Modelling infection dynamics

Miss: what is this R-number we hear about all the time?

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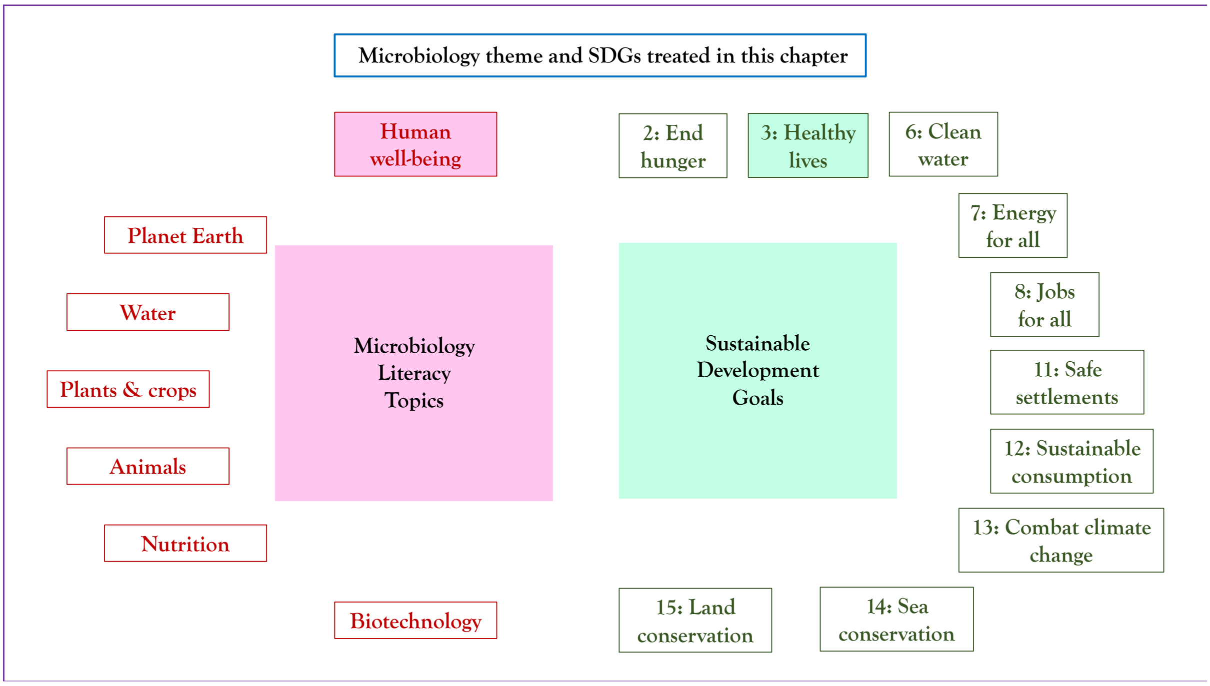
Storyline

Epidemics and pandemics of infectious diseases represent a serious burden for health systems worldwide and some, like COVID-19 and AIDS, can even cause significant temporary or permanent disruption of the 'normal' functioning of modern societies. In some ways, our current lifestyles have, made the spread of infections easier, e.g. through rapid movement of people across the globe and high population densities in cities. Fortunately, scientists have extensively studied how epidemics of infectious diseases move through populations. Mathematical models of disease dynamics help monitor ongoing epidemics, predict their progression, and can inform on effective actions to slow down or stop them.

The Microbiology and Societal Context

The microbiology: epidemics-pandemics; infection transmission; epidemiological models; reproduction number R_0; public health measures. *Sustainability issues:* health.



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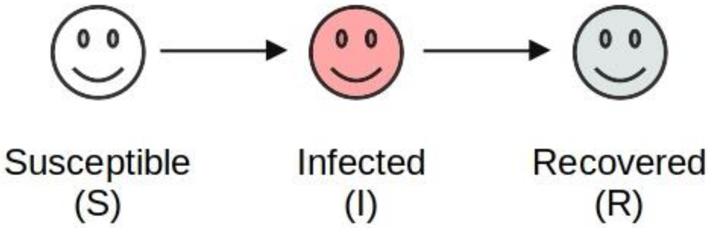
1. ***Epidemiological models.*** To understand how infections move in human and animal populations, scientists have developed many kinds of mathematical models. Rapidly spreading infections can lead to *epidemics*, where large numbers of individuals can catch the disease within a short time period. Therefore, such mathematical models are also called *epidemiological* models. With these models we can analyse how infectious disease epidemics developed in the past, and predict how they will spread in the future.

2. ***SIR Model.*** How do such models work? Most of the methods used to model infectious diseases are so-called *compartmental models*. In these models, people in the population being studied are divided into "compartments", or groups. In the most common and basic model type, these compartments are called susceptible (S), infected (I), and recovered (R). This type of model is called the "SIR model". People in the S group are *susceptible*, meaning that they are not immune to the disease, and they can become infected. People in the I group have become infected, and they are in the active phase of the disease. They can also infect new people in the susceptible S group, who are not yet infected. This is the way epidemics spread in the population. Everyone who cannot spread or contract the disease will be put in the R group. This includes people who are immune to the disease if they have recovered from it, have been vaccinated against it, or died.



Susceptible (S) - Infected (I) - Recovered (R), or "SIR" model of infection.

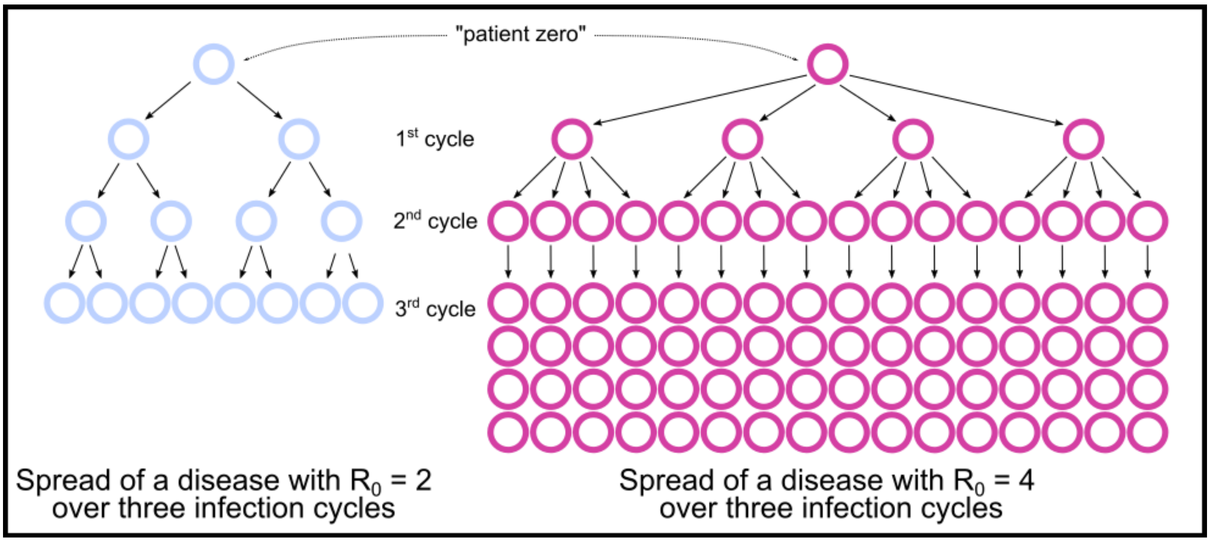
During the epidemic, the number of people in each group changes over time. In the beginning, most people are in the S group, because they did not yet become infected but are susceptible. There is, however, a small number of infected people with the disease, who are in the I group. Initially no one has recovered from the disease, and the R group is empty. As the epidemic spreads, new people in the S group contract the disease from people in the I group. When they are infected, they move from S to the I group. People in the I group will gradually recover from the disease and move from the I group to the R group.

This model describes quite well how an epidemic moves through a population. An epidemic can even start from just a single infected person, then proceed to many people being sick, and finally end up with the disease disappearing completely! Many variables affect how fast people move from S to I to R, that is: how fast the epidemic proceeds. For instance, how easily people get infected, how long they remain sick, or how easily they spread the disease to others. Every epidemic is different in this sense.

3. ***Model fitting and predicting.*** To understand real epidemics, we need to *fit* the mathematical model to measured observations in the given epidemic so that it best describes the progress of the epidemic. Model fitting is often done already at an early stage of the epidemic, because after fitting a model, scientists can use it to obtain important new estimates and predictions. These can for instance inform the scientists, public health officials and government on how the epidemic will proceed, or how it might be slowed down. However, many different variables influence the epidemic in the real world, and accurate predictions can be hard to make.

4. ***The basic reproduction number R_0.*** One important detail which can be estimated from an SIR model is the "R_0" number. This tells us how many new people are infected *on average* by one infected person in a completely susceptible population. If this number, R_0, is very high, the epidemic can proceed very quickly to infect many people at the same time. If we compare two diseases, we can see that after three infection cycles, a disease with $R_0 = 2$ results in a total of 15 people infected, whereas a disease with $R_0 = 4$ leads to 85 infected! This can have catastrophic

consequences if the disease causes people to fall seriously ill, because people will miss work and must be treated in hospitals, which can become overloaded.



The number of infected persons after several infection cycles depends on the basic reproduction number, or R_0 of the disease. In a susceptible population, a disease with R_0 of 2 will result in 15, and a disease with R_0 of 4 with 85 infected individuals, within the same time from the beginning of the disease. With small improvements in hygienic conditions, such as by hand washing, we can sometimes bring down R_0 and dramatically slow down the spread, but the details are different in every epidemic.

5. ***The R_0 number depends on many factors.*** These include how many contacts people have with one other (for example, at a football game like the one above), how long a person remains infective, and how probable it is that one person transmits the infection to another during a contact. These stem from both the biology of the disease, and the habits of the population, like how often people tend to see each other, and how close the contacts are that they have. For example, an infection might spread slower if people tend to greet each other from a short distance than if cheek kissing or hugging as a greeting is the social norm.

The spread of an epidemic can only get worse if the R_0 number is higher than 1. If it is lower than 1, people recover faster than the disease spreads, and the epidemic fizzles out on its own.

6. ***Public health measures and changes in personal behaviour can affect R_0: the R_t number.*** If an emerging disease has a high R_0 number and causes a serious illness, it can be dangerous, and the people can be instructed to undertake protective measures. These measures will reduce the "R_t", which is the effective reproduction number with the control measures in place. This can and should be followed by constructing models during the epidemic and with different control measures in place. Fortunately, similarly to R_0, if R_t is below 1, the epidemic will stop spreading!

7. ***Protective measures depend on the disease.*** The basic infectiousness and infective periods of diseases which affect the R_0 differ greatly depending on their biology, which we cannot change. This also affects the effectiveness of different protective measures, and subsequently, R_t. For these reasons, it is very important to know the biology of the disease.

One main factor is the infectious dose, which means how many virus particles or bacteria are needed to infect a person. This can range from one to several millions.

Similarly, it is important to know if the disease spreads through the air, or only through prolonged physical contact. For example, a disease with a low infectious dose which spreads through the air can be very hard to contain, while a disease which has a high infectious dose and spreads mostly through contaminated food or water can be easy to control.

Many things are now known which affect the infectivity and thus the needed protective measures. For example, the infectivity of a disease is higher if it is spread by an infected individual through just breathing or coughing. It is much harder to contract a disease which is only present in an organ or in the blood of an infected person.

Also, the persistence of the disease in the environment can be important. It is easier for many people to contract a disease which stays on surfaces, like door handles or toilet seats, for a long time and spreads through this contact.

Because of the many biological differences between diseases, it is important to study which preventive measures are effective in controlling the spread of a specific disease. For example, social distancing and mask wearing are known to be effective against COVID-19.

Finally, another way to reduce the infectivity of a disease is by vaccinations against the disease, which reduce the number of people susceptible to it. When viewed through modelling, also vaccinations eventually act through lowering the R_t!

Relevance for Sustainable Development Goals and Grand Challenges

Goal 3. Ensure healthy lives and promote well-being for all at all ages (*improve health, reduce preventable disease and premature deaths).* Infectious diseases are a major cause of global morbidity and mortality, so public health agencies are continuously monitoring national and international infections to be able to influence their epidemiology and minimize disease. This is particularly true of new epidemics and pandemics, which are unpredictable. A key tool in this effort is infection dynamics modelling which can provide important predictions on disease evolution in the population, with and without specific measures to reduce transmission.

Pupil Participation

1. ***Class discussion of the utility of modelling infections***

2. ***Exercises***
    a. Consider which disease is potentially more easily spread: one that spreads through contact with saliva, or one that spreads through contact with blood? Justify your answer.
    b. Give examples about efficient ways to mitigate the spread of an infectious disease in the population. Which of them is the most/least effective? Why?
    c. Explain in your own words how the susceptible-infected-recovered (SIR) model works.
    d. Why is the basic reproduction number R_0 so important when we study epidemics?