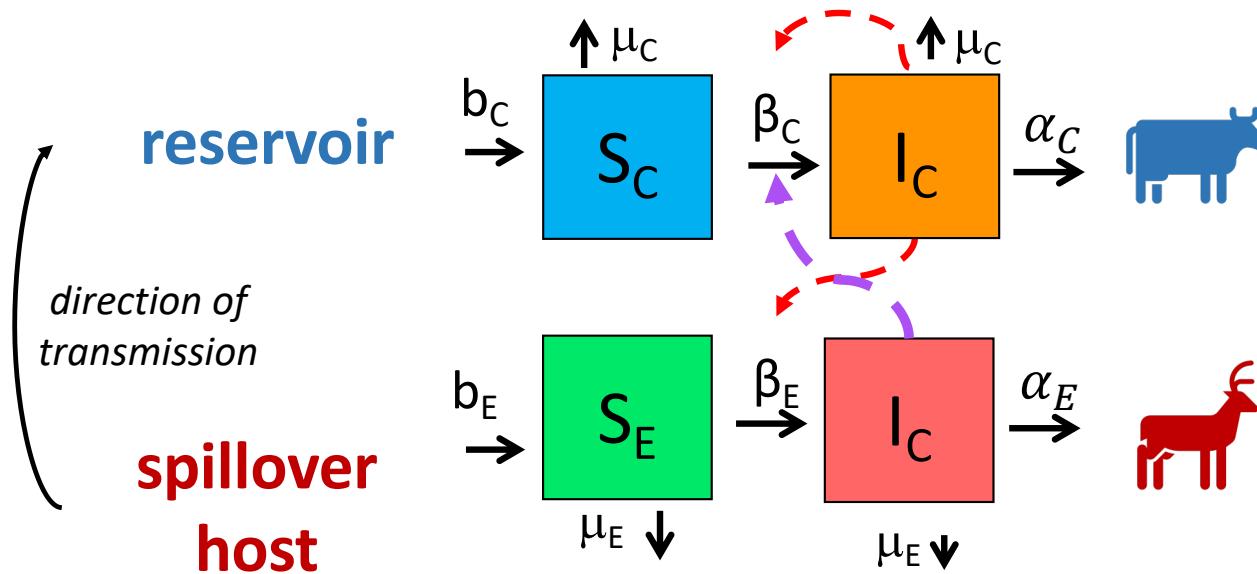
ex: SARS-CoV-2

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ex: SARS-CoV-2

Spillback occurs among wildlife as well.



ex: *Brucella* spp. in Yellowstone National Park

Pathogens can be classed according to their host relationships.

Stage I

Transmits exclusively in animals



canine parvovirus

Stage II

Human cases from spillovers only



rabies virus

Stage III

Stuttering chains of transmission in humans



monkeypox (pre-2022)

Stage IV

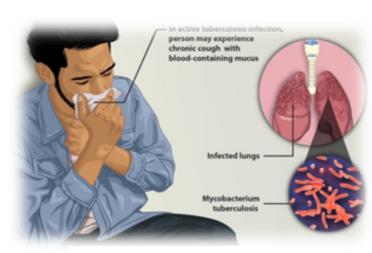
Sustained transmission and human outbreaks



Ebola virus (especially post-2014)

Stage V

Transmits exclusively in humans



Tuberculosis

Lloyd-Smith et al. 2009. *Science*.

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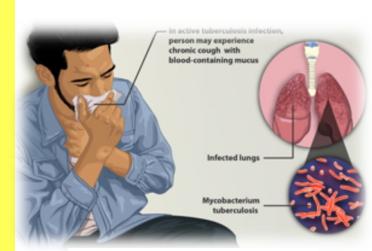
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Tuberculosis

$$R_0 < 1$$

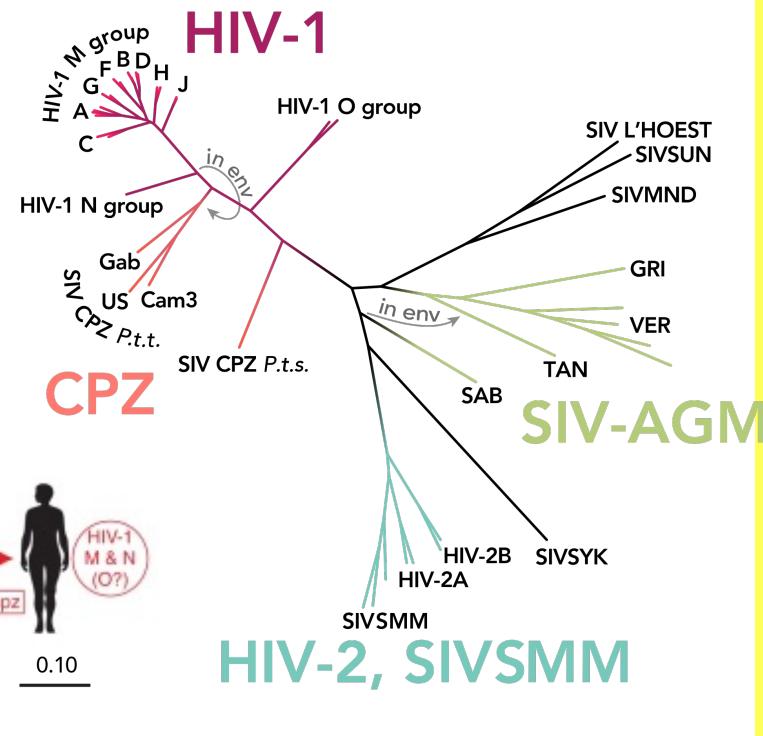
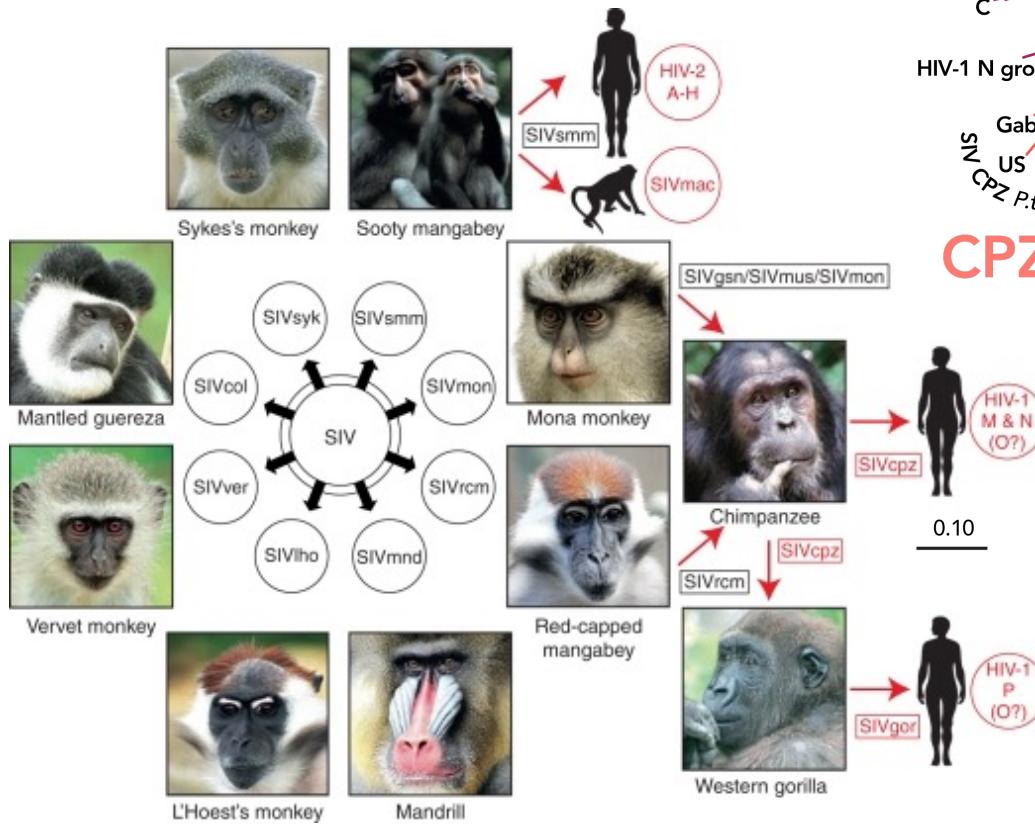
$$R_0 \approx 1$$

$$R_0 > 1$$

Zoonotic pathogens can be classed according to their R_0 in humans.

Lloyd-Smith et al. 2009. *Science*.

Most stage V pathogens once had an animal origin, as well!



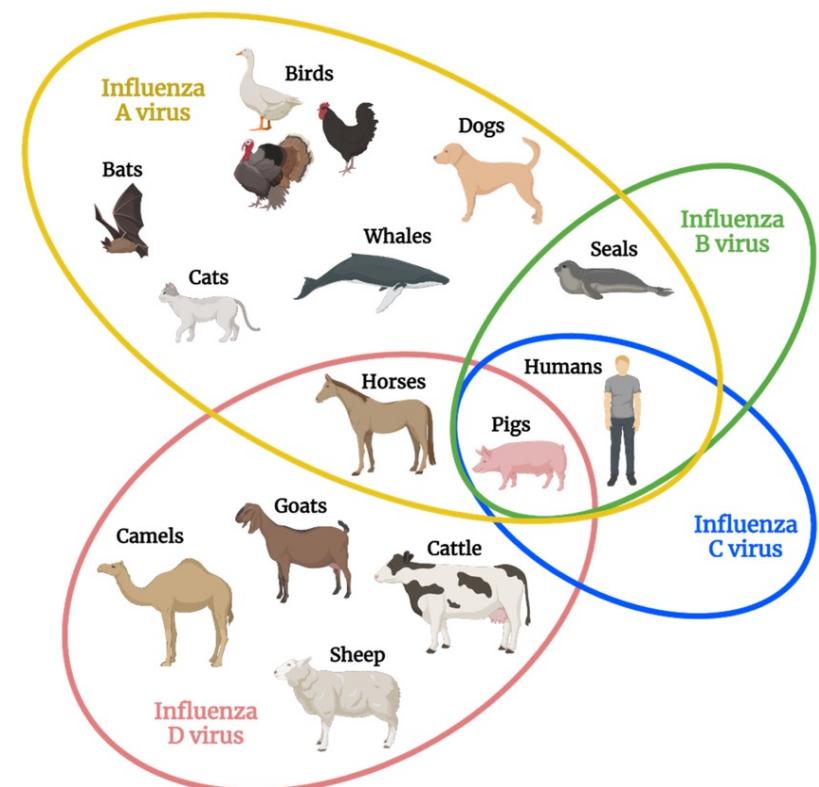
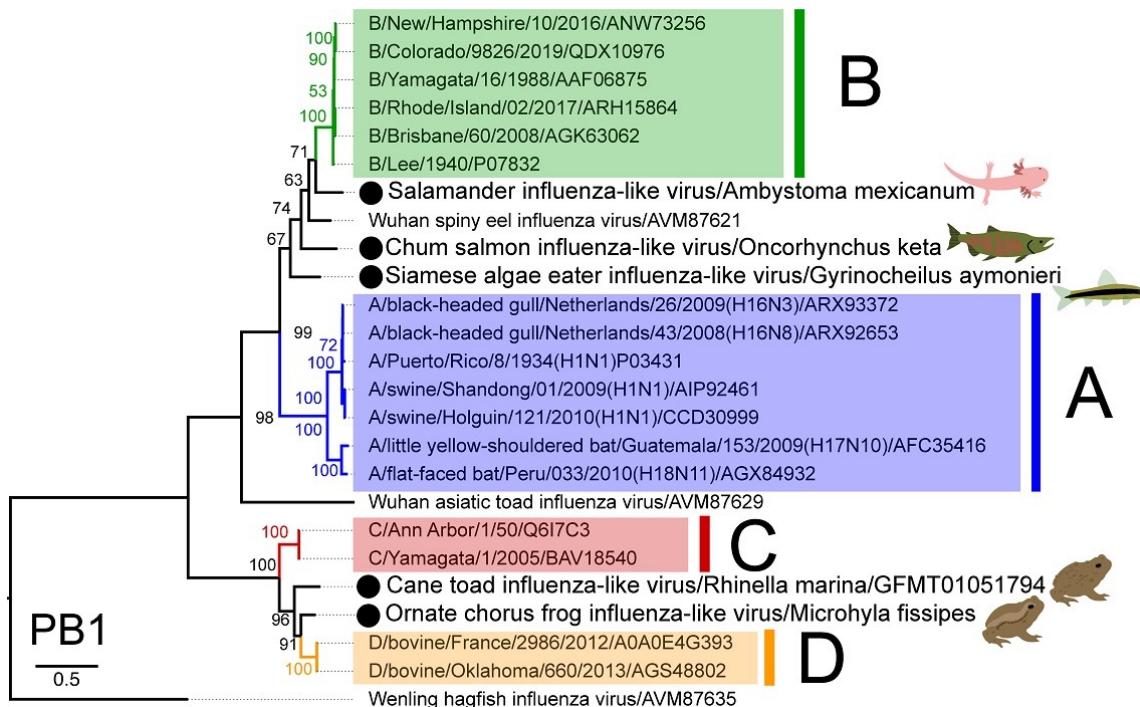
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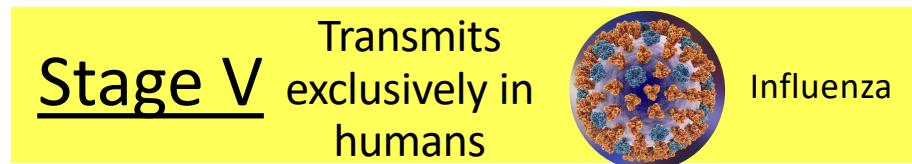
HIV

Sharp & Hahn. 2011. *Cold Spring Harb Perspect Med.*

When is influenza zoonotic?



Parry et al. 2020. *Viruses*.



Skelton & Huber. 2022. *Viruses*.



Which of the following is never a zoonotic disease?

A Plasmodium knowlesi - a macaque malaria t...

0%

B Influenza B

0%

C Toxoplasma gondii - a protozoan circulating in...

0%

D Q fever - a bacterial pathogen of livestock t...

0%

E Influenza A

0%

There are **many**
barriers to cross-
species transmission.

We can think of
zoonosis as a series of
improbable events
multiplied together.

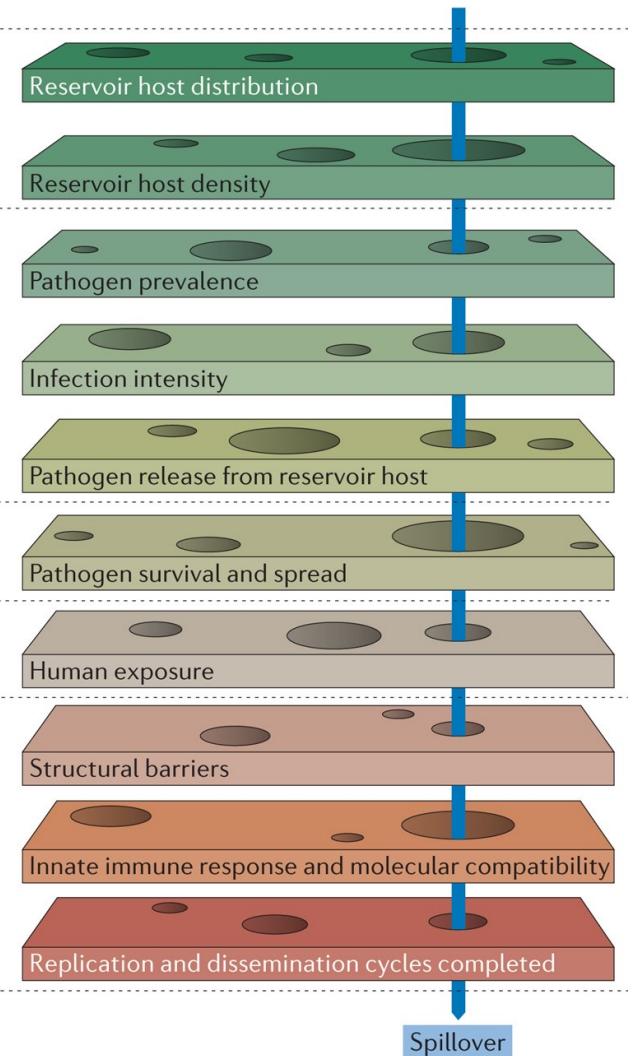
Animal ecology, population biology,
biogeography, behavioural ecology,
landscape ecology, agricultural sciences

Disease ecology, animal epidemiology,
infectious disease dynamics, immunology,
microbiology, veterinary medicine

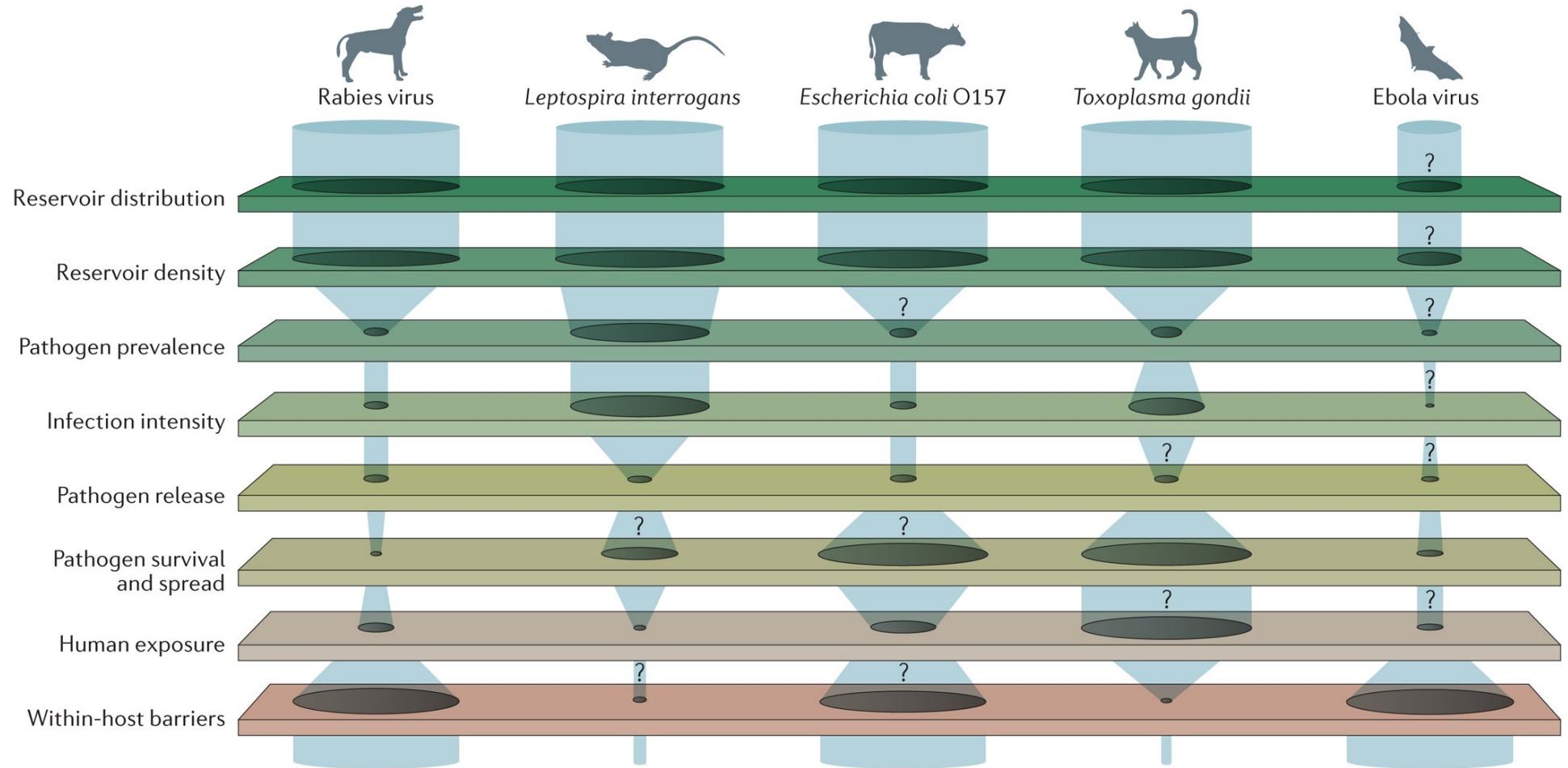
Microbiology, disease ecology, vector
ecology, epidemiology, spatial ecology,
infectious disease dynamics

Human epidemiology, medical anthropology,
vector ecology, social sciences, behavioural
ecology, infectious disease dynamics

Microbiology, innate and adaptive
immunology, cell biology of pathogen-host
interactions, pathology, genetics,
evolutionary biology



Plowright et al. 2017. *Nature Reviews Microbiology*.



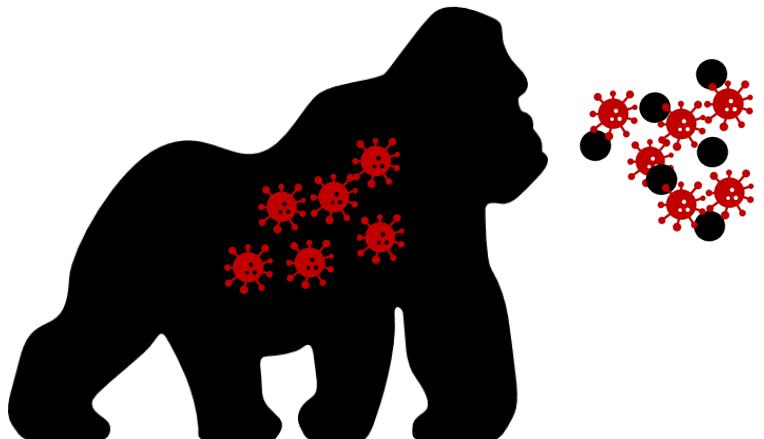
Bottlenecks to zoonotic transmission
vary for different pathogens.

Plowright et al. 2017. *Nature Reviews Microbiology*.

Why do pathogens make us sick?

A virus will evolve to
maximize its capacity for
between-host infections (R_0).

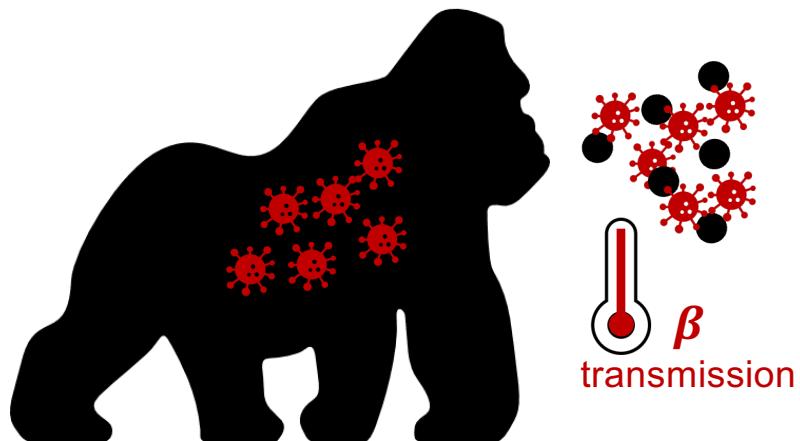
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Alizon et al. 2008. *J Evolutionary Biology*
Anderson and May 1982. *Parasitology*.

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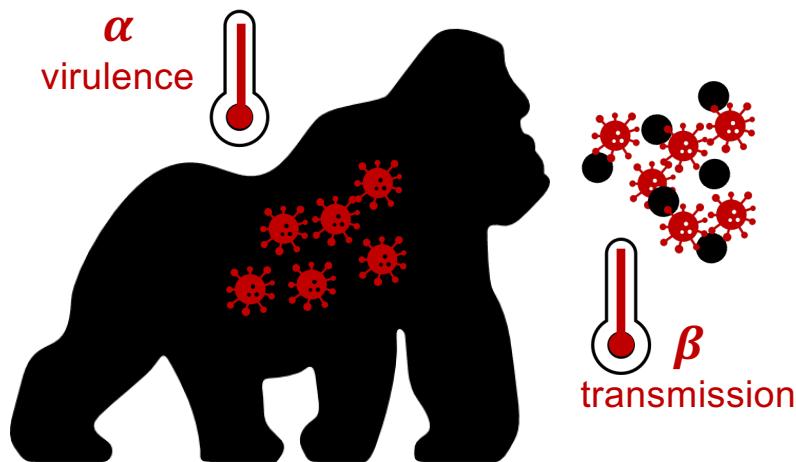
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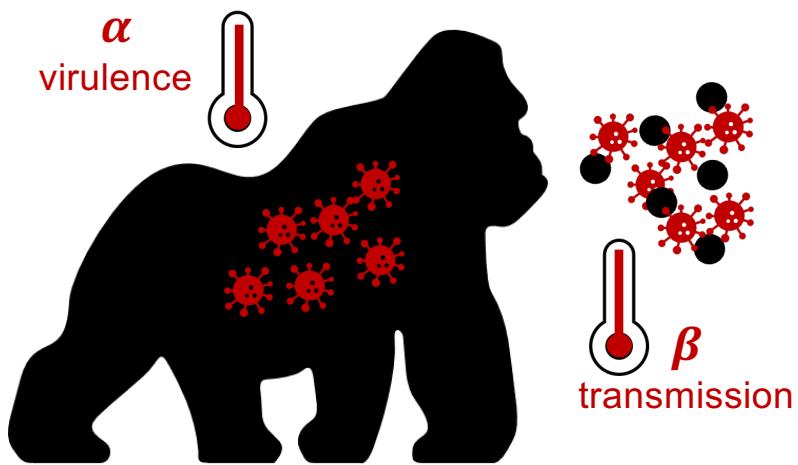
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Mechanisms that promote **transmission** may also enhance **virulence** to the host.

Alizon et al. 2008. *J Evolutionary Biology*
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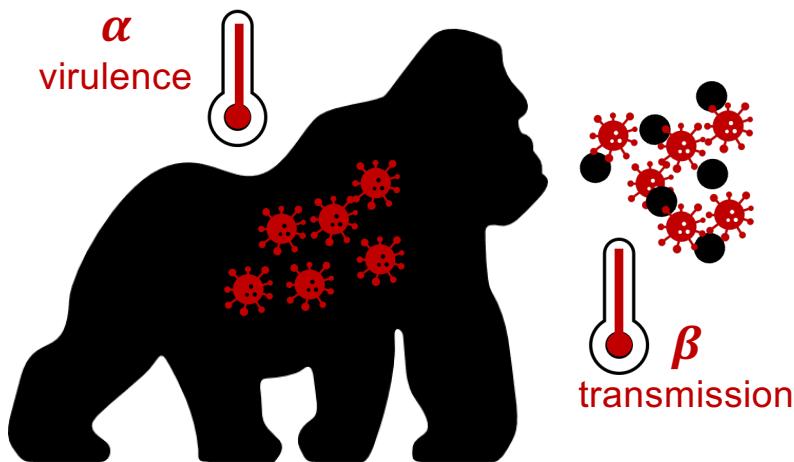
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Why do pathogens make us sick?

Virulence, then, is a by-product of a pathogen's need to transmit for reproduction!

Alizon et al. 2008. *J Evolutionary Biology*
Anderson and May 1982. *Parasitology*.

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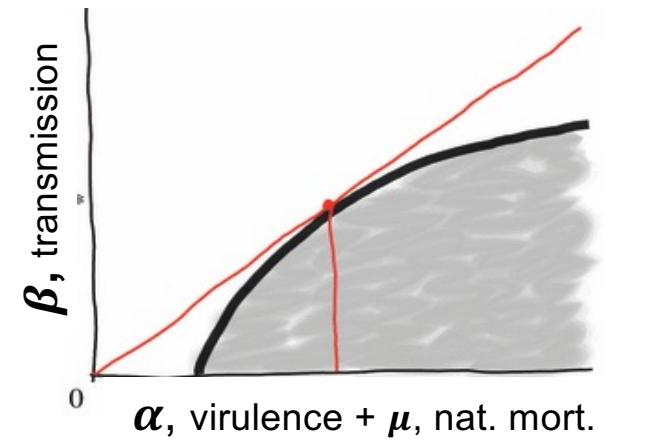


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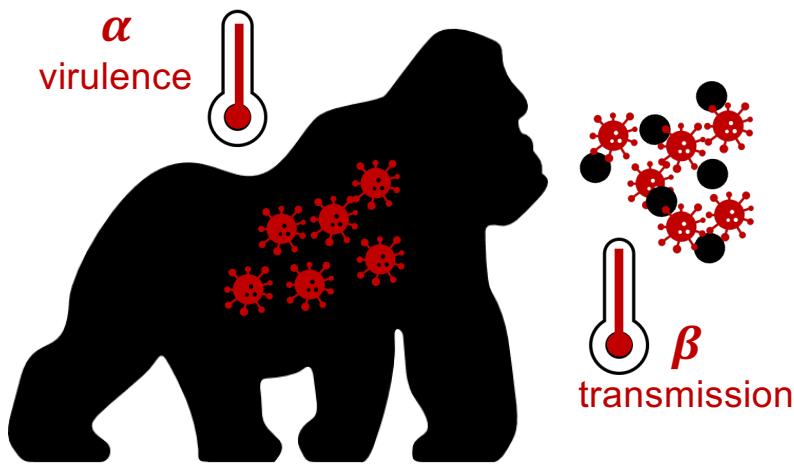
As a result, we predict the evolution of "**optimal virulence**".



$$R_0 = \frac{\beta(\text{virus density})}{\gamma + \mu + \alpha(\text{virus density})}$$

} infections created
} infections lost

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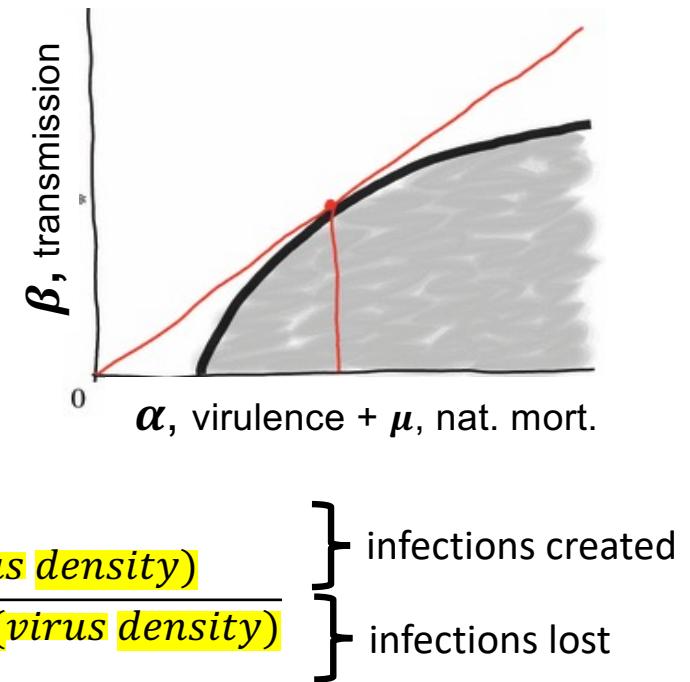
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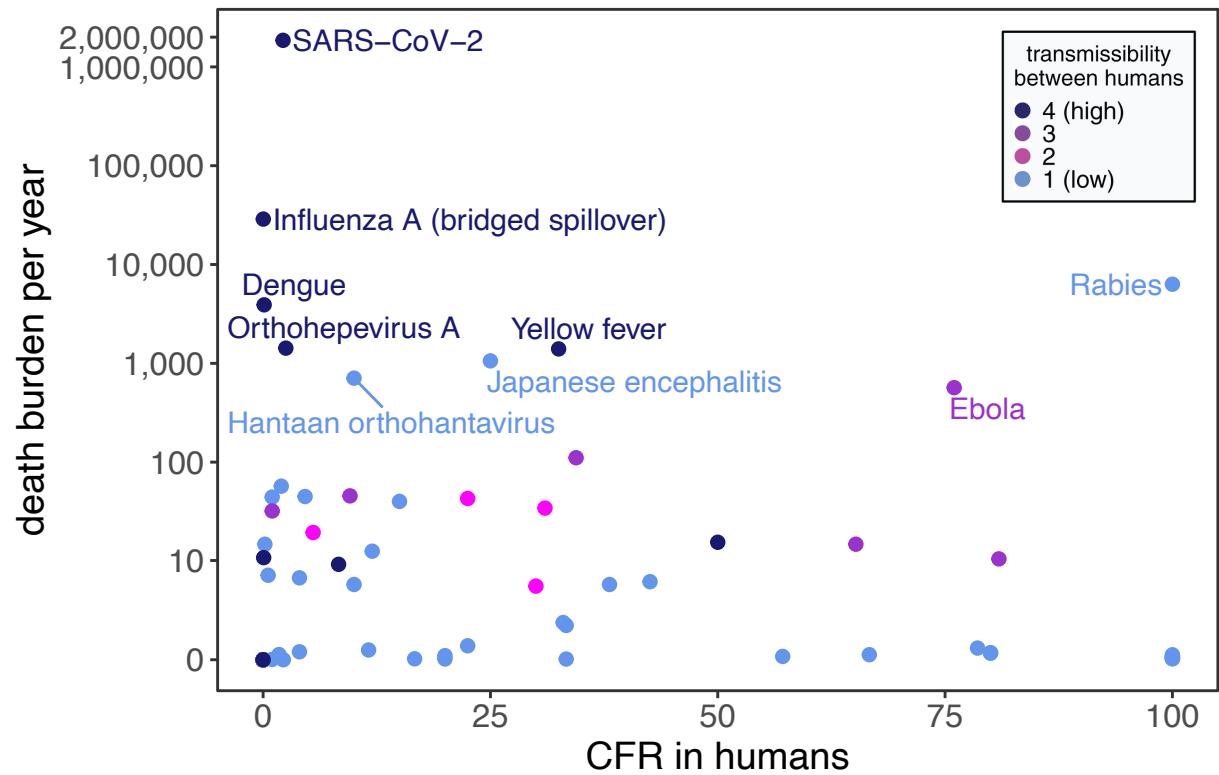
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Note that originally Anderson and May (1982) represented this link to virus density as acting on the disease recovery rate, though it is now more commonly expressed as a function of virulence!



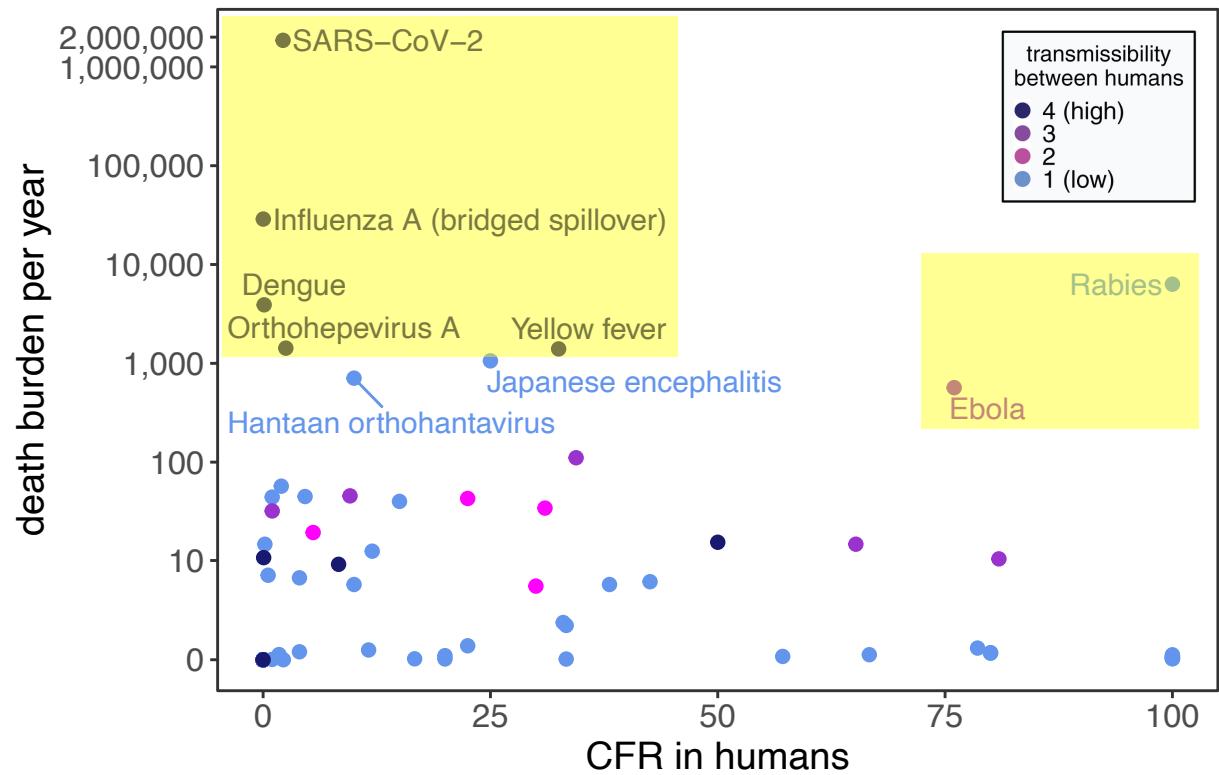
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For zoonoses,
**virulence and
transmission
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total death burden.



Guth et al. 2019. *Phil Trans Roy Soc.*
Guth et al. 2022. *PNAS*.

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The **virulence case study** of rabbit Myxoma virus

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- 1788: European rabbits brought to Australia as a food source
- Rabbits quickly became feral and numbers soared.
- 1901: Australia constructed the famous “rabbit-proof fence” to attempt to keep rabbits out of agriculture in the West.



The **virulence case study** of rabbit Myxoma virus

- 1788: European rabbits brought to Australia as a food source
- Rabbits quickly became feral and numbers soared.
- 1901: Australia constructed the famous “rabbit-proof fence” to attempt to keep rabbits out of agriculture in the West.
- Government looked to control measures, including biological controls in the 1930s.
- Tried Myxoma virus, a highly virulent European poxvirus infecting rabbits. with a CFR >99%.



Myxoma virus evolved to **intermediate virulence** in just a single year.

TABLE 4. THE VIRULENCE OF STRAINS OF MYXOMA VIRUS RECOVERED FROM THE FIELD IN AUSTRALIA BETWEEN 1951 AND 1981, EXPRESSED AS PERCENTAGES

virulence grade	I >99	II 95–99	III 70–95	IV 50–70	V <50	number of samples
case fatality rate (%)						
mean survival time/day	<13	14–16	17–28	29–50	—	
1950–51†	100					1
1952–55†	13.3	20.0	53.3	13.3	0	60
1955–58†	0.7	5.3	54.6	24.1	15.5	432
1959–63‡	1.7	11.1	60.6	21.8	4.7	449
1964–66‡	0.7	0.3	63.7	34.0	1.3	306
1967–69‡	0	0	62.4	35.8	1.7	229
1970–74‡	0.6	4.6	74.1	20.7	0	174
1975–81§	1.9	3.3	67.0	27.8	0	212

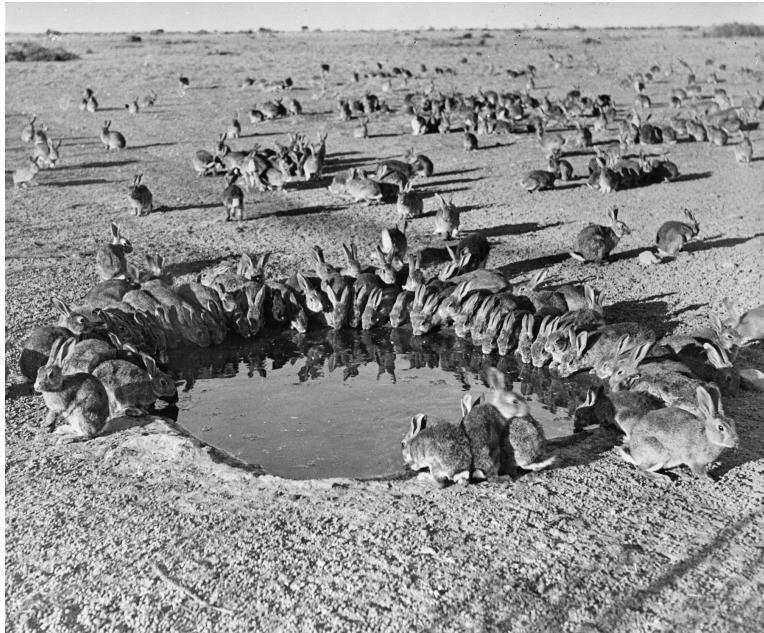
† Data from Marshall & Fenner (1960).

‡ Data from Edmonds *et al.* (1975).

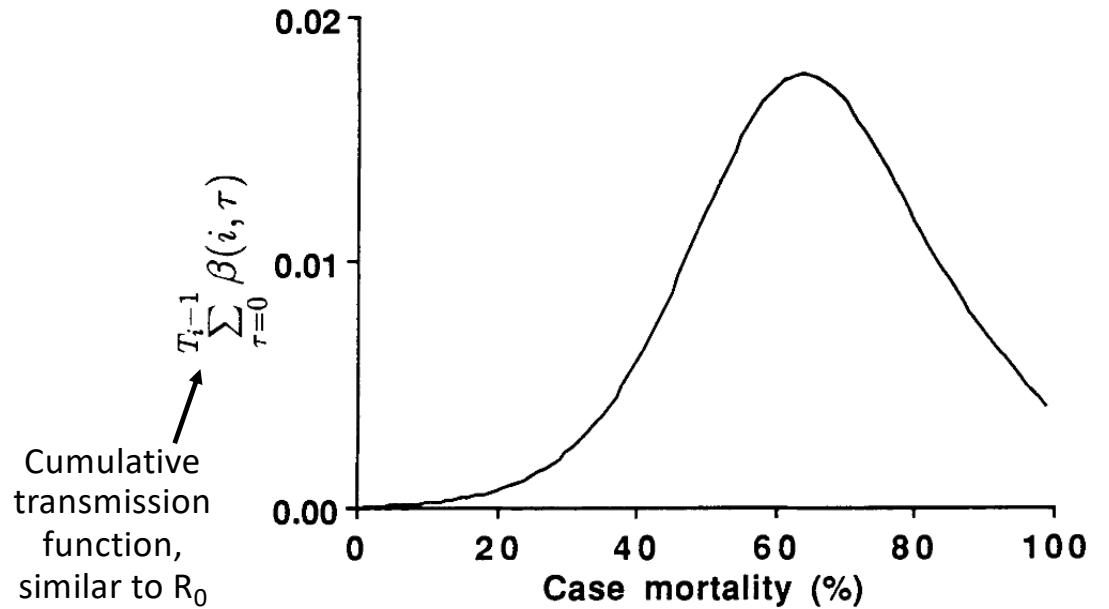
§ Data from J. W. Edmonds and R. C. H. Shepherd (personal communication, 1982).

|| Although only one strain was tested, the very high mortality rates in the initial outbreaks justify this extrapolation.

For Myxoma virus, **intermediate virulence evolution** resulted from **optimization of the tradeoffs between virulence and transmission**.



Rabbits around a waterhole in the myxomatosis trial site on Wardang Island, Australia, 1938



A SIMULATION MODEL OF THE POPULATION DYNAMICS
AND EVOLUTION OF MYXOMATOSIS¹

GREG DWYER
Department of Zoology, University of Washington, Seattle, Washington 98195 USA

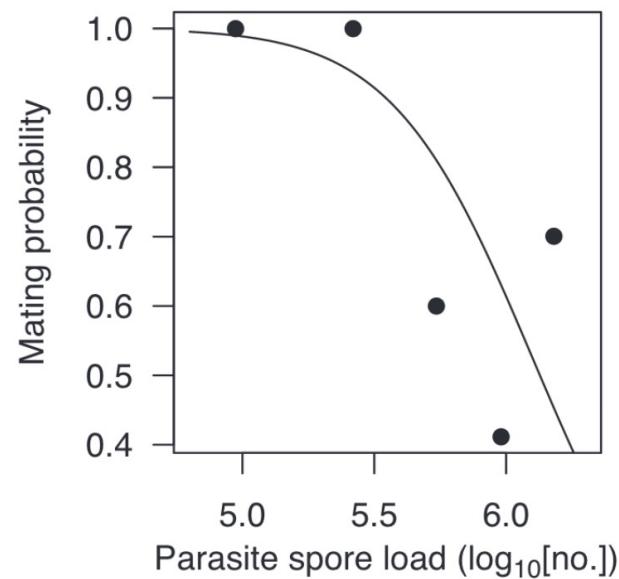
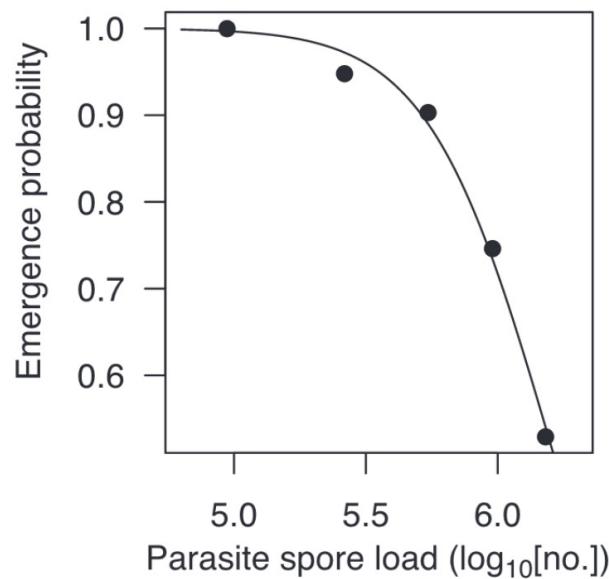
SIMON A. LEVIN
*Section of Ecology and Systematics, Corson Hall, Cornell University,
Ithaca, New York 14853 USA*

LINDA BUTTEL
*Ecosystems Research Center, Corson Hall, Cornell University,
Ithaca, New York 14853 USA*

Dwyer, Levin, and Buttel. 1990.
Ecological Monographs.

Another classic **transmission-virulence tradeoff**: parasites of monarch butterflies

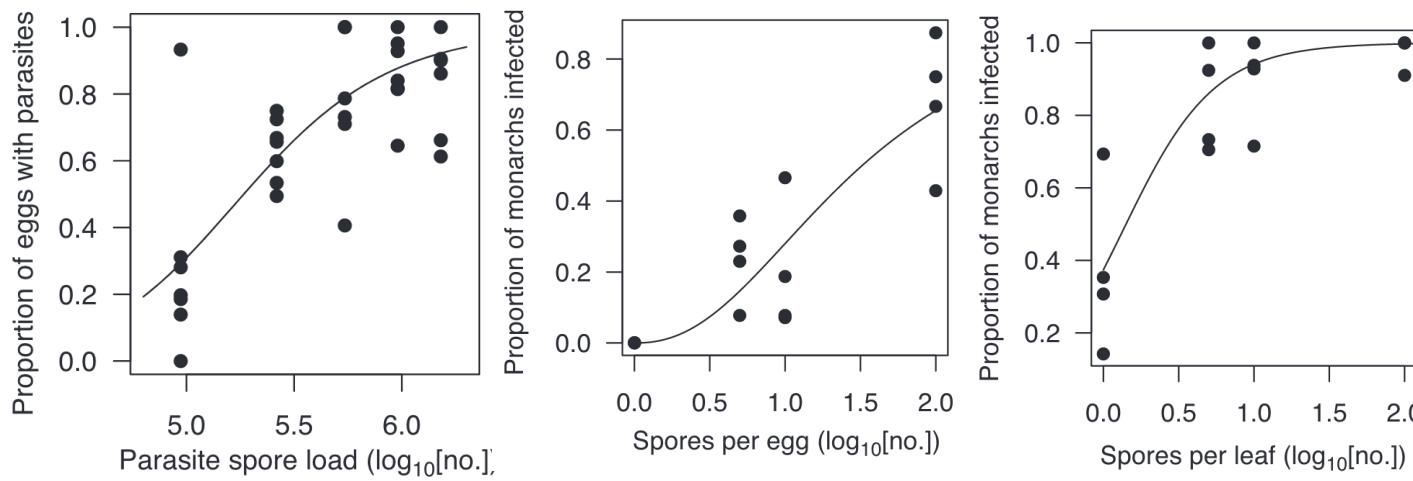
- Monarch butterflies infected with the protozoan parasite, *Ophryocystis elektroscirrha*, demonstrate reduced emergence and mating probabilities at higher parasite spore load (**virulence**).



de Roode et al. 2008. PNAS.

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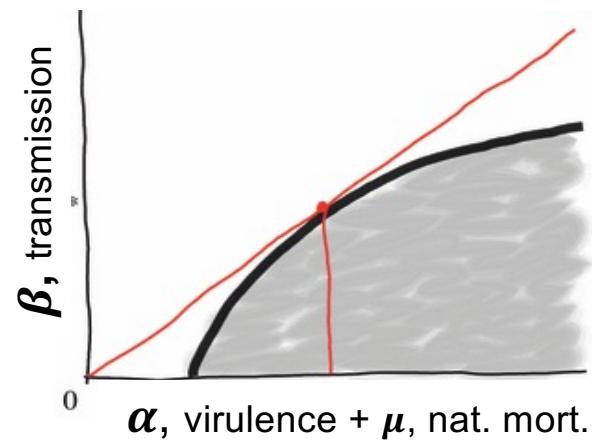
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- On the flip side, higher parasite loads also led to increased **transmission** through higher proportions of monarch eggs that acquired spores and higher numbers of parasites per egg and milkweed leaf, which increased the probability of infection.
- **Parasite fitness is calculated to be maximized at intermediate spore load.**



de Roode et al. 2008. PNAS.

Limitations of the tradeoff model

- The ‘trade-off hypothesis’ offers an explanation for the disease inflicted by parasites and pathogens on their original hosts. While well-designed theoretically, it has not been historically well-supported empirically!

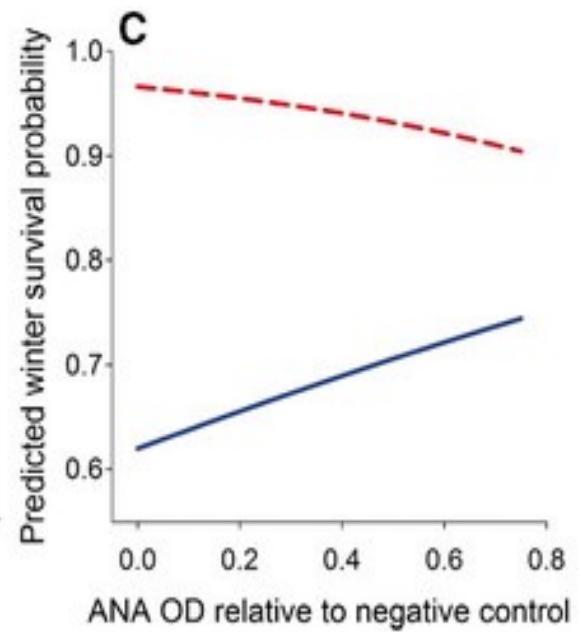
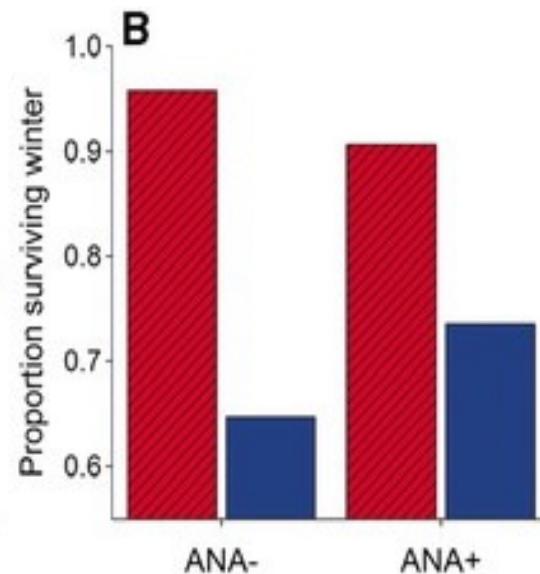
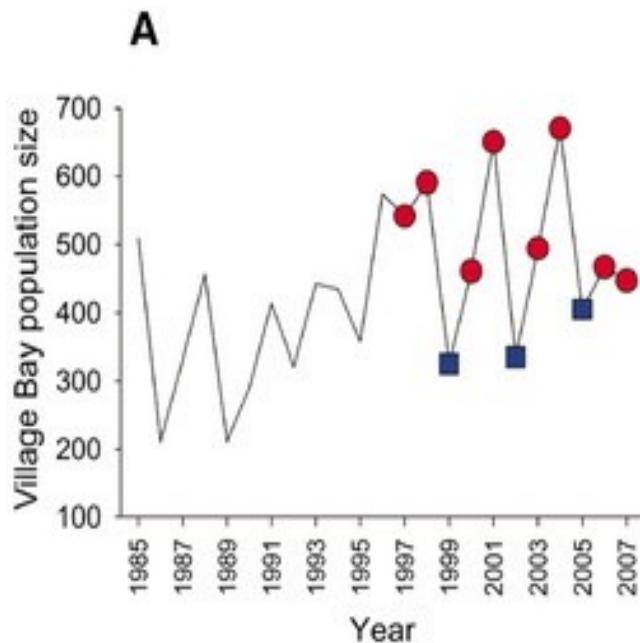
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 - Virulence is a fitness cost that the parasite inflicts on the host, but these can take diverse forms, with differing consequences for the evolution of virulence.
 - For example: Fitness effects on reproduction vs. adult mortality
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Self-reactive antibodies (ANA) **promote survival by downregulating worms in crash years** but **impede survival via immunopathology in peak years!**



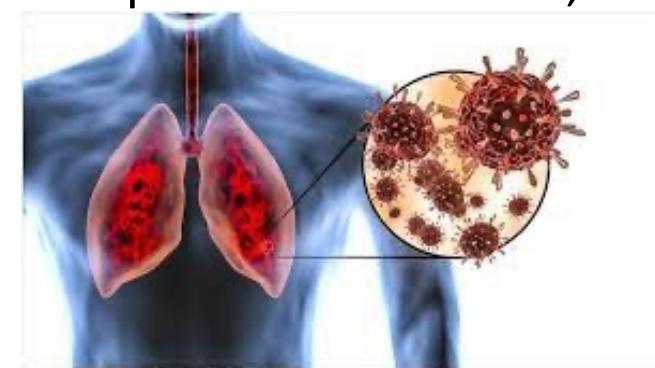
Graham et al. 2010. *Science*.

Limitations of the tradeoff model

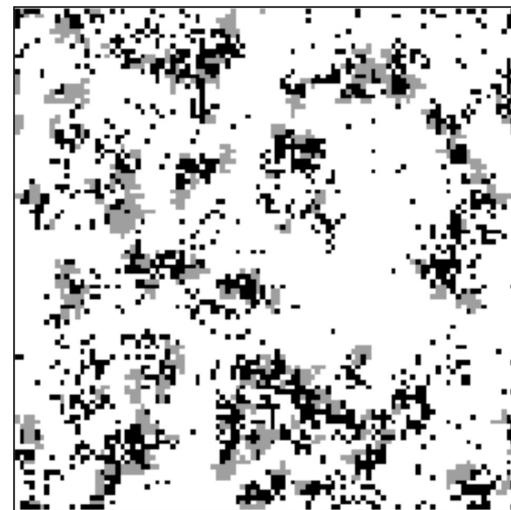
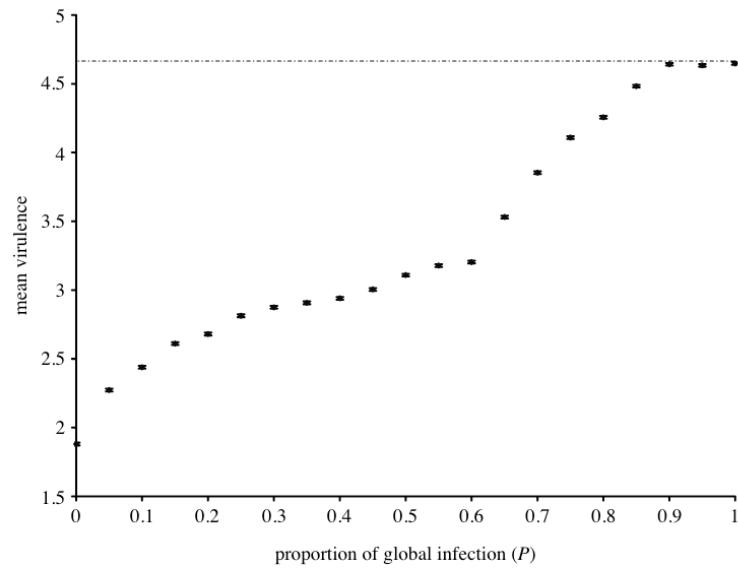
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 - In the case of zoonoses, the bulk of our measurements may be derived from a different host than the one in which the virus evolved
- Many examples of cases in which transmission is decoupled from virulence, due to more complex transmission dynamics.
 - Ex: COVID (transmission high in the respiratory tract; morbidity low in the RT)

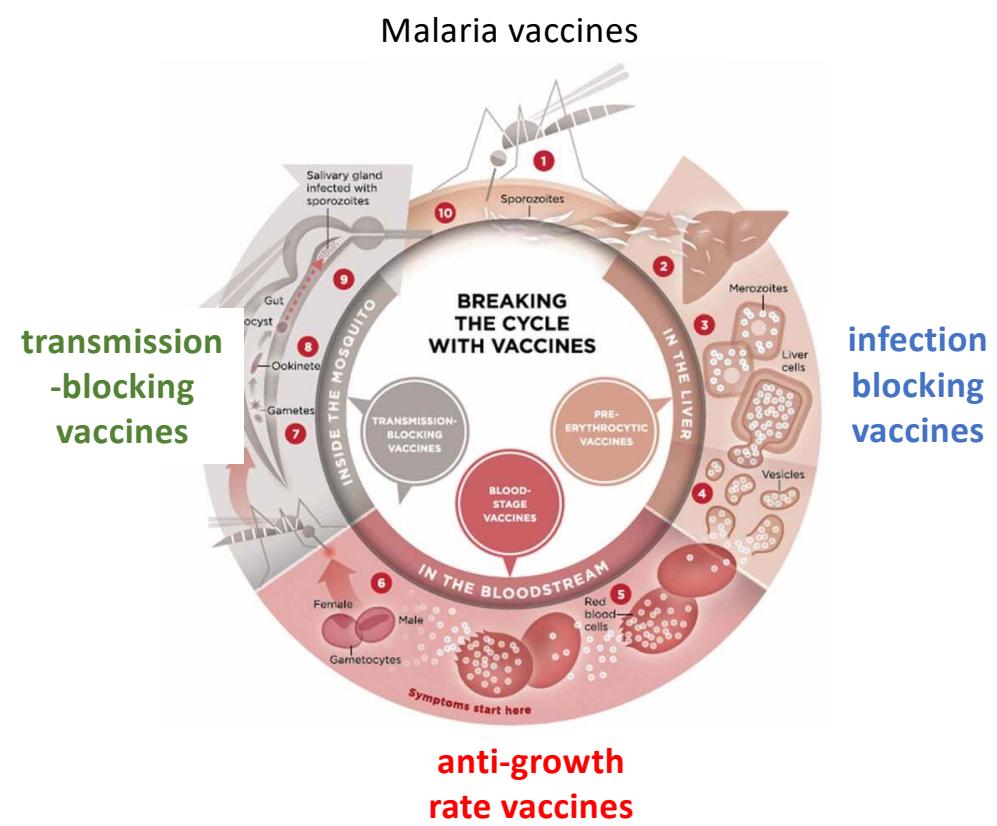
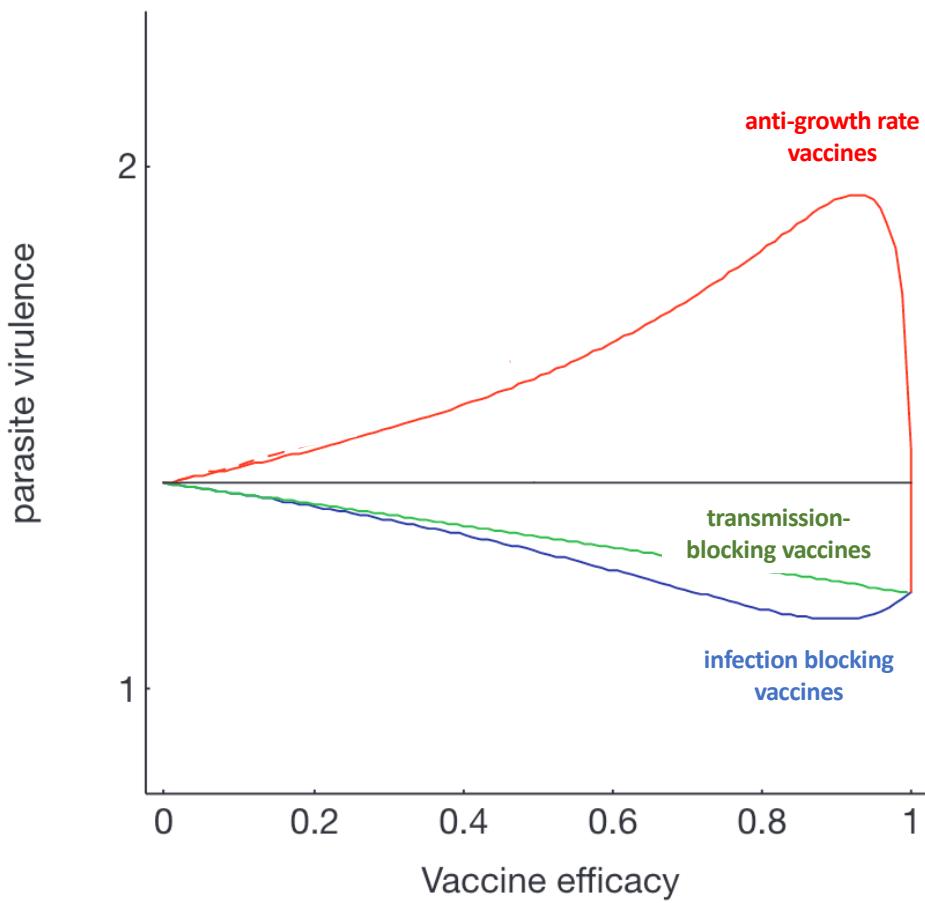


Spatial structuring generally favors reduced pathogen virulence.



Boots and Sasaki. 1999. *Proc Roy Soc B.*

Imperfect vaccination can support the evolution of higher virulence, depending on the lifestage of the pathogen that is targeted.



Que 2. In the 2014 West African Ebola epidemic, several people contracted infections during burial services by encountering the virus via contact with a recently-deceased patient. What would we expect for selective pressures on virulence evolution?

A We know Ebola became more transmissible in humans in 2014; because of the virulence-transmission tradeoff, it would also be selected for decreased virulence.

B Because virulence is decoupled from transmission in this case, it is challenging to predict the direction of selective pressure.

C The virus will be selected to be more virulent to kill more hosts in this case.

D The virus is in a stuttering transmission chain and under no selective pressure here.

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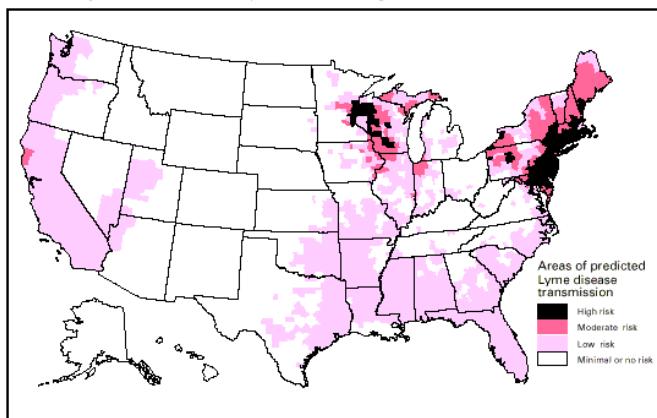
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Disease dynamics in the **broader community**

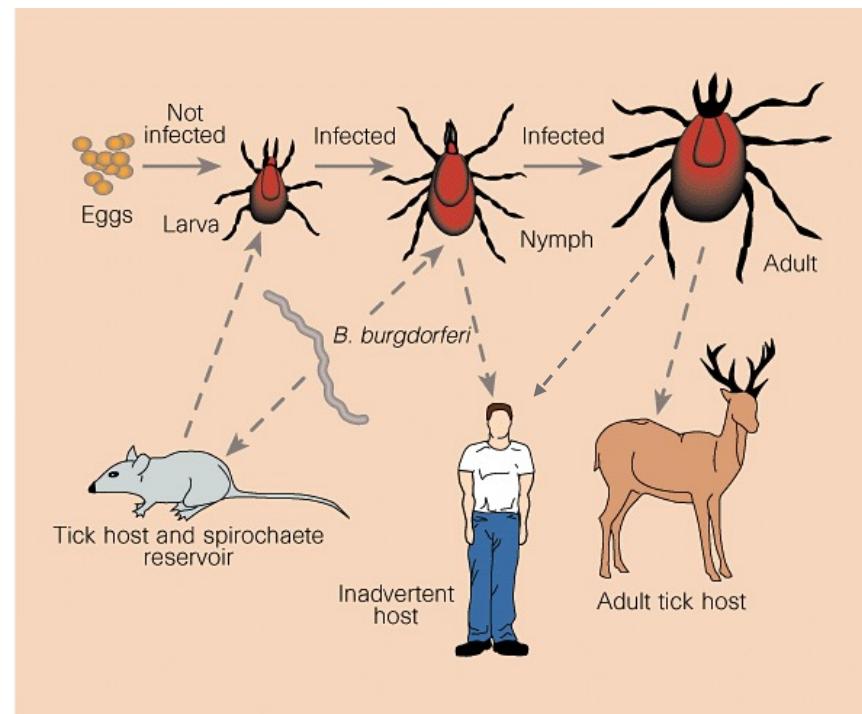
Disease dynamics in the **broader community**

Example: Lyme Disease

National Lyme disease risk map with four categories of risk



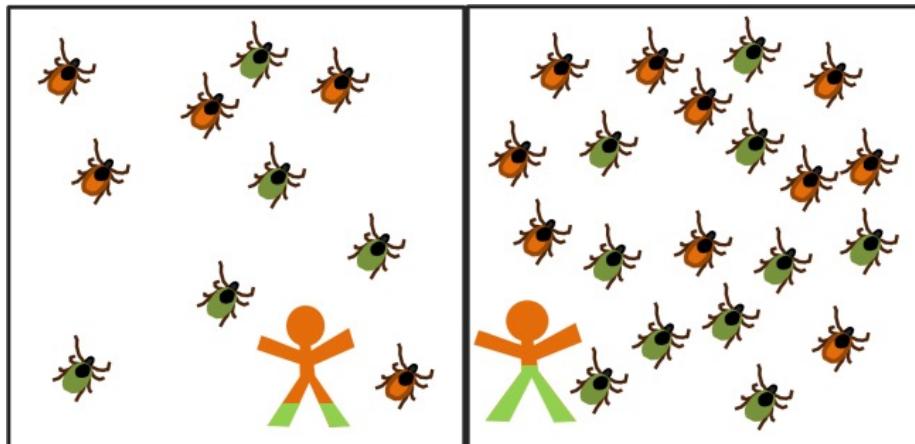
- Lyme disease is a vector-borne disease caused by the bacterium, *Borrelia burgdorferi*, vectored by *Ixodes* especially *Ixodes scapularis* ticks.
- Nymph ticks are borne in the spring, feed on small mammal hosts through the summer, then reproduce (particularly on deer) in the fall before going dormant in the winter.
- Human cases are largely concentrated in the spring and summer and result from infected tick bites.



Barbour and Zuckert 1997. *Nature*.

Human infection probability varies with both the **density of infected ticks** and the **prevalence of Lyme** in the tick population.

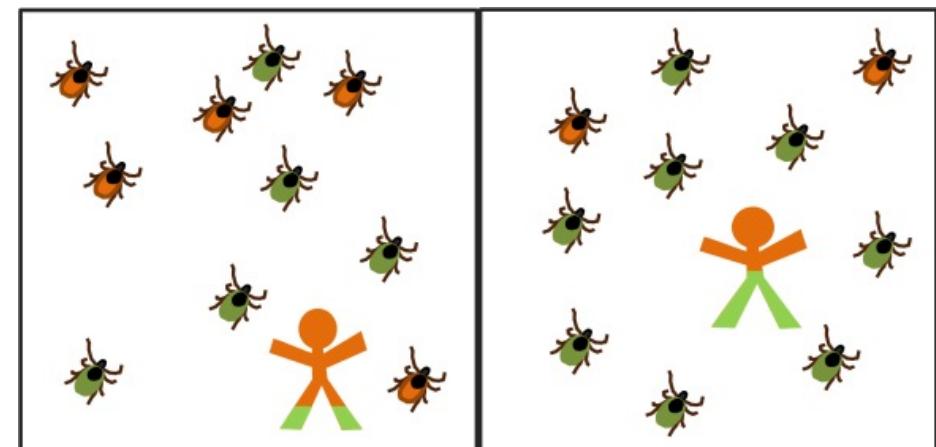
Scenario 1: Density of infected ticks



Area = 1 unit
Total Ticks = 10
Tick Density = 10 ticks/unit
Number Infected Ticks = 5
Prevalence Infected Ticks = 50%

Area = 1 unit
Total Ticks = 20
Tick Density = 20 ticks/unit
Number Infected Ticks = 10
Prevalence Infected Ticks = 50%

Scenario 2: Prevalence of Lyme in tick population



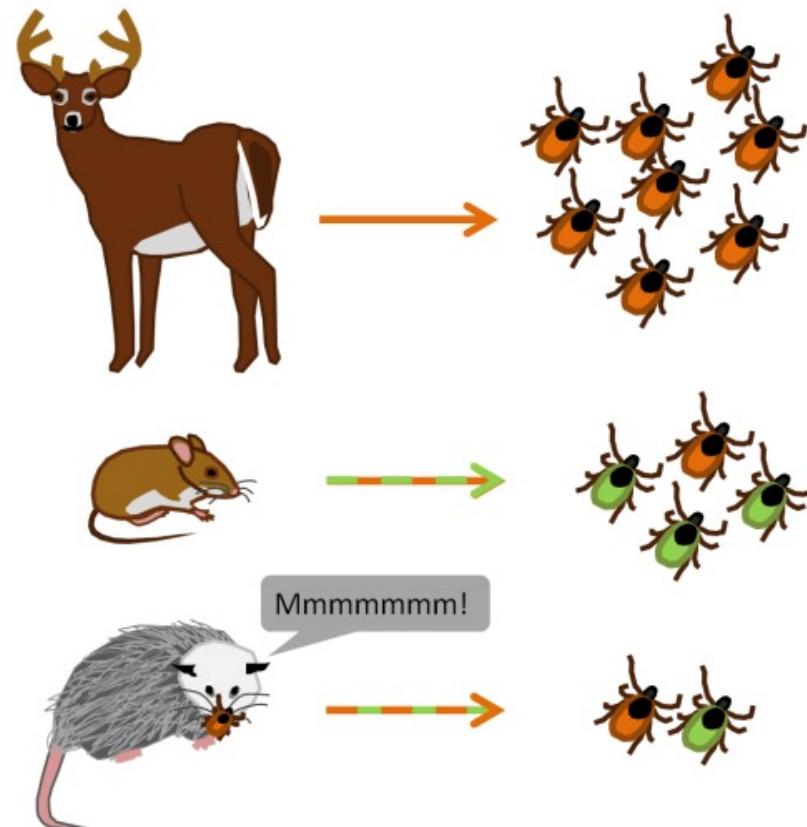
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Total Ticks = 10
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Area = 1 unit
Total Ticks = 10
Tick Density = 10 ticks/unit
Number Infected Ticks = 8
Prevalence Infected Ticks = 80%

lime = infected with Lyme

parasiteecology.wordpress.com

The broader **wildlife community impacts Lyme disease risk** for humans

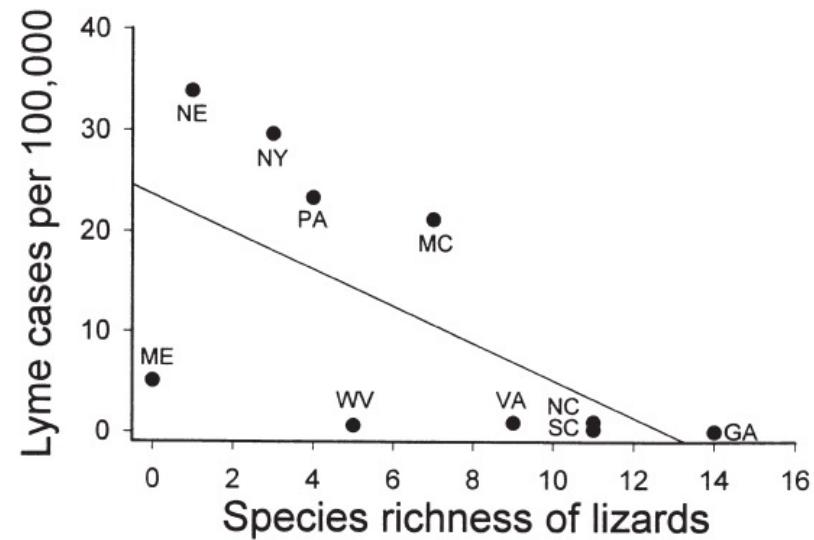
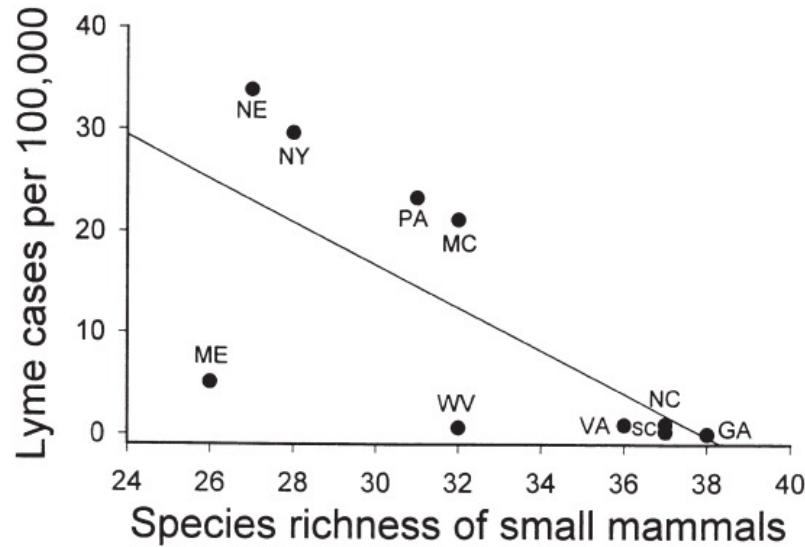


lime = infected with Lyme

- (1) Wildlife hosts vary in the extent to which they offer blood meals to ticks, thereby modulating tick abundance.
- (2) Wildlife hosts also vary in their permissibility to *B. burgdorferi* infection.

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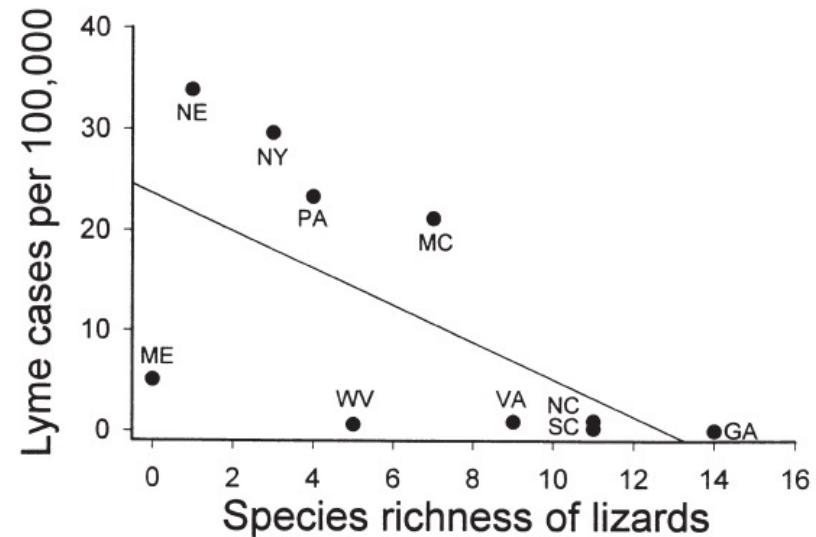
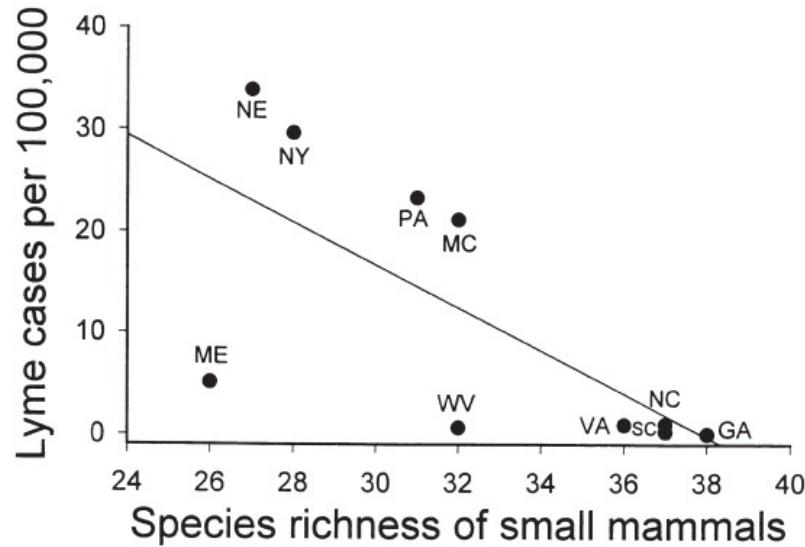


In the case of Lyme, many examples demonstrate a **negative correlation between host biodiversity and Lyme prevalence**.

Ostfeld and Keesing. 2000. *Conservation Biology*.

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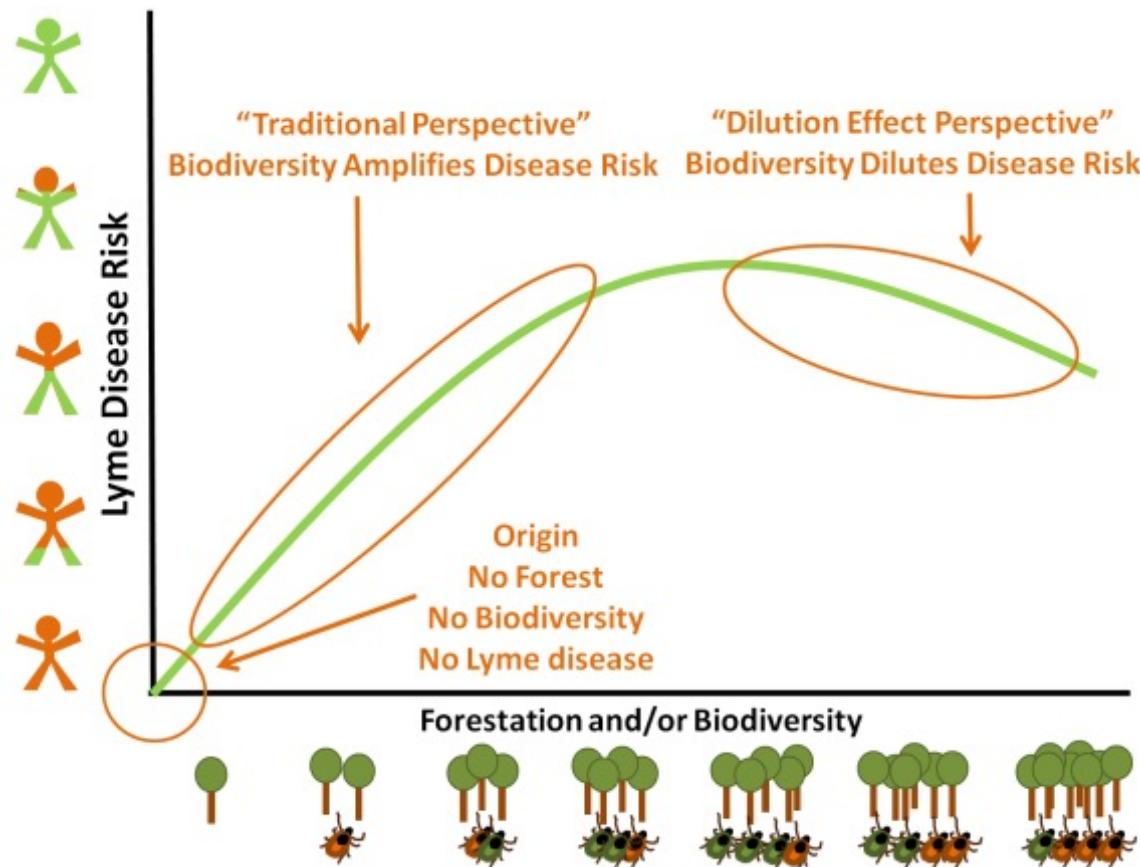
While a popular concept, it only holds in select cases!



In the case of Lyme, many examples demonstrate a **negative correlation between host biodiversity and Lyme prevalence**.

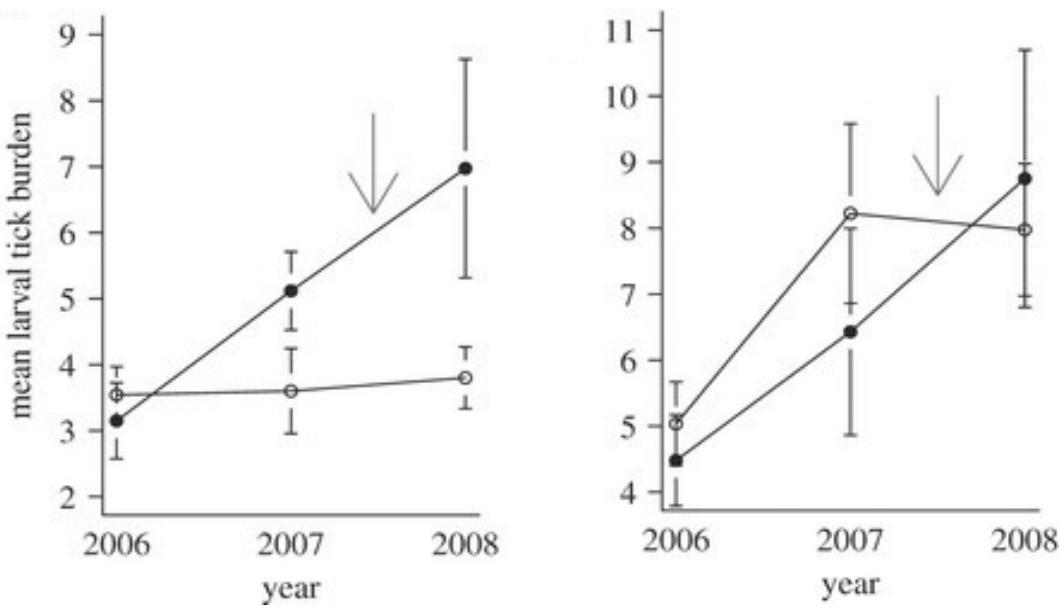
Patterns depend on the context of the wildlife community!

Human infection probability varies with both the **density of infected ticks** and the **prevalence of Lyme** in the tick population.



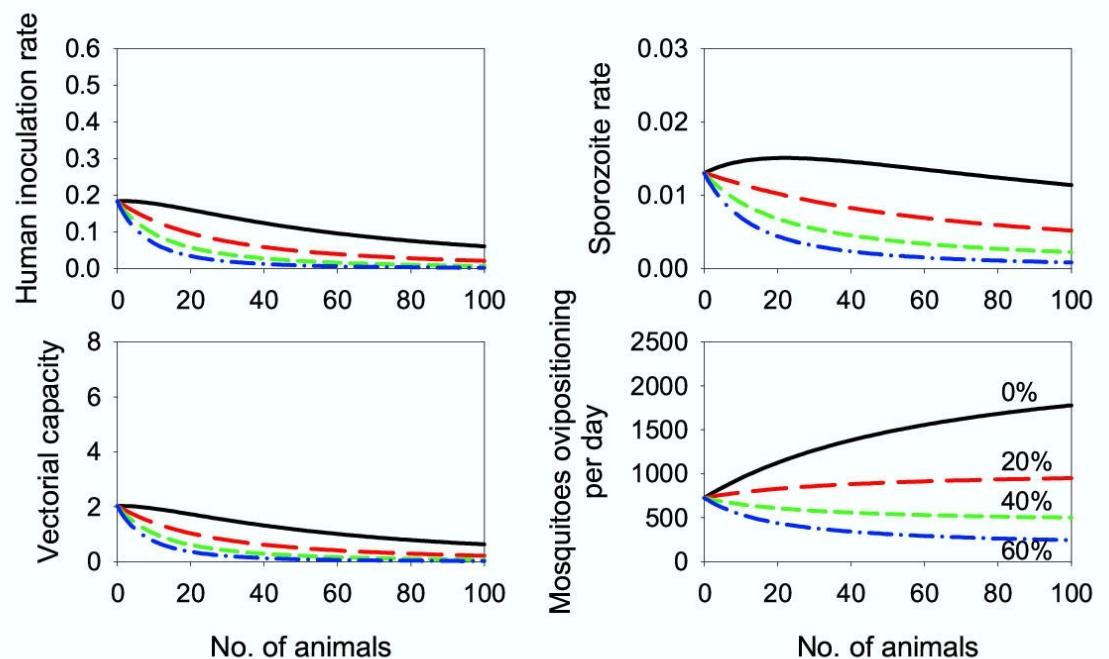
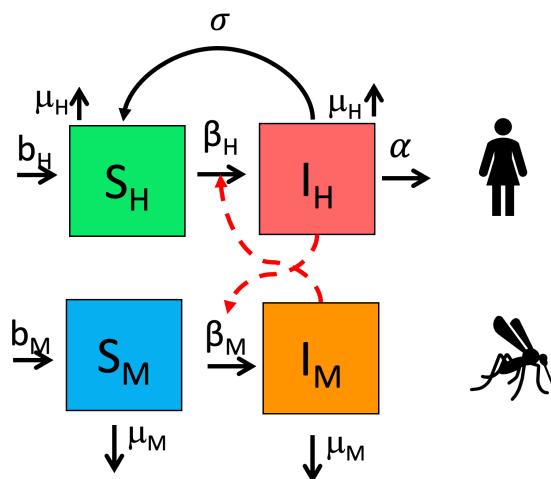
“Zooprophylaxis” is the diversion of pathogen-transmitting arthropods from humans to animals

Tick burden on female (left) and male (right) woodrats in Marin County, CA following removal of western fence lizard (*Sceloporus occidentalis*) at the end of the 2007 year in experimental (solid) and control (open circle) plots



Sceloporus occidentalis

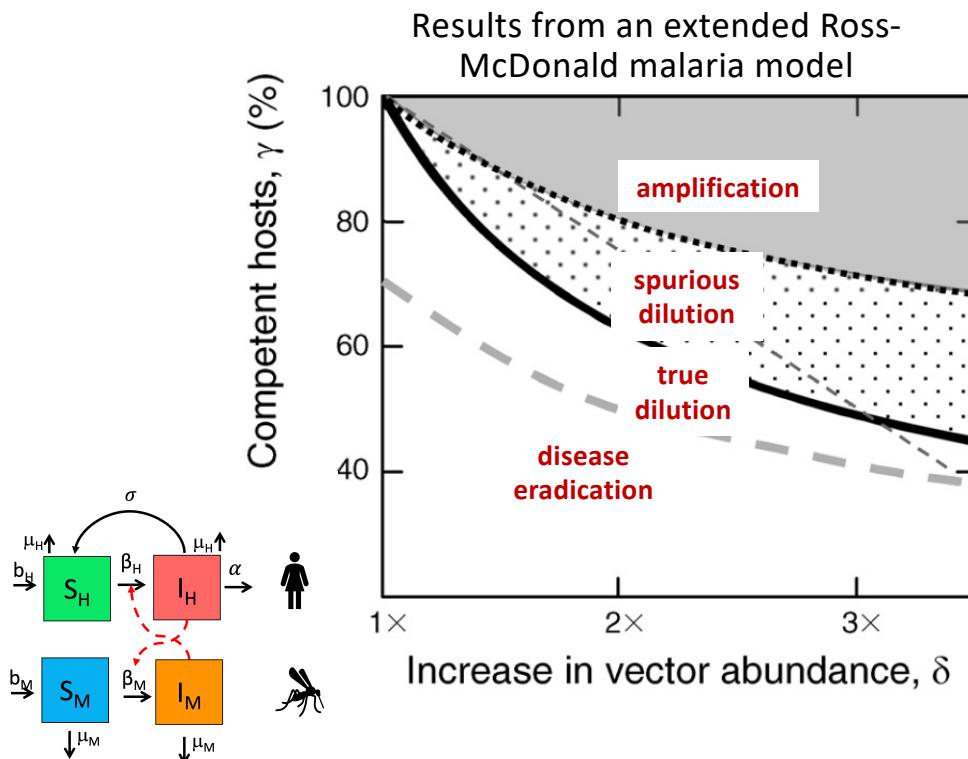
“Zooprophylaxis” has been suggested for malaria control –
but only works in cases by which livestock are used as bait to
draw mosquitoes closer to insecticides.



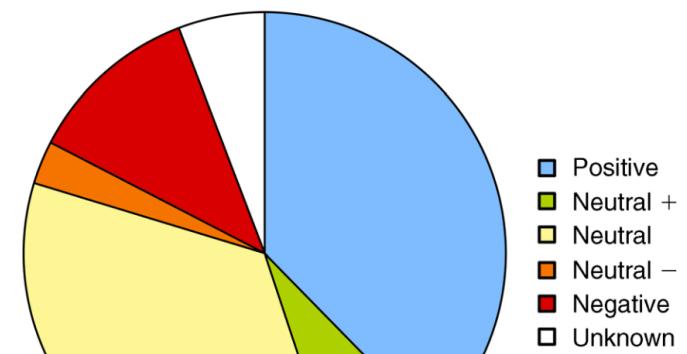
Black, red, green, blue = 0, 20, 40 or 60% chance
of being killed as a result of feeding on animals

Asale et al. 2017. *Malaria Journal*

Understanding the **underlying transmission dynamics** of the system can help predict how **wildlife biodiversity** might **amplify or dilute** human disease risk in different contexts.



Meta-analysis of biodiversity impacts on 69 common human pathogens



Wood et al. 2014. *Ecology*

Que. 3. Imagine a forest with endemic Lyme disease and a high population of deer. What outcome would you expect if the deer were experimentally removed, but the increase in grass availability leads to an explosion in the population of white-footed mice?

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- A. Lyme risk to humans will decrease because there will be fewer ticks in the forest.
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- D. We'll need to build a model to understand the most likely outcome

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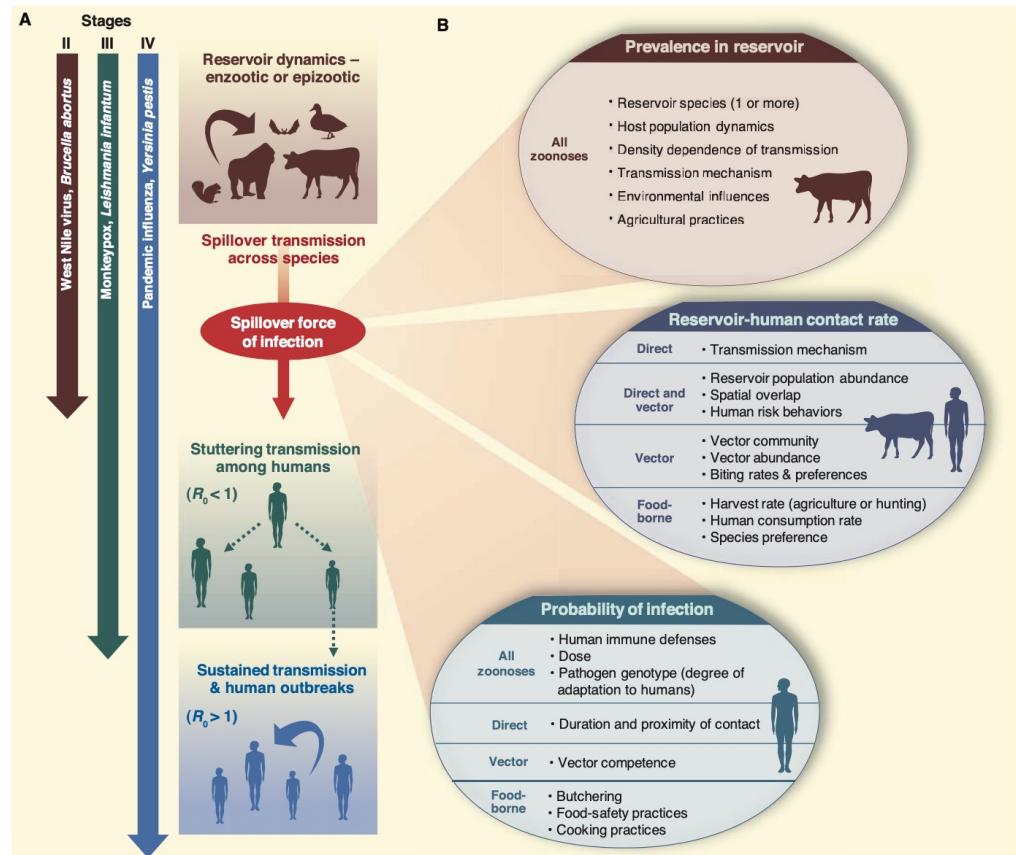
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Extra

The force of infection (FOI), λ , is the rate at which susceptibles become infected

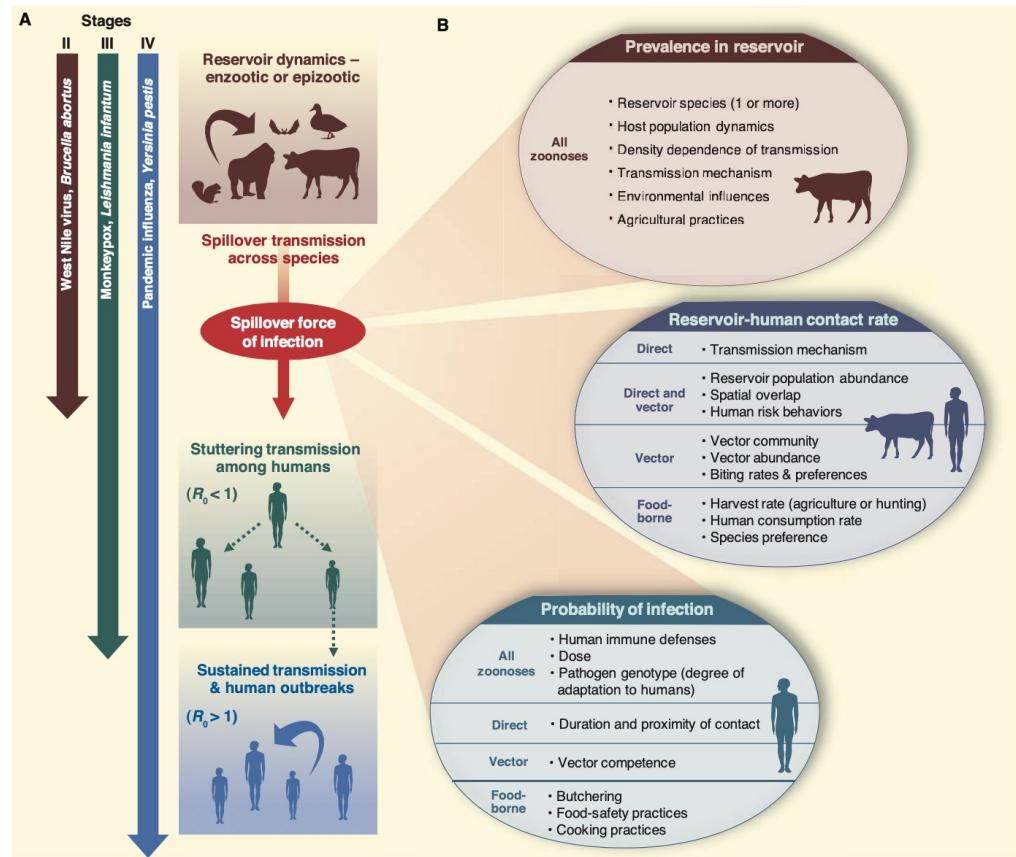
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- (**FOI = $R_0 * \text{proportion infected}$**)



Lloyd-Smith et al. 2009. *Science*.

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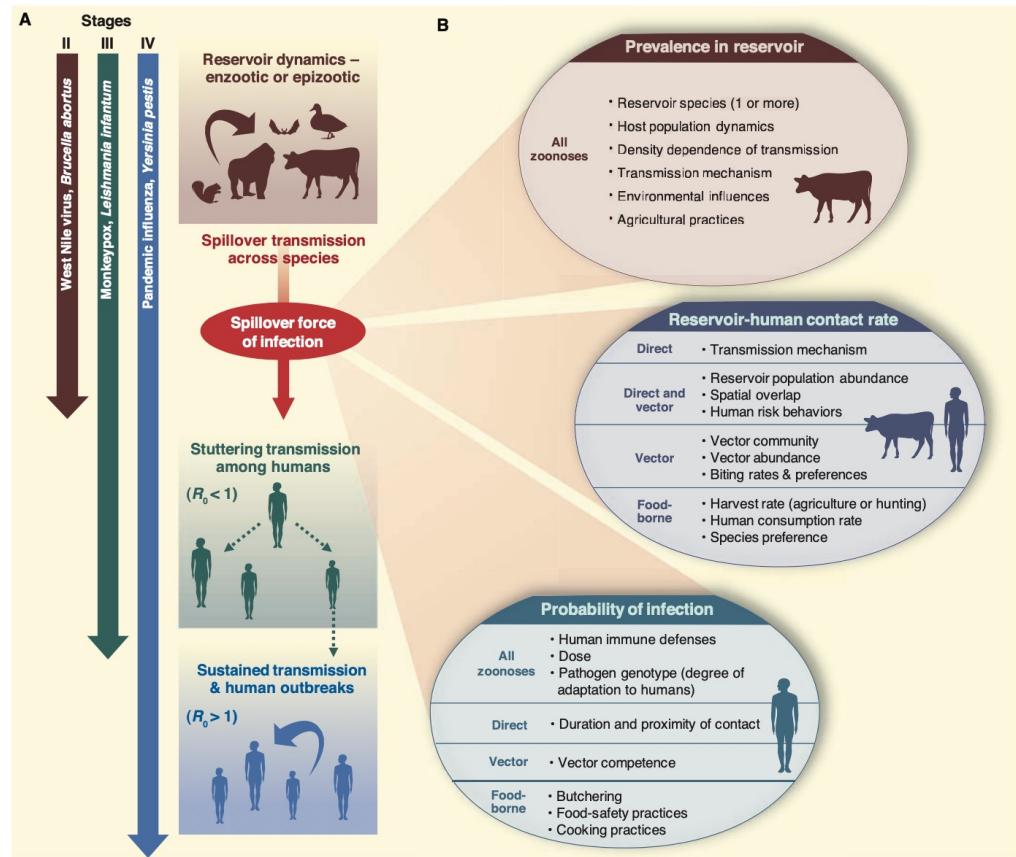
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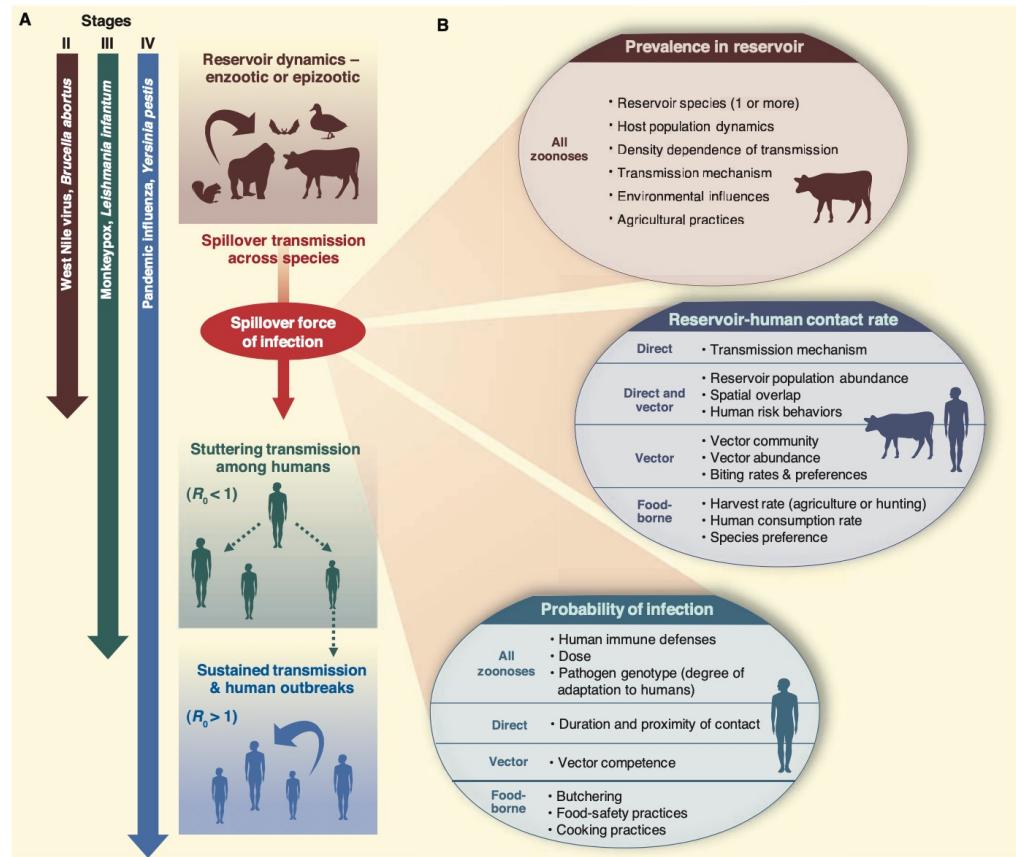
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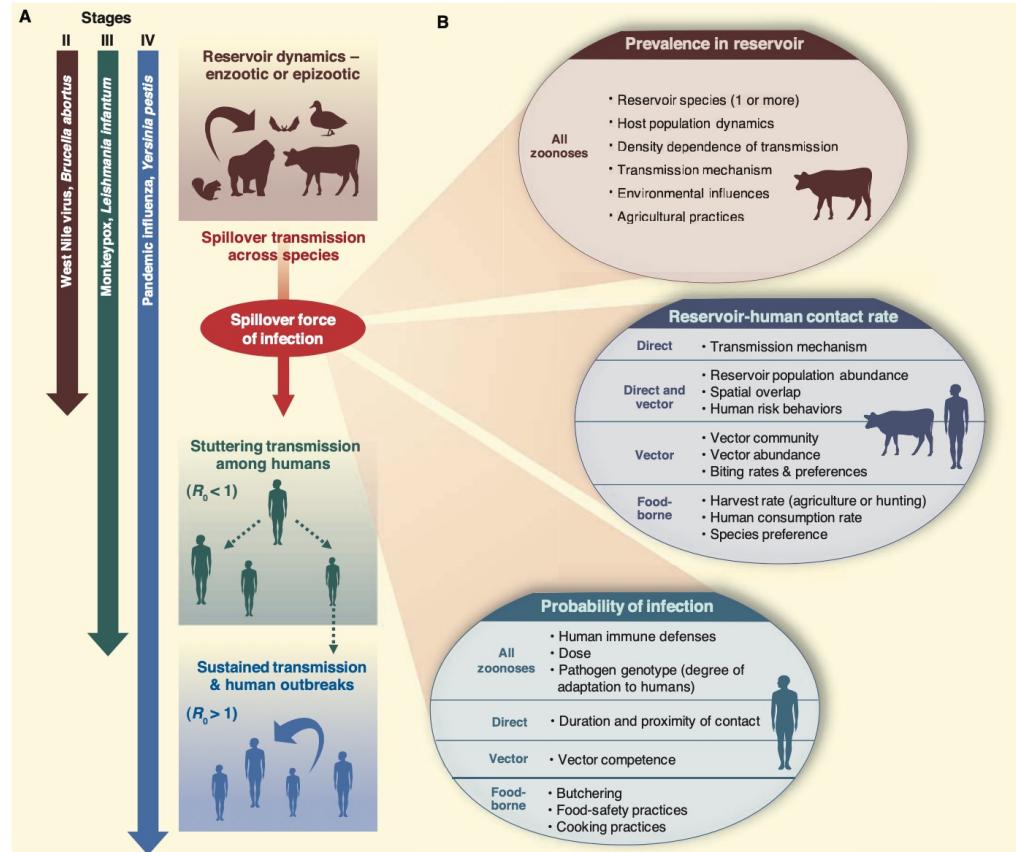


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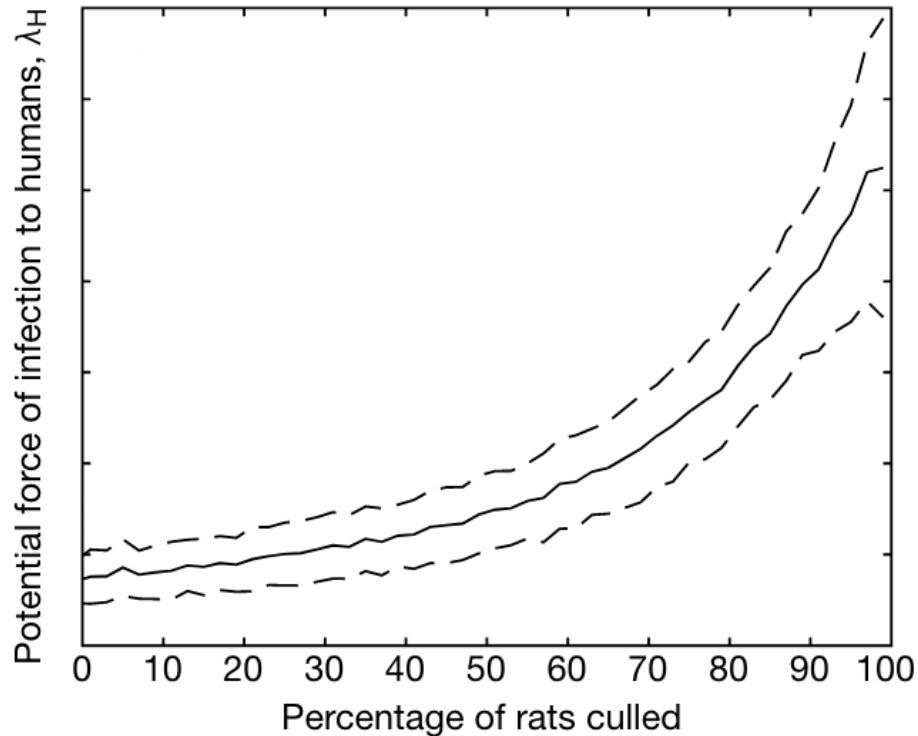
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Keeling & Gilligan model λ_H for plague as proportional to the abundance of free-living infected fleas.



Lloyd-Smith et al. 2009. *Science*.

Fleas get infected from rats.
Humans get infected from free-living infected fleas!



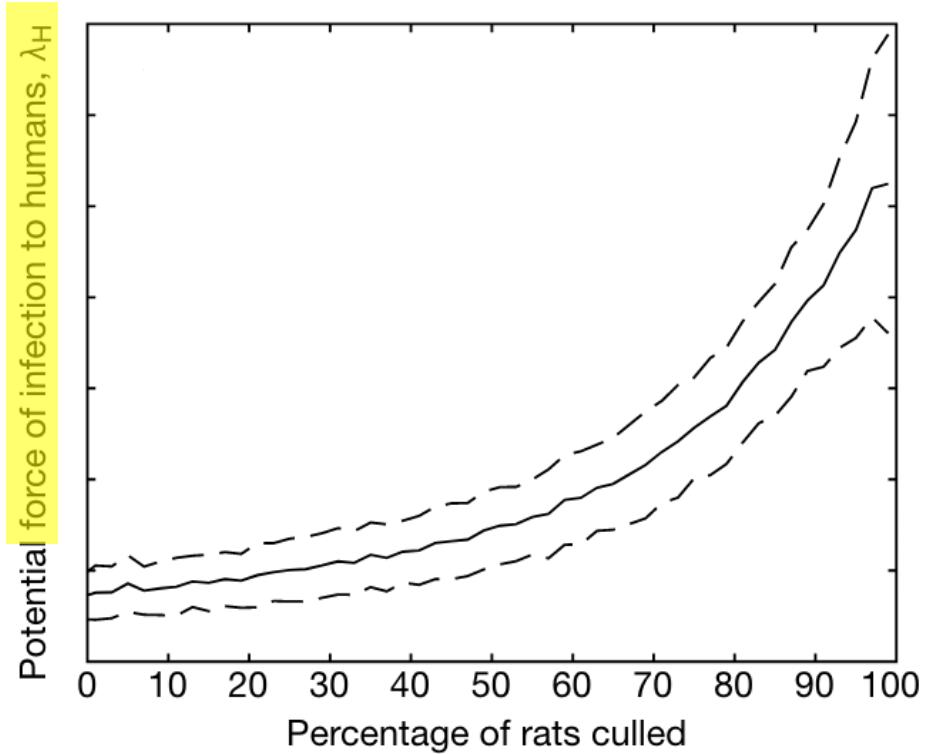
Keeling and Gilligan. 2000. *Nature*.

“...from April 18 onwards, quantities of dead or dying rats were found in factories and warehouses...From the outer suburbs to the center of the town, in all the byways where the doctor's duties took him, in every thoroughfare, rats were piled up in garbage cans or lying in long lines in the gutters...On the fourth day the rats began to come out and die in batches...”

--*La Peste*, Albert Camus (1948)

Plague is BOTH vector-borne and zoonotic!

Humans get infected from free-living infected fleas!



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