Global dispersal of fungal pathogens of plants[1]

Granny: what are those funny blotches on the geranium leaves?

Robert F. Park

The University of Sydney, Plant Breeding Institute, School of Life and Environmental Sciences, Faculty of Science, Sydney, Australia

[1] *"Lo que separa la civilización de la anarquía son solo siete comidas"*
"Civilisation and anarchy are only seven meals apart" – Spanish proverb

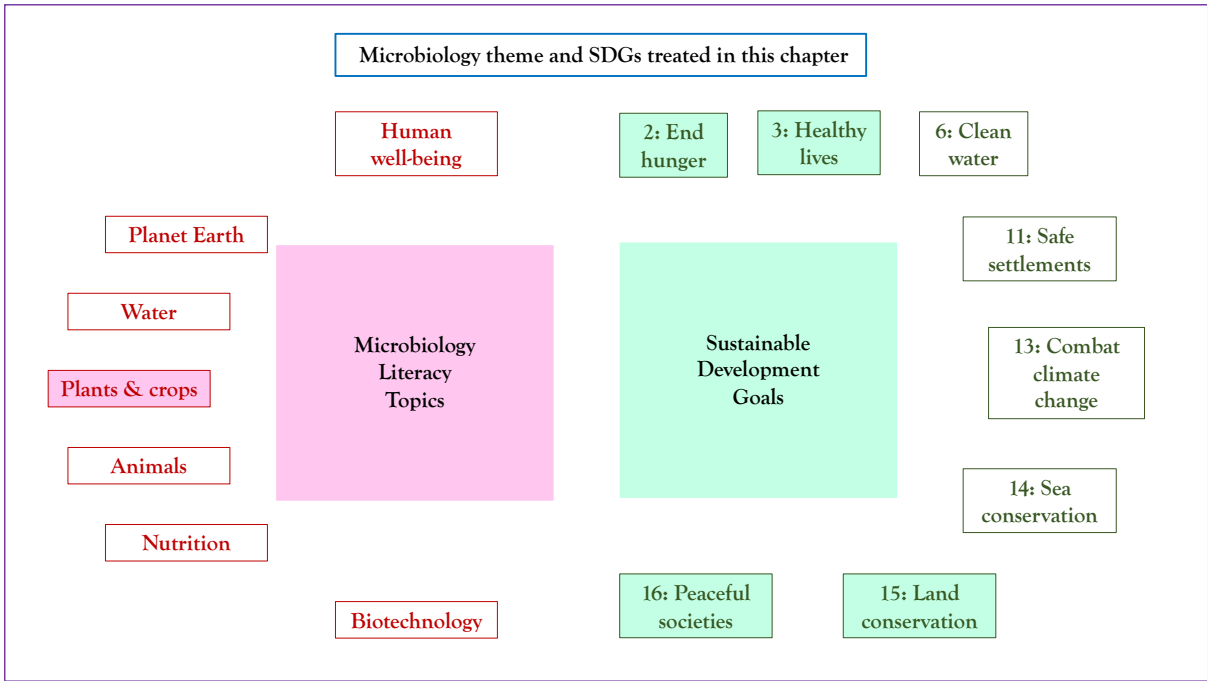
Global dispersal of fungal pathogens of plants

Storyline

Plants are the basis of all life on earth - the wellbeing of all humans is entirely dependent on them. Since the dawn of humanity, plants have provided all of the essential things we need to survive: clean air, clean water, food, clothing, and shelter from the elements. They have also provided important medicines used to prevent and treat illnesses. Most people in the developed world buy their food from shops, or plant products like timber from a hardware store, with very little idea of how they are produced or the factors that threaten their production. Just like animals (including of course humans), plants are attacked by pathogenic microbes such as viruses, bacteria, oomycetes and fungi. One of the most graphic historical accounts of the impact of a pathogen on crop production is that of the Irish potato famine (1846 to 1850), precipitated by the destruction of potato crops by late blight, caused by the oomycete *Phytophthora infestans*. The net result of the famine was about one million deaths from starvation and the emigration of more than one million people. The suffering experienced and the resulting upheaval caused by this plant pathogen defy imagination.

The Microbiology and Societal Context

The microbiology: The most damaging diseases of plants are caused by microscopic fungi. Fungi are not plants or animals – they occupy a Kingdom of their own and are in fact more closely related to animals than they are to plants. It has been estimated about 98% of the estimated 2.8 to 3.8 million species of fungi remain unknown to science. To put this into context, based on the current rate of discovery, it will take at least another 2,840 years to discover all fungal species on Earth. Fungi are abundant across the world, and in general are not visible due to their small size. Some have evolved to become pathogens; the most important fungal pathogens of plants belong to the same phyla as the mushrooms ("Basidiomycetes") or the yeasts ("Ascomycetes").
Impact in food production: The microbes that attack plants reduce global plant production by a conservative 10%. In agriculture and in forestry, they not only reduce yield but also add to the cost of production by necessitating the use of pesticides such as fungicides, which also results in environmental contamination and increased carbon emissions due to the operation of spray rigs etc. Plant pathogens have had huge impact in urban landscapes and native ecosystems, even contributing to the extinction of some plant species. Some of the most devastating plant disease epidemics have resulted from the movement of fungal plant pathogens from one part of the world to another. In some cases, a pathogen of a given plant species has moved to an area that was previously free of the pathogen, in other cases plant pathogens have unexpectedly attacked plant species that were not known to be vulnerable ("new encounter" diseases).
Sustainability issues: Diseases of plants can be controlled by cultural practices (e.g. cultivation (practiced much less these days so as to conserve soil and soil moisture), crop rotation, genetics (e.g. plant breeding, genetic engineering, gene editing), or pesticides. The use of fungicides in agriculture has resulted in the emergence of fungal variants with resistance to fungicides; this has included non-target fungi that live in the soil and can infect humans with weakened immune systems. This has led to very high mortality rates in humans because the fungicides used to spray crops have the same activity as the same drugs used to treat fungal infections in humans.



Plant Diseases: the Microbiology

1. Pathogenic fungi cause huge losses to agricultural production. Fungal pathogens cause some of the most damaging plant diseases. For example, wheat is the most commonly consumed cereal in the world, with global production of about 600 million tonnes in 2007, and demand predicted to increase by more than 1.5% annually up to 2020. A recent study estimated that diseases reduce global wheat production by 21.5%. Some 31 wheat pests and pathogens were identified as problematic, with just four of these, all fungi, accounting for half of all losses: leaf rust (caused by *Puccinia triticina*), Fusarium head-blight/scab (*Fusarium graminearum*), Septoria tritici blotch (*Zymoseptoria tritici*) and stripe (yellow) rust (*Puccinia striiformis*). To put these losses into perspective, it was estimated in 2015 that global annual losses to the fourth ranked stripe rust were 5.47 million tonnes (US$979 million) – enough to feed ca. 35 million people.

2. Plant pathogenic fungi in native ecosystems. Pathogens and hosts coexist in natural undisturbed ecosystems in such a way that a balance is reached and maintained. This balance is reached after many years of the host and the pathogen coevolving. However, pathogens introduced into ecosystems in which they did not previously exist (see point 4 below), i.e. in which no co-evolution with the host has taken place, can cause significant damage and even lead to the extinction of plant species. A recent example of this is the globally invasive myrtle rust pathogen *Austropuccinia psidii*. This rust pathogen is native to South America, where it caused damage in plantations of eucalypts that had been introduced from Australia in the early 1900s. In 2005, it was detected in Hawaii and since then has spread from the Americas to Asia, the Pacific, and South Africa. It was detected in Australia in 2010 and has since spread throughout native forests in eastern Australia and caused the decline of many myrtaceous species and severe impacts to native plant communities.

There are many fungal pathogens of plants. These images show examples of some of the 7,000 species of rust fungal pathogens that attack plants [A] rust (*Uromyces bidentis*) on the weed Black Jack (*Bidens pilosa*) [B] rust (*Coleosporium plumeriae*) on frangipani (*Plumeria*) [C] rust (*Uromyces eragrostidis*) on teff (*Eragrostis tef*) [D] rust (*Puccinia pelargonii-zonalis*) on geranium (*Pelargonium*) [E] rust (*Phragmidium rubi-idaei*) on raspberry (Rubus) [F] stripe rust (*Puccinia striiformis* f. sp. *tritici*) on wheat (*Triticum aestivum*).

3. The emergence of fungicide resistant plant pathogens and implications for human health. The increased use of fungicides has also resulted in the emergence of pathogen (plant and human) genotypes with insensitivity to the chemicals being used, principally the triazole (Demethylation Inhibitors or DMI, also used in human and veterinary medicine) and Quinone outside Inhibitors (QoI) –based chemistries. This ongoing reduction in the spectrum of pathogens that can be controlled by fungicides makes them less appealing.

Fungal infections kill 1.5-2 million people annually, more than that caused by malaria or tuberculosis. Of concern has been the emergence of plant and human pathogen isolates with insensitivity (resistance) to some classes of fungicide. DMI–insensitive isolates of the human fungal pathogen *Aspergillus* have arisen in many parts of the world, likely as a direct result of fungicide use in agriculture. Because DMIs are used to treat fungal infections in humans, insensitive *Aspergillus* strains now cause some 100,000 human deaths per year. This is a dramatic example of One Health, the integral nature of human health and environmental processes.

4. The spread of plant pathogenic fungi within and between continents. Some of the most graphic and damaging examples of epidemics caused by fungal pathogens of plants result from the movement of these pathogens between continents. Dutch elm disease, caused by the fungus *Ophiostoma nova-ulmi*, was accidentally introduced into Europe in 1967, quite probably via logs imported from Canada. It killed more than 25 million elm trees in the UK and resulted in the loss of 97% of all elm trees in France. Rust diseases, including myrtle rust (see above) are among the most feared of all plant diseases. They produce billions of microscopic rust-coloured spores that can be spread across thousands of kilometres on prevailing winds, making them truly "transboundary" pathogens. Because wheat rust pathogens can kill wheat crops, they have been very carefully monitored in some parts of the world for many years. Continuous monitoring of these pathogen in Australia since 1921 has detected 15 instances in which new wheat rust strains have been introduced onto Australia from overseas. Concerningly, the rate at which these incursions have occurred has increased with time, presumably because more people are travelling, increasing the chance of accidental human-mediated movement of fungal spores. Two strains of the wheat stem rust pathogen that were detected in 1969 are believed to have been transported to Australia across the Indian Ocean on high altitude winds, while strains of the wheat stripe rust pathogen are believed to have been inadvertently introduced on contaminated clothing or personal effects from either Europe, northern Africa, the USA or South America in 1979, 2002, 2017 and 2018. All of these incursions have caused significant economic losses; for example, an estimated AUD$40 to $90 million was spent on fungicides each year in 2003, 2004 and 2005 as a direct result of the 2002 stripe rust incursion.

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 2. Zero hunger: End hunger, achieve food security and improved nutrition and promote sustainable agriculture.** Achieving SDG 2, Zero Hunger, presents significant challenges especially when viewed against the backdrop of an increasing global population, climate change, and the need to minimise the environmental impacts of human activities. The World Health Organisation has estimated that already, about one third of the world's population is well fed, one third underfed, and one third is starving. Plant diseases are a significant contributor to this imbalance, with conservative estimates of global losses to plant diseases in the order of 10%, both from direct loss of yield and also from contamination causing reduced quality and, in some cases, toxins in food and fodder products.
- **Goal 3. Good health and well-being: ensure healthy lives and promote well-being for all at all ages.** Reducing or even eliminating the need for fungicides will result in safer food for consumers, a safer workplace, and a cleaner environment.
- **Goal 15. Life on land: protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**. In 1798, when less than a billion people inhabited the earth, English scholar Thomas Malthus published an essay in which he warned that population growth would outstrip food production until it was checked by famine, war and illness. Today, the world is home to 6.7 billion people - by 2050, it is expected to reach 9.2 billion. Agricultural output will need to have doubled to meet the ensuing demand. Is this achievable, and if so, how? Ongoing concerns about the effects of climate change, soil loss and rising energy costs, mean that providing adequate quantities of safe and healthy food for all is certain to remain an important challenge for humanity. We cannot simply cut down more forests to create more land for agriculture.

Reducing or eliminating the impact of plant attacking fungi is an important part of increasing future agricultural productivity.

- **Goal 16. Peace, justice and strong institutions: promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels**. Food security is essential for political, economic and social stability. Dramatic increases in food prices in 2007–2008 created great angst across the globe. The political and economic instability that followed provide a stark reminder of the importance of food in regional and global stability. The role played by food security in world stability is best exemplified by the 1970 Nobel **Peace** Prize being awarded to Dr Norman Borlaug for his work in tackling hunger. This work, which became known as the "Green Revolution", began in earnest in the late 1960s and involved the development of high yielding cereal cultivars and the adoption of a range of improved agronomic practices. The Green Revolution is credited with saving more human lives than any other initiative in history.

Potential Implications for Decisions

1. ***Individual***
    a. Should I only buy fruit and vegetables with no blemishes at all (this leads to food wastage as vendors have to throw out the food people do not buy)?
    b. Exercise care in washing all personal effects, not just shoes, when returning from overseas, to ensure diseases are not accidentally brought into the country.
    c. Do not bring plant seeds or parts back from another country after international travel, because these can harbour dangerous plant pathogens.

2. ***Community policies***
    a. Local environmental consequences of using pesticides in food production (both broad acre farming and horticultural production).

3. ***National policies relating to plant diseases***
    a. Environmental pollution from the use of fungicides – exposure of non-target microbes, contamination of waterways, use of tractors, etc., to apply fungicides (increased carbon emissions)
    b. Healthcare – exceeding maximum permissible levels of agrochemicals in food; in Australia for example, annual monitoring of Maximum Permissible Residue Limits (MRLs) for fungicides in wheat during 2013-14 found 7 cases in which the MRL for the fungicide flutriafol had been exceeded, and 2 cases in which the MRL for thiabendazole had been exceeded, from 3,112 samples tested.
    c. Biosecurity: 'come clean, go clean' – dirty boots, pants, etc.
    d. Trade: Some countries ban importation of some plant products because of the risk of introducing pathogens. While necessary, there have been cases where exporting countries have complained that this has been used as an artificial trade barrier to protect local producers from competition.

Pupil Participation

1. ***Class discussion of the issues associated with plant diseases***

2. ***Pupil stakeholder awareness***
    a. How can we increase food production without increasing the physical (i.e. land used) and environmental footprints?
    b. Is it better to spray crops with pesticides or grow transgenic disease resistant crops that can be grown organically?
    c. Can you think of anything you could do to reduce the environmental footprint of controlling diseases in plants?

3. ***Exercises***
    a. If you have a garden at home, ask your parents if they have ever had any problems with diseases on plants.
    b. Some pesticides have had adverse effects on the environment, and there are continuing concerns around their use in food production. What other sustainable approaches could be used to control pathogens on plants?

The Evidence Base, Further Reading and Teaching Aids

Large EC (2003). The Advance of the Fungi. Jonathan Cape Publishers.
Carefoot GL and Sprott ER (1969). Famine on the Wind. Angus and Robertson Publishers.

Glossary

Biosecurity: The practice of minimising the risk of infectious diseases caused by mircobes.
Fungicide: A compound that can inhibit fungal growth or kill fungi.
Fungus: a multicellular eucaryotic organism that cannot make its own food and has chitin in its cell wall. It is believed that there are between 2.2 and 3.8 million species of fungi, some of which are pathogens of animals and plants.
Pathogen: A mico-organism that can cause disease.
Rust: a fungal pathogen that infects plants. So-called because of the multitude of rusty coloured spores that are produced on the plant host. It has been estimated that there are about 7,000 species of rust fungi.
Spore: A minute reproductive unit that can grow to give a new individual of the species to which it belongs in the absence of sexual fusion.
Strain: A genetic variant within a species. Usually used to describe a variant that differs from others I its ability to infect or sensitivity to an antimicrobial compound.