Crises arising from global connectivity

Daddy: How did this plastic bag end up in the middle of the ocean? Well, Darling, some things we do have global impacts.

Paulo Oliveira/Alamy Stock Photo, https://www.nationalgeographic.org/article/travel-restrictions/

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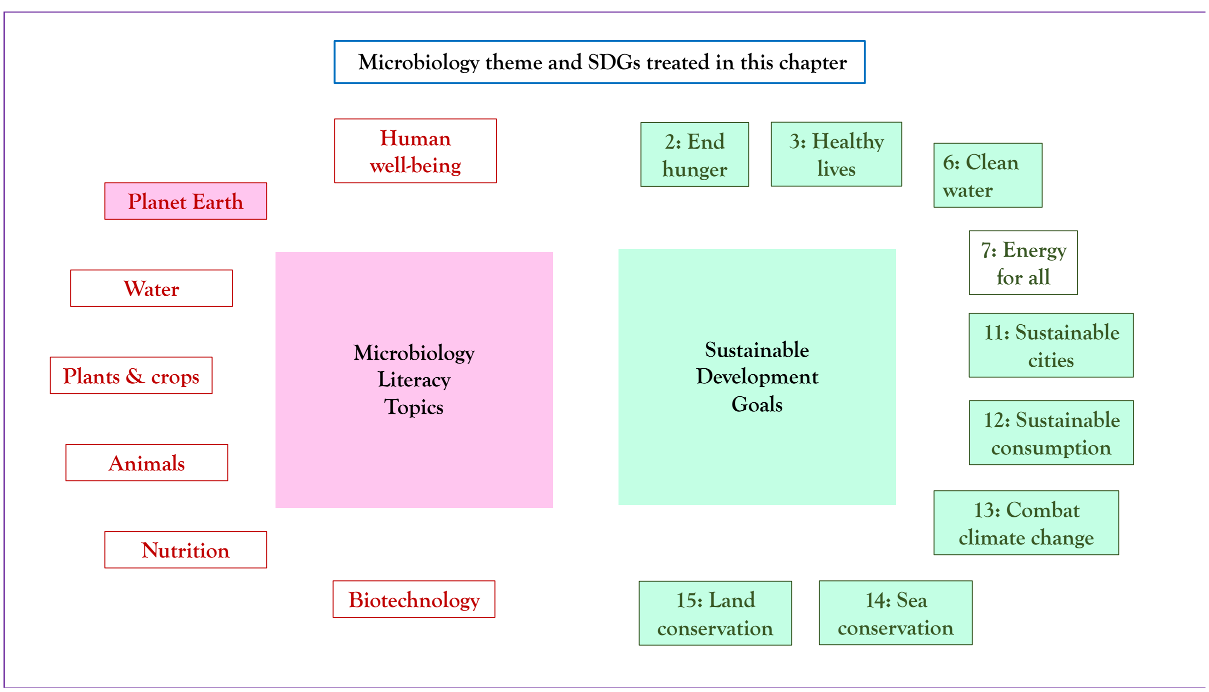
The global connectivity issue

Storyline

We live in an interconnected environment where species form complex networks of interactions (competition, predation, mutualism, parasitism) with other species (plants and animals) and their environment (soil, water, host) that shape local biodiversity and drive ecosystem functioning and services. Any disruption of these networks (loss of species, introduction of invasive species, degradation of habitat) can have direct local impacts, some of which contribute to global scale changes. Among these networks, microbes – including viruses – can play a tremendous role, given their capabilities to disperse over large distances and thrive in a range of regions, habitats or hosts. The connectivity of and with microbial networks can sometimes be beneficial to help an individual or an ecosystem to respond to perturbation, or be harmful causing important ecosystem, health or economic issues. For instance, the explanation for what happens to a lake that experiences degradation of water quality and occurrence of cyanobacteria blooms is often found outside of its own boundaries, namely, manure and nutrients applied in farmlands which are exported to freshwater ecosystems. The connectivity among microbial networks and their environment has therefore multiple consequences for Sustainable Development Goals.

The Microbiology and Societal Context

The microbiology: infections and pandemic; vaccination; pollution; eutrophication and toxic algal blooms; invasive species, greenhouse gas production. *Sustainability issues*: health, food, economy and employment; environmental pollution; global warming.



Crises arising from global connectivity: The microbiology

1. ***Local activities, global impacts: long-range transport of pollutants.*** Human activities, such as industries, are well known for their adverse impact on ecosystem health. For example, mining has a direct impact on the landscape structure and can also impair water quality of nearby streams, rivers and lakes. Traditionally, remote regions like the Arctic have been considered to be pristine, where direct anthropogenic activities are limited (although ongoing economic development of the North may change this perspective). During the last few decades, however, evidence has been accumulating of high concentrations of industrial pollutants in high latitude regions. What kind of pollutants and where do they come from? One of the most widespread pollutants in the North are the persistent organic pollutants (POPs, which include polychlorinated biphenyls – PCBs) used for instance in plastic bottles. POPs are by definition resistant to degradation and are therefore easily maintained in the atmosphere and re-deposited in areas like the Arctic, far from where they were first used or emitted. Given their refractory nature, they can persist in the environment and be bioaccumulated through the trophic food chain from algae to fishes and marine mammals. This explains why high concentrations of PCBs have been measured in polar bears and seals. This is of great concern as this represents a threat to the health of northern native communities who, according to their traditional culture, heavily rely on seasonal hunting of marine mammals and fishing.

2. ***Local activities, global impacts: plastic pollution.*** During the last three decades, the intensive use of plastics for packaging (e.g. food), transportation, industry and agriculture, has become one of the most serious threats to the environment and to the global ocean in particular. Predictive models estimate the total floating plastic debris on the surface of the ocean to be at least 5.25 trillion particles weighing 268,940 tons. In particular, small pieces of plastic, called "microplastics" (<5 mm), in marine systems may cover 4.2 million km^2 of the sea surface. The main source of plastics found in the Ocean originate from mismanaged wastes inland that enter the ocean via inland waterways, wastewater outflows, and transport by wind or tides. The manifold effects of plastic on the marine environment are deleterious: their degradation by weathering can release toxic compounds into the water and contribute to the release of greenhouse gas to the atmosphere, they entangle and are ingested by wildlife, as shown in the image above, and they transport invasive and potentially harmful species (e.g. microalga *Ostreopsis*) as well as pathogens (e.g. *Vibrio*) that colonize plastic surfaces (aka '*Plastisphere*'). Given their light weight and recalcitrant nature to degradation (despite the fact that some microbes show capabilities to degrade different types of polymers), they can remain for a long time in the ocean and are easily transported over long distances.

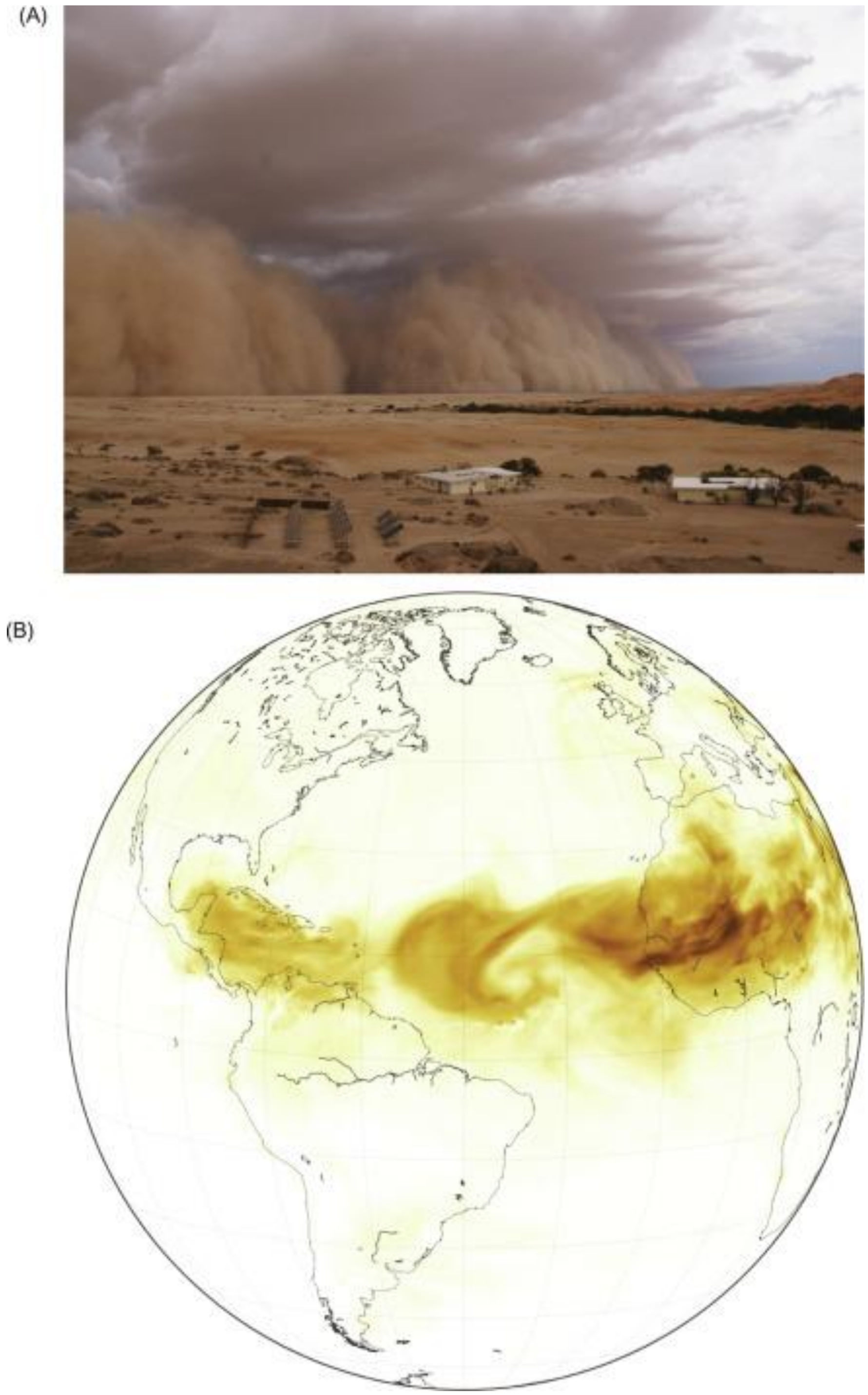


Figure 1: An example of dust storm and its long-range dispersal, source: Landcaster and Mountney (2021)

3. ***Long-range transport of microbes: aerosols.*** Because of their small size and large numbers, microbes (bacteria, archaea, fungi, viruses) can be easily dispersed over long distances. Strong winds on arid lands like deserts result in 'dust storms' that create airborne dust particles carrying attached microorganisms along with bound organic and inorganic

nutrients (Fig.1). In addition, ocean sprays jettison microbes into the air within water droplets. Microbes thus ejected from their original soil or water compartment environments into the air compartment then become subject to wind dispersal. Despite harsh environmental conditions in the atmosphere, like UV exposure, cold temperature and desiccation, some microbes persist (aka airborne microbes or bioaerosols). For example, it has been shown that Saharan- and north African-derived dust aerosols, which are responsible for more than half of the world's aerosol load, can by their deposition impact high-mountain lake microbial assemblages in Spain. Once deposited in a new environment, microbes face challenges: they have to adapt to new habitat conditions, compete with an already well established community, and resources may not be optimal for their growth, especially for viruses that need suitable hosts. The long-range dispersal of microbes and their deposition to new ecosystems should not necessarily be compared to the introduction of invasive species, but rather to a seed bank of organisms that enrich diversity and may help ecosystems respond to future environmental perturbations.

4. ***Natural connectivity among ecosystems.*** In 1887, Stephen Alfred Forbes published his famous piece "lakes as microcosms" that states among other things that aquatic biota are somehow independent of the land around them. More than a century later, there is clear evidence that terrestrial and aquatic ecosystems are in fact highly connected with high rates of transfer of both matter and organisms, including microbes. For example, at the scale of a watershed, it is now well documented that a fraction of a lake's microbiome has a terrestrial origin with streams and rivers being both the main connecting corridors and additional sources of diversity for downstream aquatic ecosystems. Other studies have shown that snow can represent an important source of diversity for Arctic lakes, which has important implications for the structure and functioning of these snow-fed northern waterbodies in the context of global warming, as snow cover is expected to change in the future. In the global ocean, *Pelagibacter ubique,* an Alphaproteobacteria member of the *SAR11* clade, is a marine cosmopolitan bacterium present in all marine water bodies that are all connected to each other by marine currents and gyres.

5. ***Animals as agents of connectivity: vectors of microbes.*** In addition to being dispersed by aerosols, microbes can be carried by animals (zoochory) and birds, in particular those that can fly over long distances during seasonal migration. Hence, microorganisms can live in or on birds and can travel along with them. The best known examples are infectious diseases, such as avian influenza, but other microorganisms can be dispersed in association with other propagules dispersed by birds, including parasites (swimmer's itch), viruses and bacteria associated with ectoparasites such as Lyme disease in ticks. Another example is that flamingos can directly impact aquatic ecosystems by resuspending nutrients from the sediments, and by fertilising with guano, both of which stimulate microbial growth.

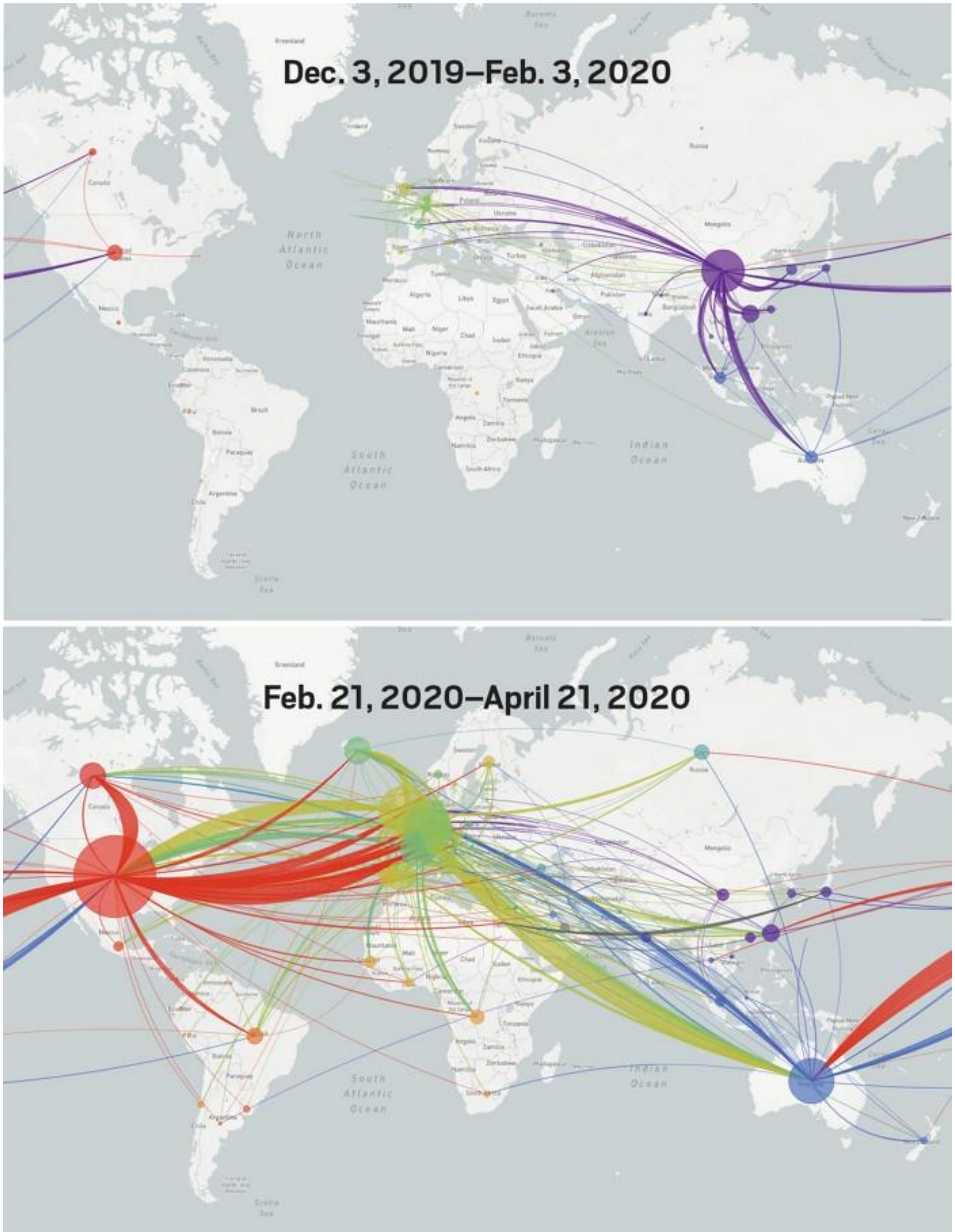


Figure 2: Spread of the COVID-19 pandemic. From a single location (Wuhan, China), the infection spreads rapidly (upper panel). Within a few weeks the pandemic has developed globally and new variants are being detected (colour code on figure) as the virus continues to disperse (lower panel). Epidemiologists investigate the phylogeny and evolution of viruses to identify their origins and routes of dispersal. Nextstrain allows following the genomic epidemiology of SARS-CoV-2 (Source: NextStrain.org)

6. ***Humans as agents of connectivity: vectors of microbes.*** The ongoing pandemic of COVID-19 is probably the most dramatic but also the most effective way of illustrating human-induced global connectivity. A local infection in Wuhan, China, spread quickly across the city, the country, and then the rest of the world within a few months (Fig. 2), causing the death of more than 1 million people and many billions of dollars of economic loss. The main reasons for the rapid spread of the virus are the massive movement of people when traveling by ground, plane or boat, and the high densities, and hence close proximities, among individuals that facilitate transfer and transmission of the virus. Human activities can also promote the dispersal of pathogens such as *Legionella* by the built environment (cooling systems, spas, fountains). Besides pathogens, humans can transport invading species including fishes and arthropods, but also microbes, through sea freight. Ballast water is considered an important vector for invasive species, such as harmful algae, bacterial pathogens, and viruses, which has led to the development of treatment procedures of ballast waters (separation and filtration; ozone, electrical currents, UV radiation, chlorination).

7. ***Connectivity between climate and microbes***. The circumpolar North is experiencing severe pressure on its structure and functioning as a result of climate change. Changes in climate can impact northern microbial assemblages by the release of previously frozen cells in permafrost to streams and lakes or by selecting taxa able to cope with changes in their habitat (e.g. temperature, nutrient regimes). Hence cold-adapted taxa may be pushed toward extinction as climate continues to warm. In contrast, warming temperatures may favor the establishment of others, like cyanobacteria, that are conspicuously absent from the phytoplankton of most northern lakes. Microbes can also impact on climate. The thawing of permafrost has led to the increase in numbers and size of thermokarst ponds and lakes that are net emitters of greenhouse gases to the atmosphere. Thawing permafrost releases carbon that was trapped for millenia and now becomes available for microbial degradation. The unique physico-chemical structure of these small waterbodies makes them biogeochemical hotspots with high levels of methane production by methanogens, and methane consumption by methanotrophs. At the global scale, the balance between these two fundamental microbial processes mediate the greenhouse effect and warming, which may in turn accelerate the thawing of permafrost.

8. ***Global spread of antibiotic resistance.*** Antibiotics are used to treat infections caused by microbes. The use of antibiotics has increased during the last decades with the development of modern medicine. Although saving lives, antibiotics can select the development of resistance by microbes they are supposed to eliminate. Antibiotics are excreted unaltered in faeces and urine. Waste from food animal farms, hospitals and municipalities are therefore major sources of both antibiotic resistant microbes and antibiotic pollution in the environment. Once antibiotic resistance emerges, it can spread into new settings and disperse over long distances with humans and goods. Migratory birds are also particularly effective at spreading resistant microbes over long distances. Resistant microbes can share their resistance genes with others by horizontal gene transfer of genetic materials, like plasmids. Thus: while the resistant microbes transferred to new locations may

find habitat conditions that are not conducive to propagation, they can transfer their resistances to indigenous microbes which will propagate them.

Relevance for Sustainable Development Goals and Grand Challenges

The microbial dimension of our globally-connected world relates to several SDGs (*microbial aspects in italics*), including:

- **Goal 2. End hunger, achieve food security and improve sustainable agriculture** *(end hunger and malnutrition, increase agricultural productivity).* The production and export of vast ranges of goods and foods are central to the global economy and contribute to meet the nutritious needs of the world's population. The parallel transportation of exotic microbes and pathogens may harm local cultures and human communities. Hence, improved agricultural practices and sanitation during transport of goods is essential to limit the risks of outbreak of foodborne illness such as the 2011 *E. coli* outbreak in Germany that caused the death of 53 people and the infection of over 3000 people affected in many countries.

- **Goal 3. Ensure healthy lives and promote well-being for all at all ages** *(improve health, reduce preventable disease and premature deaths).* Living in the human body are trillions of microbes, collectively known as the microbiota, scattered across our organs. In the gut, microbes help with the degradation and absorption of nutritious components we eat and protect us against pathogens. The diet may influence the gut microbial communities and there is no doubt that a diverse and healthy diet will favour the presence of beneficial microbes, which in turn should reduce the risk of developing illness and the cost of health budgets. Microbes can be used as pest controls to reduce the health risks and costs of animal vectors that transmit human infections. For instance, the application of a naturally occurring bacterium found in soils (*Bacillus thuringiensis subspecies israelensis,* BTI) to control mosquitoes may reduce the spread of the West Nile Virus disease across different regions of the world.

- **Goal 6. Ensure availability and sustainable management of water and sanitation for all** *(assure safe drinking water, improve water quality, reduce pollution, protect water-related ecosystems, improve water and sanitation management).* Streams, rivers, lakes, and freshwaters in general provide essential drinking water resources for human populations. These waters are connected to the land and to other water bodies, which may become polluted by high inputs of nutrients causing harmful microbial blooms or by faecal coliforms and other pathogens from wastewaters. As such, any action (e.g., sanitation, filtration, purification processes) preventing the release and spread of water pollutants downstream will help protect drinking water supplies and the general condition of aquatic systems, reducing health costs and improving ecosystem and economic (fisheries, recreational use) productivity.

- **Goal 11. Healthy Environments** *(protect water-related ecosystems, improve ecosystem productivity, promote economic growth).* The chemical, microbial as well as the physical world determine the quality of the environments in which we live. The connectivity between land and water, and between aquatic systems, influences all three aspects that shape healthy environments. The release and hydrological transport of water pollutants influence not only the local environment, but may also alter the functioning of remote aquatic ecosystems and the benefits they provide to humankind. Such benefits include productive fisheries, safe access to drinking water, recreational activities, and ultimately an infection-minimal life.

- **Goal 12. Ensure sustainable consumption and production patterns** *(achieve sustainable production and use/consumption practices, reduce waste production/pollutant release into the environment, attain zero waste lifecycles, inform people about sustainable development practices).* The long-distance transport of goods and food requires a tremendous amount of energy and unsustainable natural resources, such as oil, and facilitates the spread of viruses and bacteria around the globe. Producing and buying locally will dampen these effects. Reducing meat production and consumption, which relies heavily on nutrient-demanding crops such as corn and soy, decreases the propagation of harmful cyanobacterial blooms and improves water quality.

- **Goal 13. Take urgent action to combat climate change and its impacts** *(reduce greenhouse gas emissions, mitigate consequences of global warming, develop early warning systems for global warming consequences, improve education about greenhouse gas production and global warming).* Industries, transportation, and farming release greenhouse gases to the atmosphere, and due to global air circulation, cause increases in temperature in far distant regions, such as the Arctic. The thawing of Arctic permafrost exposes old carbon stocks to microbial degradation. By converting soil carbon into carbon dioxide and methane, microbes further contribute to the production of greenhouse gases and act as a positive feedback loop on climate. This feedback loop may then accelerate the rise in temperature and cause serious threats to human populations via heat waves, flooding, and decreased water availability.

- **Goal 14. Sea conservation** *(protect marine ecosystems, reduce pollution, prevent biodiversity loss).* The global ocean is experiencing drastic changes in its structure and functioning as a result of climate change and human activities. The melting of glaciers and ice shelves in polar regions represent a threat to several coastal cities and villages as well as offering new routes of navigation for commercial and tourist industries (North-West passage in the Arctic Ocean) in fragile ecosystems. Non-sustainable fisheries practices, oil and gas extraction platforms, mining of the sea bed for minerals, commercial and tourist transport, and mismanaged plastic wastes, further add pressure on marine ecosystems that lead to biodiversity erosion (e.g. coral bleaching, decrease in marine mammal populations). The creation of protected marine areas, better practises in fisheries and industries, combined with reduced use of plastics, are management plans that as a whole can impact on the health of the global ocean.

- **Goal 15. Land conservation** *(protect terrestrial ecosystems, reduce pollution, increase ecosystem productivity, prevent biodiversity loss).* The conversion of forested to agricultural land and urban areas is a primary factor leading to biodiversity erosion and environmental pollution both on land, and because of the soil-water connectivity, in water ecosystems as well. Habitat loss, excess nutrients and use of pesticides in modern agriculture are associated with shifts in land use around the globe. The conservation of natural forests and grasslands, better agricultural practices (e.g., reduced fertilizers and pesticides utilization, addition of physical barriers preventing soil erosion, growing leguminous plants) and reduction in impermeable surfaces in cities are conservation actions in watersheds that have an immediate impact on water quality, algal blooms and pathogens transport.

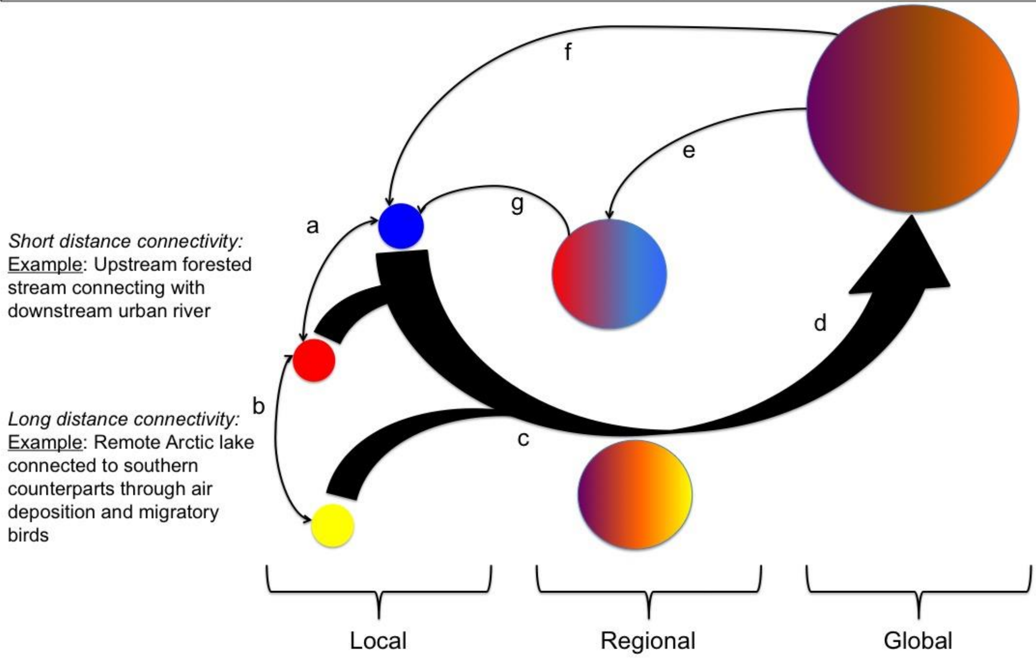
Potential Implications for Decisions

1. ***Local scale***
    a. Ensuring safe drinking water supplies
    b. Implementation of better agricultural practices and urban development strategies
    c. Installation/renovation/improvement of waste water treatment plans
    d. Contamination assessment by faecal coliforms in public beaches
    e. Ban on use of plastics (bags, bottles)

2. **Regional-National scale**
    a. Pollution of inter-connected, downstream water bodies
    b. Coordinated regional and national regulations of environmental and microbial pollution across the land to water interface
    c. Health costs associated with polluted waters
    d. Improved disposal strategies of plastic wastes

3. **Global scale**
    a. Greenhouse gases production and global warming
    b. Improve pandemic surveillance and decision making
    c. Long-distance food and goods transport and traceability
    d. International traveling and tourism as vectors of pathogens transport

Box 2: Connectivity shapes microbial and pollutant dispersal from local to global scales



Microbial assemblages and chemicals can be transported from the local (city, farm, individual) to the regional (suburban area, watershed, neighborhood) (c) and global (intercontinental transport) by waterways, land corridors and oceanic currents, air deposition respectively (d). Individual systems are not isolated at the local scale and therefore are connected to one another by short (a) and long (b) range distance processes. Global processes (greenhouse gas production and global warming) can in turn impact systems at the local (e.g. enhanced thermal stratification in lakes with anoxia in bottoms layers, f) and regional scales (e.g. changes in hydrologic regimes, e). Changes at the regional scales can also have direct impact at the local scales (g) with for example, an increase in fecal pollution and cyanobacteria blooms following important changes in land-use.

Pupil participation

1. Class discussion of the issues associated with microbial transfer (e.g. pandemic) and connectivity between human activities and ecosystems health

2. Pupil reflection on their connectivity with their environment

a. What is your opinion about microbes? Are they just harmful or do you think of anything microbes can help with important challenges the society is facing (e.g. pandemic, climate change)?

b. Can you think of anything that might be done to reduce the occurrence of microbial infection outbreaks in the future?

c. Can you think of anything you might personally do to reduce your environmental footprint and the dispersal of microbes?

3. Exercises and experiments

a. Estimate the CO_2 emission related to your daily travel.

The evidence base, further reading and teaching aids

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Glossary

Agricultural land: Land area that is either arable, under permanent crops, or under permanent pastures.
Antibiotic-resistant microbes: Microbes that evolve mechanisms that protect them from the effects of antimicrobials such as antibiotics for bacteria.
Antibiotics: Drugs that kill or reduce the growth of bacteria that cause infection.
Arctic: There are several definitions of the Arctic. One of the most common ones is from the North Pole to the Arctic Circle at 66.6°N. Another definition is from the North Pole to the southern limit of permafrost.
Bioaerosols: Airborne particles consisting of living organisms such as bacteria, fungi and viruses or originating from living organisms, such as metabolites, toxins or fragments of microorganisms.
Blooms: Rapid excessive growth of cyanobacteria or algae in freshwater or marine water systems, and is often associated with the discoloration in the water.
Carbon dioxide: A greenhouse gas that has several origins, some natural (e.g. respiration) and some anthropogenic (burning of fossil fuel). It is known as one of the main contributors to climate change but also at the base of a fundamental biological process: photosynthesis.
Connectivity: Degree to which the landscape facilitates or reduces movement of particles and organisms between habitats.
Disease control: Reducing the number of new infections, the number of people currently infected, and the number of people who become sick or die from a disease in local settings
Disease transmission: Means by which contagious, pathogenic microorganisms are spread from one person to another.
Environmental footprint: Environment necessary to produce the goods and services necessary to support a particular lifestyle
Eutrophication: Process in which a water body becomes enriched with nutrients (phosphorus, nitrogen), which alters its physical and chemical structure and results in the occurrence of plant and algal blooms.
Fertilizers: Any natural or artificial substance containing the chemical elements that improve growth and productiveness of plants.
Fecal coliforms: Group of bacteria that are passed through the fecal excrement of humans, livestock and wildlife.

Greenhouse gas: Gases that allow the sun's rays to pass through and warm the earth by trapping the sun's heat, but prevent this warmth from escaping our atmosphere, which results in an increase in global temperature.
Infections: The invasion and multiplication of microorganisms such as bacteria, viruses, and parasites that are not normally present within the body.
Lake: Body of water that is surrounded by land. Although lakes are globally distributed, they vary in size, in their origins as well as in their main characteristics including salinity, pH, depth, mixing regime.
Methane: A greenhouse gas that has several origins, some natural (metabolism of some Archaea under anoxic condition, i.e without oxygen) and some anthropogenic (oil and gas drilling).
Microbiote/microbiome: The **microbiome** refers to the collection of genomes from all the microorganisms in the environment. **Microbiota**, on the other hand, usually refers to specific microorganisms that are found within a specific environment.
Pathogen: any disease-causing organism, for example certain viruses, bacteria, protozoa, fungi, algae, worms, etc.
Pandemic: An disease outbreak that spread over a very wide area (i.e. across countries and continents) and that affect many organisms.
Permafrost: Soil that remains frozen (temperature below 0°C) for at least two consecutive years.
Pesticides: A chemical used to control, repel, or destroy pests of any sort.
Plasmids: Small, circular molecules of DNA that are physically separate from, and can replicate independently of, chromosomal DNA within a cell.
Plastics/Plastisphere: Microplastics refer to small pieces of plastic smaller than 5 microns. Microbial consortia colonizing their surfaces and eventually contributing to their degradation are known as plastisphere.
Pollution: Introduction of contaminants into the environment that cause adverse change in ecosystem structure an functioning and have implications for ecosystem and human health.
Ponds: Inland bodies of standing water that are smaller and shallower than lakes.
River: A directional natural flowing watercourse from headwater (underground source, snowmelt, glacier) downstream (a sea or an ocean).
Salmonellosis: Infection with a bacteria called Salmonella, Salmonella live in the intestinal tracts of animals, including birds.
Sanitation: The development and application of sanitary measures for the sake of cleanliness and protecting health.
Streams: A flowing body of water that is smaller than a river and which connect to a river.
Wastewater treatment plant: Facility in which a combination of various processes (e.g., physical, chemical and biological) are used to treat industrial wastewater and remove pollutants.
Watershed: Land area that channels rainfall and snowmelt to creeks, streams, and rivers, and eventually to outflow points such as reservoirs, bays, and the ocean.