Public Health perspectives. Epidemiological parameters, R0 and reservoirs.

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Reservoir workshop

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Modelling Infectious Diseases in Humans and Animals (Keeling and Rohani)

Concept of reservoir

Definition

- Reservoir/maintenance population
- Population in which the pathogen persists even in the complete absence of transmission from other hosts.
- In other words, a population in which endemicity of the pathogen can occur.

Characterization of a reservoir/maintenance population with epidemiological models

- Formalize the epidemiological system (host population-pathogen) with a dynamic model

- Describe the behaviour of this model

- Determine the conditions under which the pathogen persists over the long term (endemicity) according to the model

Basic epidemiological models for a single population

The SIR model for a closed population

Equations of the SIR model describe the change in the composition of the host population regarding epidemiological status over a short time period *dt*

Proportion of Susceptibles: $\frac{dS}{dt} = -\beta SI$

Proportion of Infectious: $\frac{dI}{dt} = \beta SI - \gamma I$

Proportion of Recovered: $\frac{dR}{dt} = \gamma I$

- Model parameters
  - β : transmission parameter, is the number of infective contacts per time unit
    - $\beta = -\kappa \log(1 - c)$
      - κ is the number of contacts of an individuals with other invdividuals over a time unit
      - c is the probability of successful disease transmission during a contact
  - $1/\beta$ is the average time between infective contacts
  - γ: is the probability of recovering for an infectious individual by time unit
  - $1/\gamma$: is the average time until recovery
  - $R_0 = \frac{\beta}{\gamma}$ is the basic reproductive rate. It is the number of secondary cases arising from an average primary case in an entirely susceptible population. If $R_0<1$, the disease can not spread in the population

The SIR model for a closed population

- SIR models for closed populations are irrelevant for the characterization of a maintenance population because in such models, the pathogens always eventually goes extinct

- At some point, the proportion of infectives declines and the proportion of recovered increases to levels at which transmission cannot occur anymore.

- The SIR model for a closed population is useful
  - to assess whether a pathogen can generate an epidemic in a population
  - and to assess the proportion of the population that eventually contract the infection

- To characterize the conditions under which endemicity can occur one needs to consider the demography of the host population

The SIR model with host demography

Proportion of susceptibles: $\frac{dS}{dt} = \mu - \beta SI - \mu S$

Proportion of Infectious: $\frac{dI}{dt} = \beta SI - \gamma I - \mu I$

Proportion of Recovered: $\frac{dR}{dt} = \gamma I - \mu R$

- Demographic process is described by a single parameter μ
  - μ : rate at which individuals in any epidemiological compartment suffer from natural mortality
  - μ is also by assumption of population stability the population's birth rate
  - The larger is μ the larger is the turnover of individuals in general and in particular of susceptible individuals in the population.
- In a model with demography, there is an influx of new susceptibles through births and endemicity is possible.
- The behaviour of such models is the convergence towards an equilibrium

The equilibrium in a SIR model with demography

Two types of equilibrium states are possible

Disease free equilibrium : $I^* = 0$

Endemic equilibrium: $I^* = \frac{\mu}{\beta}(R_0 - 1)$ where $R_0 = \frac{\beta}{\mu+\gamma}$

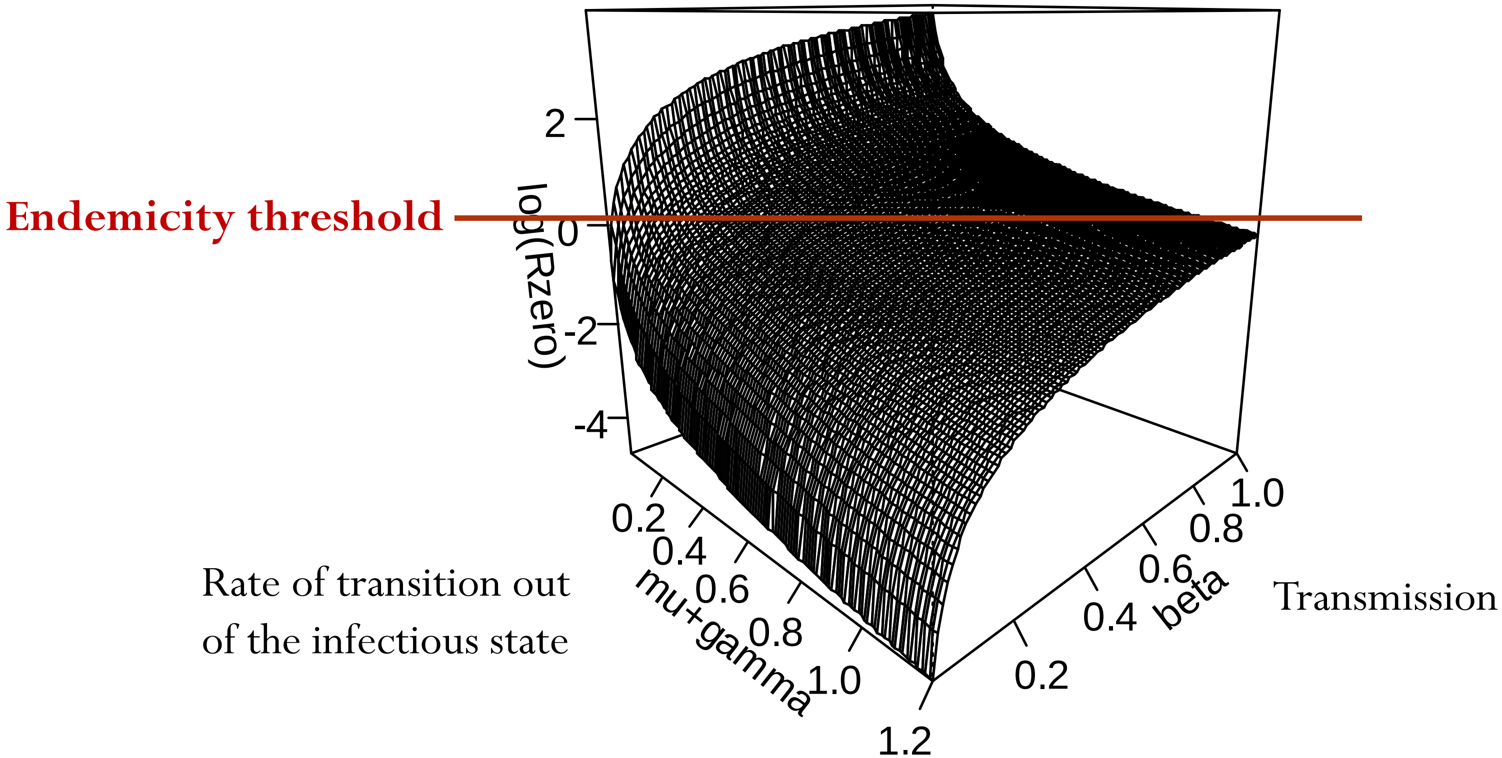
- R_0 is the basic reproductive rate. It is the number of secondary cases arising from an average primary case in an entirely susceptible population
- The behaviour of such models is the **convergence towards an endemic equilibrium whenever $R_0 > 1$** (whenever the pathogen is able to invade an entirely suscpetible population).
- This occurs because in this model there is a constant influx of new susceptible individuals through births
- The endemic equilibrium is reached after a period of damped oscillations

Relevant quantities for the identification/characterization of a maintenance/reservoir population

Can a host population be a reservoir/maintenance compartment

- $R_0 = \frac{\beta}{\mu+\gamma}$ **reflects whether a host population can be a maintenance/reservoir compartment of a given disease (*R_0*>0)**

Variation of R_0 as a function of the transmission parameter and of the rate of transition out of the infectious state



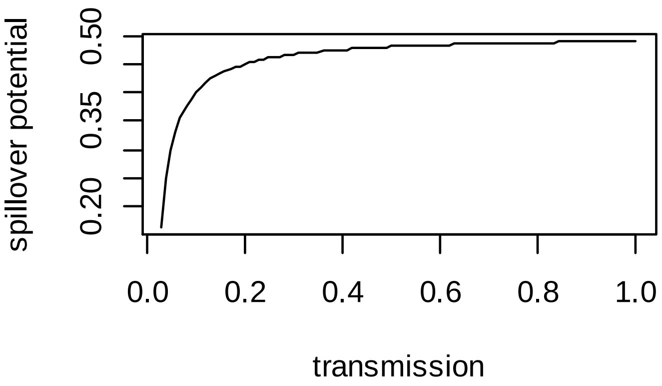
A population can be a maintenance/reservoir compartment if

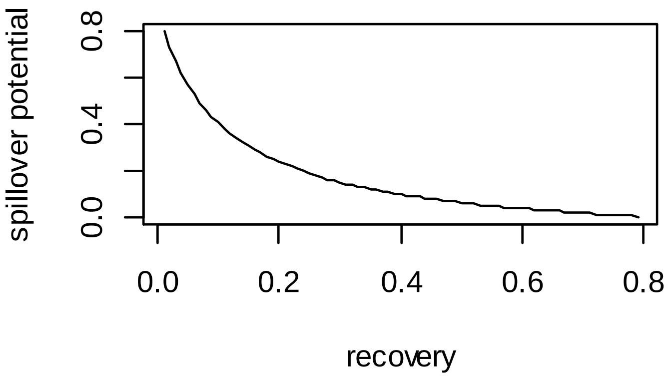
- disease transmission among individuals is efficient enough (large value of β)
- duration of the infectious state is large enough (large value of $\frac{1}{\mu+\gamma}$)

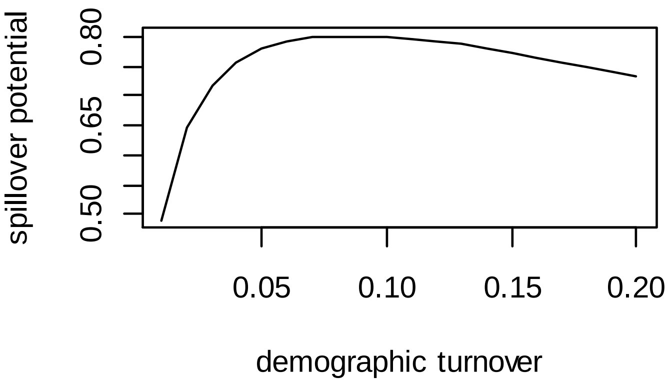
Spillover capacity 1

- $R_0 = \frac{\beta}{\mu+\gamma}$ reflects whether a host population can be a maintenance/reservoir compartment of a given disease (R_0>0)
- **There is in addition an other important quantity to characterize a maintenance/reservoir population which is I^*: the proportion of infectious individuals at the endemic equilibrium. This reflects the capacity of the population to infect individuals from other populations. Let us thus refer to I^* as the spillover capacity**
  - **The larger is I^*, the larger is the associated spillover capacity**
  - **Endemic equilibrium:** $I^* = \frac{\mu}{\beta}(R_0 - 1) = \frac{\mu}{\beta}\left(\frac{\beta}{\mu+\gamma} - 1\right) = \frac{\mu\beta}{\beta\mu+\beta\gamma} - \frac{\mu}{\beta}$

Spillover capacity







In maintenance/reservoir populations (R_0>0), the spillover capacity increases with:

- Increasing transmission rate
- Decreasing recovery rate
- Increases and then decreases with increasing demographic turnover

Spillover capacity 2

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  - The larger is I^*, the larger is the associated spillover capacity
  - Endemic equilibrium: $I^* = \frac{\mu}{\beta}(R_0 - 1) = \frac{\mu}{\beta}\left(\frac{\beta}{\mu+\gamma} - 1\right) = \frac{\mu\beta}{\beta\mu+\beta\gamma} - \frac{\mu}{\beta}$
- **In addition, the size of the population can be important as a larger populations will generate a larger number of infectious individuals at the endemic equilibrium**

Stability of the endemic equilibrium

- $R_0 = \frac{\beta}{\mu+\gamma}$ reflects whether a host population can be a maintenance/reservoir compartment of a given disease (R_0>0)
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- In addition, the size of the population can be important as a large population will generate a larger number of infectious individuals at the endemic equilibrium
- **Finally, the stability of the endemic equilibrium is important. Stability is the capacity of the system to reach again the endemic equilibrium state following a perturbation (a modification of the distribution of individuals in the population in the different epidemiological states). This is assessed through a perturbation/stability analysis.**

The assumptions of the simple SIR model with demography

- The disease does not incur any additional mortality (low virulence).
- Infection results in lifelong immunity
- The influx of susceptibles through births is constant
- The size of the population is very large
- The population is stable (constant population size)
- There is homogeneous mixing in the population (each individual has a homogeneous probability of contact with any other individual in the population)

Relaxing the assumptions of the simple SIR model with demography: more complex situations

Relaxing the assumptions of the SIR model with demography

- The disease incurs additional mortality (high virulence).
  - The transmission rate required for the endemic equilibrium to be possible increases

- Immunity is not life-long (waning immunity)
  - Conditions for the existence of an endemic equilibrium do not change
  - However, the equilibrium is reached faster and the spillover capacity (the proportion if infectious individuals at the endemic equilibrium) increases

- The influx of susceptibles through births is seasonal (pulsed birth)
  - The equilibrium state is no longer a constant composition
  - Annual or even multi-annual cycles can occur
  - This can lead to extinction of the pathogen

Relaxing the assumptions of the SIR model with demography

- The size of the population is small
  - The epidemiological processes are stochastic processes
  - When population size is small, chance has a stronger influence on the dynamics
  - In small populations, extinction of the pathogen can occur by chance even when the epidemiological parameters would allow long term persistence in a large population
  - This leads to the concept of **Critical Community Size**, which is the smallest population size observed not to suffer disease extinction

Relaxing the assumptions of the SIR model with demography

- Contacts in the population are structured (not homogeneous).
  - This can lead to increased rates of local extinctions but not necessarily of global extinction (rescue effect)

- The disease is vector-borne
  - The conditions for long-term persistence now also depends on the population dynamics of the vector.
  - If the vector has a strongly seasonal dynamic, transmission can be highly reduced during specific seasons
  - However, the pathogen can also persist in the vector population through vertical transmission

Conclusion

Is the maintenance/reservoir status a characteristic of a species or of a population ?

- Characteristics of the **host species** regarding interactions with the pathogen are important (susceptibility, duration of the infectious period, etc…) The Species
- But **population** size is also an important determinant
  - Through its influence on the probability of pathogen extinction
- As well as population density
  - $\beta = -\kappa \log(1 - c)$
    - κ is the number of contacts of an individuals with other invdividuals over a time unit
    - c is the probability of successful disease transmission during a contact
- And contact structure

It is a characteristic not only of the host species but also of the population, and host populations **communities**

Characteristic of a maintenance/reservoir species/population

- Large population
- High susceptibility
- High infectivity
- Long infectious period
- No additional mortality (co-adaptation)
- High enough demographic turnover
- Frequent inter-individual interactions (contacts)
- Waning immunity