How do we stop plants getting sick?

Plant Health

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Plant Health

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Translator's note

This publication has been translated from Dutch, and you will notice that some parts are written from a Dutch perspective. Despite its modest size, the Netherlands is a major global exporter of agricultural and horticultural products and a world-leading player in innovative agricultural research. Much of what is happening in the Netherlands is also going on in other countries or can stimulate good ideas. We therefore very much hope that you too will draw inspiration from the examples nurtured on Dutch soil.

Foreword

THE YEAR 2020 was declared the International Year of Plant Health by the World Food Organisation (FAO). But most of all, 2020 will be remembered as the year of the coronavirus. The coronavirus has disrupted lives all over the world, and its effects extend far beyond health, severely impacting on other areas including economies, logistics and food production. From one day to the next, many producers – from fishers to growers of chipping potatoes and sprouting vegetables – found themselves unable to sell their products. When the hospitality sector closed its doors, their markets disappeared overnight.

This publication is about plant health. Unlike the coronavirus, plant diseases cannot transfer to humans. And yet there are some major parallels between the coronavirus and plant diseases: they too can have serious consequences for agriculture and nature, but also for global trade.

A textbook example of a plant disease is potato late blight. In the mid-nineteenth century, this disease caused almost the entire Irish potato crop to fail, leading to the Irish Potato Famine and forcing many Irish people to emigrate to North America. Potato late blight is still a much feared disease, although nowadays there are methods to control it and research into it continues apace. Another very recent example of a severe plant disease is caused by *Xylella*, which affects olive trees. This bacterium has already infected millions of olive trees in Italy. Trees as much as a thousand years old that have survived plague, wars and forest fires are now under attack from a bacterium from America, which is thought to have arrived in Southern Italy via Costa Rica and the Netherlands. The fear is that it may spread to other trees and bushes, such as almonds, peaches, grapes and rosemary. There is no cure for the disease as yet.

In our twenty-first century world, everything is connected to everything else, and plant diseases spread their tentacles farther afield than ever. This is another lesson we can learn from the coronavirus. The way we live our lives enables viruses, fungi or pests to spread much faster than in the past. And when harvests fail in other parts of the world, we notice it on our dinner tables here. This can put global food security under pressure, especially as the world's population continues to grow. Another factor compounding the risks of plant diseases is climate change. Seen from this perspective, it is only right that plant health received additional global attention in 2020. This publication has been produced to highlight the importance of the subject.

The subject of plant health is not just a tale of threat, doom and gloom but also a story of hope, innovation and teamwork. Scientists, farmers and governments the world over are working on plant health. The subject also receives a lot of attention at the Dutch Ministry of Agriculture, Nature and Food Quality (LNV). In 2018, the Dutch Minister of LNV, Cornelia Schouten, published her vision for the development of agriculture. This vision is not only geared towards achieving good yields and making prudent use of raw materials and energy but also towards minimising our impact on the climate, the environment and nature. The future of

agriculture and food production will need to focus more on circular processes and the development of precision agriculture.

Plant health plays a special role in this vision. In our efforts to prevent and control plant diseases, the emphasis is shifting from crop protection to resilient plants and cropping systems. Developments in scientific knowledge, methods and technologies are key in this regard. How can we lessen the risks to plant health with innovative production methods? Can we use plant breeding to mitigate the risks posed by pests and diseases? These methods not only benefit our food and health, they also give a boost to agricultural innovation in the Netherlands, which strengthens our position on the world market. In the Netherlands, scientific and practical research are already closely enmeshed, enabling businesses to apply innovations quickly both at home and abroad.

The transition to circular agriculture will call for innovations in many areas. The Netherlands can and must play a prominent role in innovating in production methods, both in our own country and in global food markets. With our expertise and products, we can set an example for other countries in how to produce food efficiently in circular systems that help to protect the ecosystem of water, soil and air and repair the damage already caused to it.

I hope this publication will inspire you by showing you how many highly skilled, dedicated people are working on plant health in the interests of nature, our fellow humans and those who will inhabit this beautiful Earth after us.

Marjolijn Sonnema
Director General Agro, Ministry of Agriculture, Nature and Food Quality

Introduction:
What is Plant Health and why is it important?

Plants are everywhere. By far the largest percentage of land on earth is covered with a green layer of forests, jungles and grasslands, and the oceans, too, are full of primitive plants in the form of algae. Without plants, we humans can't survive: without plants there would be very little oxygen and no food. The chlorophyll that gives plants their green colour is the engine driving all this. Powered by sunlight, this enables plants to produce oxygen from water and sugars from carbon dioxide (CO_2). This unique process is called photosynthesis. Plants convert the sugars into proteins, fats and starch and store them in fruits, grains, pulses and bulbs, many of which are, in turn, eaten by animals and humans. Plants are therefore at the base of the food pyramid.

Without plants, our whole ecosystem would collapse. The Earth would be one huge desert, complete with sandstorms. A good soil containing digested plant residues in addition to sand and clay particles can retain water and will not simply be blown away. Plants also provide shade, absorb noise and increase humidity around them. Plants in the home and in the workplace make people healthier.

Without plants, therefore, our health and our living environment would be at risk. But just like people, plants can also become sick, sometimes with dire consequences. Take the Irish Potato Famine of 1845, for example. Potato plants withered in the fields and diseased potatoes rotted in warehouses. The disease responsible for this destruction had suddenly appeared in Europe. It was an infectious disease caused by a microorganism, for which there was no cure. Millions of Irish people became ill from hunger. Many died or fled abroad.

Diseases in plants can also be an attack on biodiversity. For example, the survival of the majestic kauri tree is threatened by an infectious disease. Kauris, which are unique to New Zealand and can

INTERNATIONAL YEAR OF
PLANT HEALTH
2020

live to the ripe old age of 2,000, are part of the cultural heritage of the Maori people, the indigenous inhabitants of this country. As the trees die the Maoris lose part of their identity.

This publication is about plant health. The central question is: How do we stop plants from getting sick? Or in other words, how do we keep plants – especially our crops – healthy? Healthy crops are essential for our food supply and therefore for human health – after all, they are brimming with valuable nutrients. It is not easy to keep plants healthy. Plant pathogens and pests, such as viruses, bacteria, fungi, oomycetes (water moulds) and insects, are a lurking danger everywhere and often hitch a ride with traded plants. As much as 30 percent of our crops are currently lost worldwide due to plant pests and diseases, including as a result of problems in storing harvested produce. Trees and ornamental plants also fall sick regularly. Think of Dutch elm disease and ash dieback, or the various pests and diseases affecting lilies and roses.

2020 was declared the International Year of Plant Health by the United Nations General Assembly in order to raise awareness of the importance of plant health. Healthy plants help eliminate hunger, fight poverty, protect the environment and stimulate economic development.

The availability of sufficient quantities of affordable food is a prerequisite for reducing poverty and ensuring social stability. The Irish Potato Famine of the 19th century led to social and cultural disruption. Many Irish people moved to America, where they left a significant mark on the development of the US. It was a turning point in history, caused by just one single microorganism. Can anything like this happen again? Without a doubt. Even today, some 820 million people across the globe are going short of food and starving. The causes are often complex: bad political systems, under-

performing economies, poor or no education and underdeveloped agriculture. Poor quality seed, lack of fertilisers, drought: whatever the cause, plant health is always at risk. And when crops don't grow well, they are also more susceptible to pests and diseases.

Here in the Netherlands, hunger is not something we have to worry about. Our agricultural and horticultural sectors are highly developed. After the USA, our small country is the second largest food exporter in the world. We account for 40 percent of the global trade in vegetable seeds and as much as 60 percent of the world's seed potato trade. We do everything we can to prevent pests and diseases.

So don't we have problems in our country? We most certainly do. For one thing, the use of crop protection products is under a lot of pressure. These products may have unwanted side effects, such as killing insects. The Dutch government wants farmers to phase out chemical crop protection products within ten years. But will that work? Can we manage without them altogether in crop production? Scientists and growers are certainly doing their utmost to meet the government's target. They are constantly on the lookout for innovative ways to improve plant health. Using efficient and targeted methods, they are introducing resistance genes into crops and developing prevention and control strategies based on biological principles. 'Learning from nature' is the motto. Strip or mixed cropping can be just as productive as monocultural systems but with less disease pressure. Microorganisms in the soil are outstanding weapons in the quest to protect plants against attack. It will be interesting to see where we are in ten years' time.

The Dutch government wants farmers to abandon chemical crop protection products within ten years. But will that work?

In the Netherlands alone, there are thousands of people working in plant health: in research and education, as advisers, inspectors or policy officers, at inspection services and breeding companies, and in the agrochemical and biotechnological sectors. In this publication you can read about what they are working on every day and why. Take a look behind the scenes of plant health and you may well find yourself looking at the well-stocked fresh produce shelves in your local greengrocer's or the successful (or otherwise) crop in your vegetable garden through different eyes.

Prof. Francine Govers, Dr. Aad Termorshuizen and Prof. Corné Pieterse

When you see how many plant pathogens there are, it's nothing short of a miracle that most plants stay healthy. But it's actually a shaky balance.

1 Plants get sick too

We humans spend a lot of time thinking about our own health, especially when we catch a virus or fall sick in some other way. But we also need to keep a close eye on the health of plants, because agricultural crops, trees and ornamental plants are constantly under attack from pathogens and insects. Sometimes these pests disappear for years, only to strike again when we least expect them. Where do they come from, what impact do they have and how are they identified by the plant doctors of today?

Plants: source of our energy

DR. CHARLOTTE GOMMERS

Like us humans, plants use raw materials and fuels to grow and to react to their environment. We get the energy we need from sugars in plants. Plants make their own sugars. This puts them at the root of almost all life on earth.

Plants make sugars through photosynthesis, a reaction in which light energy is converted into chemical energy. This reaction takes place in chloroplasts, specialised components of cells usually found in the leaves. The chlorophyll in the chloroplasts is very efficient at absorbing energy-rich blue and red light and reflecting green light. This is why plants look green to our eyes. The actual work is done by the chlorophyll molecules. They absorb energy-rich particles of light called photons and, with the help of water, create the energy-rich compounds ATP (adenosine triphosphate) and NADPH (nicotinamide adenine dinucleotide phosphate). Oxygen is released as a by-product of this process. As it is not actually needed for photosynthesis, it leaves the plant, ready for us to inhale.

The energy-rich compounds ATP and NADPH are used in the next stage of the photosynthesis process, known as the 'dark reaction'. Unlike what the name suggests, this reaction doesn't only take place in the dark; it simply means that no more light energy is used from this point onwards. During the dark reaction, the plant converts carbon dioxide (CO_2) into glucose with the help of ATP, NADPH and more water.

Many plant species have therefore developed ingenious strategies to help them keep growing well

Glucose and other sugars are distributed throughout the plant and stored for later use as an energy source. Sugars are also a food source for animals, and some plants use that to their advantage. Because they store large amounts of sugars in their fruits, their seeds are eaten by hungry animals and then dispersed. Some plants store their energy for extended periods of time and pass it on in their seeds. In this case, sugar is converted into starch. That is why pulses and cereals contain so much starch. Starch can also be stored in specialised plant structures such as tubers (e.g. potatoes) and taproots (e.g. carrots), enabling the plant to build up an energy reserve and grow rapidly after the winter. We humans also make good use of this: many of our crops have been selected and cross-bred to maximise the sugar and starch content.

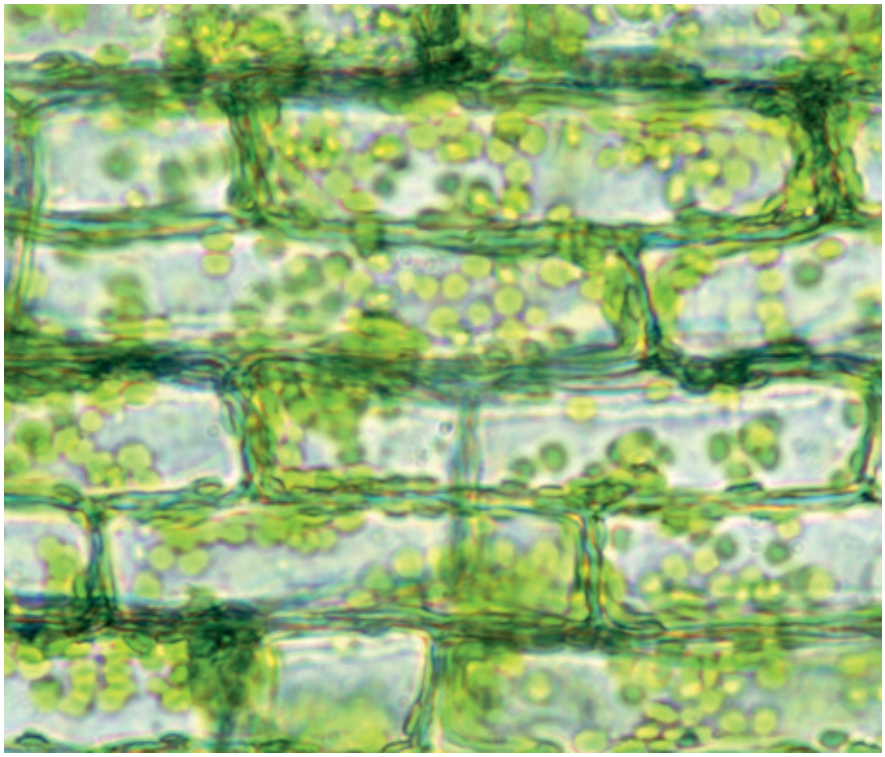
When the plant itself needs energy to grow, glucose is broken down, releasing ATP. This provides it with the energy it needs for cell division and other chemical reactions. This process, which involves burning glucose and oxygen, is called respiration. Besides ATP, CO_2 and water are also released during respiration. This takes place in specialised components of the cell called mitochondria, which perform the same function in animal cells.

The photosynthesis reaction is vital for the plant's survival, so it is important that it keeps on working. For that to happen, it needs enough light, water, CO_2 oxygen and nutrients. Because a plant can't move from one place to another, it can sometimes be a huge challenge to obtain a constant supply of these raw materials. Many plant species have therefore developed ingenious strategies to help them keep growing well.

Light receptors

To enable its leaves to absorb enough light, a plant collects information about its surroundings. For this purpose, it uses specialised light receptors that can detect different colours. A lot of red and blue light is good news: the leaf is in the ideal position for photosynthesis. A lot of far-red light warns the plant that other plants are getting too close and are threatening to overshadow it. When that happens, the light receptors emit a signal that makes the plant grow faster to outcompete its neighbours. Other light receptors cause a plant to bend towards light coming from one direction, as we can see when we place house plants on a windowsill. But too much light is not good either, because the plant's photosystems can't process that much energy and the plant becomes stressed. A common reaction to this is the production of red pigments to shield the chlorophyll.

Plants have an extremely ingenious root system. The roots absorb water containing nutrient solutions from the soil. The water flows into the plant through a series of specialised cell layers which filter out harmful substances. Eventually it reaches the transport vessels (xylem) in the root. These are hollow, elongated cells consisting only of an outer wall. Lying end-to-end, they form tubes that run through the entire plant. Together with the other type of transport vessels, the phloem, they form the plant's vascular bundles. The phloem distributes sugars from the leaves through the rest of the plant, ensuring that enough sugars are supplied to parts of the plant that don't photosynthesise, such as roots, or that store large amounts of sugars, such as fruits. The vascular bundles run through the whole plant and transport water to where it is needed: the leaves. They are the engine behind the plant's water transport system. Leaves transpire water by opening tiny holes in the surface called stomata. Each stoma is formed by two guard cells in the leaf surface which open and close by shrinking and swelling. Transpiration creates underpressure in the xylem, causing the roots to suck in water.



Chloroplasts in the leaves convert light energy into chemical energy.

Raw materials from the soil

The stomata regulate gas exchange in the leaf. When a plant is actively photosynthesising, it takes in CO_2 from the environment and gives off oxygen. But when it is growing fast, almost all the oxygen it creates will be used for burning sugars. In hot, dry climates, plants tend to keep their stomata closed during the day to prevent too much water from evaporating through the leaves. But that can cause problems, because they need a simultaneous supply of light and CO_2 for photosynthesis. Some plants are well adapted to dry climates and have a solution for that. They store CO_2 in the form of malic acid or a similar compound at night when their stomata are open. The malic acid is broken down again when it is light during the day, releasing CO_2 for photosynthesis.

Plants depend on raw materials from the soil for growth and maintenance. Micronutrients such as iron, zinc and copper are needed in small amounts, and macronutrients such as nitrogen, phosphorus and calcium in large amounts. Plants use these nutrients to build proteins, DNA and cell structures. The optimum amount of nutrients differs depending on the type of plant. When nutrients are in short supply, a plant will become stressed. Some plants then break down the chlorophyll in their older leaves and reuse the nutrients this releases in younger leaves. This makes the plant start to look yellow.

Plant roots are constantly searching for nutrients in the soil. If there is more phosphorus or nitrogen in one spot in the soil than in another, the roots can sense this and more lateral roots will grow towards that spot. All in all, plants can look after themselves very well. They find everything they need around them. And if one of the raw materials they need to survive looks set to become scarce, they are flexible enough to adapt.

Double trouble

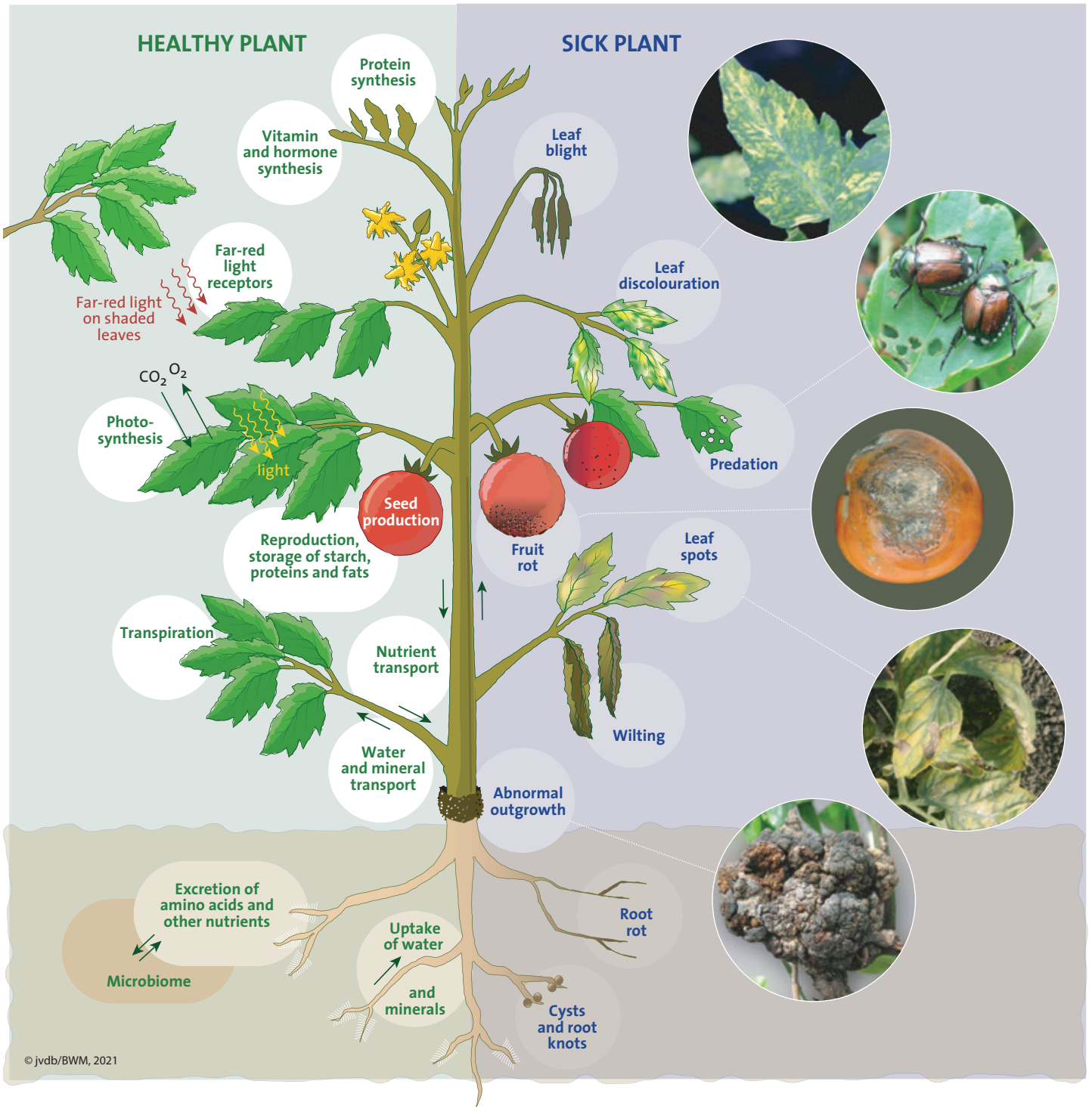
DORIET WILLEMEN MSC

This pattern on the bark of the ash tree is not the work of an artist, but of the emerald ash borer (*Agrilus planipennis*).

Groups of trees with bare branches and shrivelled, wilted leaves are a forlorn sight in the landscape. Like elsewhere in Europe, forests in the Netherlands are not being spared. Ash dieback was officially recorded for the first time in the Netherlands ten years ago (Groningen, 2010) and has since spread all over the country. The dead and dying trees not only look desolate; falling branches also pose a danger to walkers and traffic. Affected ash trees are therefore being felled en masse, also in the hope of stopping the disease from spreading. The root of this particular evil is a fungus, *Hymenoscyphus fraxineus*, which grows in the xylem of the ash tree. The vessels become clogged, causing branches to dry out and die. There is no treatment. But not all ash trees are equally susceptible, and researchers are working on identifying and selecting species and cultivars that are more resistant to the disease. Dutch citizens are helping them in the citizen science project 'Essentaksterfte.nu'.

The fungal spores, which are formed in fruiting bodies, mainly on leaf petioles, can spread to other trees on the wind. They can also travel over longer distances via trade in trees carrying the disease undetected. International trade greatly increases the risk of a plant pathogen or pest being imported. Customs controls, phytosanitary declarations and compulsory plant passports go some way to countering this, but even items such as wooden pallets and packaging materials pose a risk because harmful insects (such as the eggs, larvae or pupae of various longhorned beetles) can be imported on them.

To make matters worse, ash trees in Europe are now also threatened by the arrival of the emerald ash borer (*Agrilus planipennis*) from Asia. This metallic green beetle, which has wreaked havoc in the forests of America and Canada, has already been spotted in Ukraine. It is no longer a question of whether the beetle will arrive, but when. So we need to be alert, otherwise the trees currently surviving ash dieback could soon succumb to this beetle.


HEALTHY PLANT
SICK PLANT
Protein synthesis
Vitamin and hormone synthesis
Far-red light receptors
Far-red light on shaded leaves
CO_2 O_2
Photo-synthesis
light
Seed production
Reproduction, storage of starch, proteins and fats
Transpiration
Nutrient transport
Water and mineral transport
Excretion of amino acids and other nutrients
Microbiome
Uptake of water and minerals
Leaf blight
Leaf discolouration
Predation
Fruit rot
Leaf spots
Wilting
Abnormal outgrowth
Root rot
Cysts and root knots
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Pathogens and their cunning ways

PROF. FRANCINE GOVERS, DR. AAD TERMORSHUIZEN, PROF. CORNÉ PIETERSE

Most plants and trees in our environment grow and flourish and look healthy. But just like humans, they are occasionally struck down by disease. Most diseases are caused by microorganisms such as viruses, bacteria and fungi. Nematodes and parasitic plants also play a part. What characteristics do these organisms have and how do they affect plant health?

PLANT PATHOGENS

PHYTOPLASMAS

These single-celled organisms are bacteria without a cell wall. They live in the phloem tissue and disrupt the host plant's growth and development.

VIROIDS

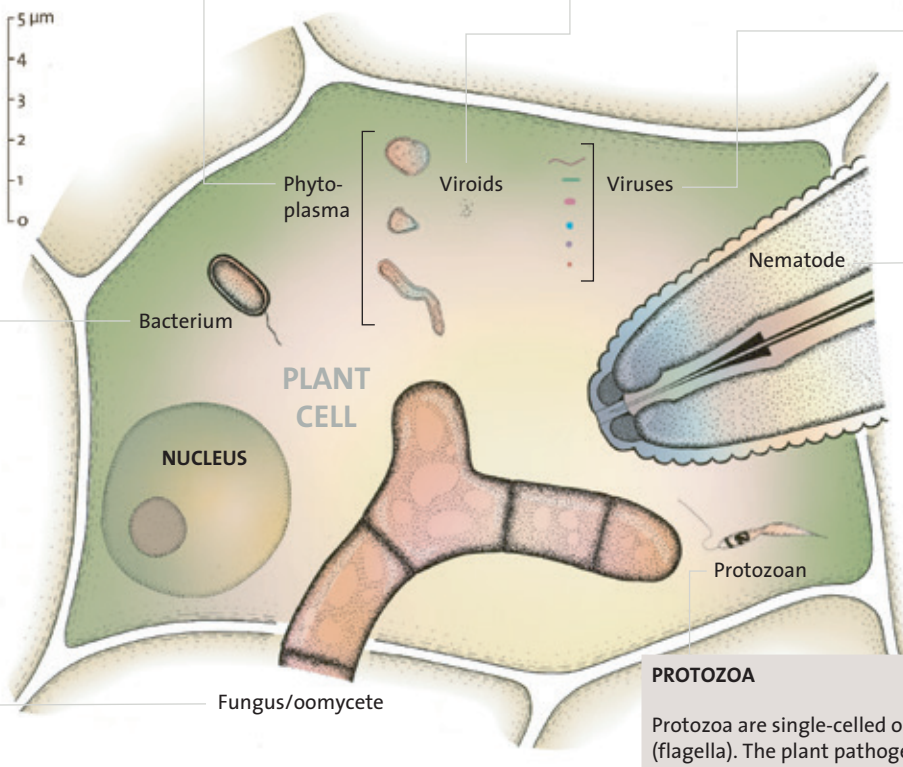
Viroids are naked circular molecules of RNA varying from around 250 to 470 nucleotides in length. A viroid has been shown to be the culprit in at least forty diseases on different plant species.

VIRUSES

Viruses are rod-shaped or spherical particles consisting of RNA or DNA wrapped in proteins. Viruses can only survive and replicate in a host cell and are dependent on vectors, usually insects, to spread. They disrupt the cell, causing leaves to discolour or curl and inhibiting growth.

BACTERIA

These single-celled organisms are very common. Bacteria that parasitise on plants digest the tissue with enzymes, produce toxins to kill cells or use effectors to manipulate the host plant into suppressing defence against infection. This allows these uninvited guests to grow unhindered at the host plant's expense.



NEMATODES

These are multi-cellular, worm-like organisms that occur in vast numbers in the soil. Nematodes that parasitise plants use a microsyringe to puncture roots and inject saliva into plant cells. This triggers the production of nutrient cells in the plant, providing food and building blocks that boost the development of the nematodes.

FUNGI AND OOMYCETES

These thread-like organisms grow between the cells or penetrate into them. They use similar mechanisms to bacteria to digest or deceive the host plant. A fungal thread (hypha) is shown here, recognisable by the cross-walls (septa) dividing it. Oomycetes have no cross-walls.

PROTOZOA

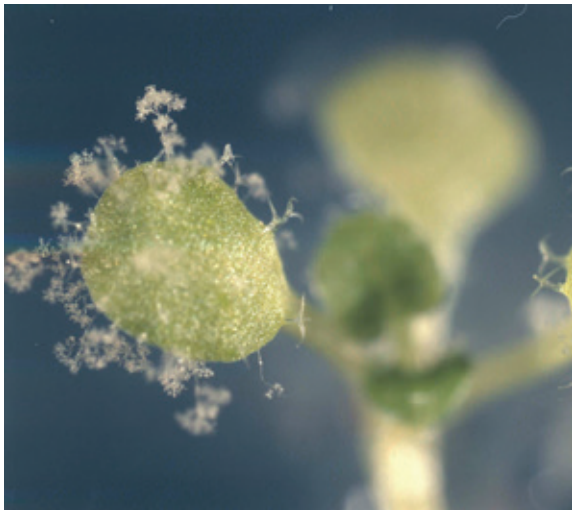
Protozoa are single-celled organisms with whip-like hairs (flagella). The plant pathogenic species, phytomonads, are transmitted from plant to plant by insects. Economically significant protozoan diseases are phloem necrosis in coffee plants and wilting and rot in coconut and oil palms.

An aphid punctures a leaf with its stylet, potentially infecting the plant with viruses.

VIRUSES are rod-shaped or spherical particles. They consist solely of DNA or RNA surrounded by a protein coat. They invade a living cell and are completely dependent on their host, such as a plant, for survival and reproduction. They disrupt the cell's basic processes, causing leaves to discolour or curl and inhibiting growth or flowering. Around 1,800 viruses have been described that only infect plants. That is around 30 percent of all described viruses but only a fraction of the actual number of viruses in existence. Insects – especially aphids – transfer viruses from plant to plant when they pierce the stems with their stylets to suck up food. If the plant is infected, the virus is transported along with the aphid and is injected into the next plant on which the aphid feeds. Viruses can also be transmitted via cuttings, seeds or plant sap that is released when a plant is wounded, such as during pruning or predation.

BACTERIA are single-celled organisms, which can be spherical, rod-shaped or spiral. They have a layer of mucus on the outside and often have one or more whip hairs (flagella) which assist with movement. Unlike viruses, bacteria do not need a host cell to multiply. They grow rapidly, multiply by division and form colonies in which they cooperate and share tasks. Around 10,000 species of bacteria have been described, but this too is only a fraction of the actual number. About 80 species are known to infect plants. Some forms, known as necrotrophs, live off dead or killed plant material. They can kill plant tissue by breaking down cell walls and then feeding off the contents of the cells. Other forms of bacteria, known as biotrophs, feed on living plants. Using a kind of microsyringe, they inject substances known as effectors into plant cells to suppress the plant's defences and then take control in the cell, paving the way for unhindered growth at the plant's expense. Other types of bacteria transfer a piece of their DNA to the plant cell, which will then become part of the plant's genetic material. This causes the plant to produce extra hormones, leading to uncontrolled cell division. A tumour forms from which the bacterium benefits.

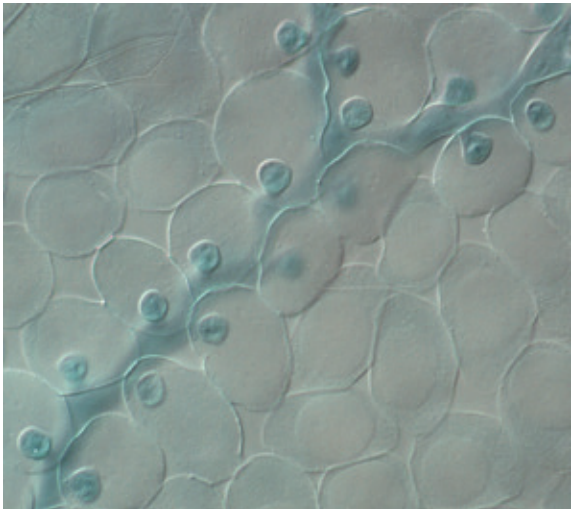
Rod-shaped bacterium with long whip hairs which assist with movement.



Downy mildew (an oomycete) on the leaves of a seedling.

FUNGI and **OOMYCETES** are organisms that are very similar in appearance. They produce threads (hyphae), which branch to form a network (mycelium). Spores are formed on the hyphae, which are spread by wind or water and can develop into a new mycelium. Fungi and oomycetes are not related but occupy the same ecological niche, having taken on the same shape and life cycle through evolution. Fungi are close to animals in the tree of life. Oomycetes, which are also known as water moulds, are found in a completely different branch along with brown algae and diatoms, far removed from fungi and animals. The best known fungi are visible mushrooms, but most of the estimated four million species are so small that they are more or less invisible. Many fungi are useful natural cleaners: they are saprophytic, which means that they break down organic material. Other fungi live in symbiosis with plants (mycorrhizae) or algae (lichens).

Oomycetes are mainly familiar to us as pathogens. Around 2,000 species have been described, but their actual number is estimated to be more than ten times that. Only a small proportion of the many species of fungi and oomycetes – around 8,000 – are pathogens. They are often grouped together as filamentous plant pathogens. Their strategy for making plants sick is similar to that of bacteria, with cell wall degrading enzymes that kill off the plant tissue or effectors that manipulate the host and suppress its natural defences against infection. Instead of using a microsyringe, as some bacteria do, filamentous plant pathogens deliver effectors via nutrient-absorbing outgrowths known as haustoria. These are spherical or finger-shaped protrusions of hyphae which penetrate the plant cell to increase the contact surface between pathogen and plant and facilitate the exchange of effectors and nutrients. Toxins produced by fungi (mycotoxins) are also fearsome weapons for weakening their hosts. Mycotoxins can also be toxic to humans.



Filamentous plant pathogens, such as this downy mildew, use nutrient-absorbing outgrowths to introduce substances into or retrieve them from the plant.

A nematode can pierce a root of the potato plant with this stylet, injecting it with saliva containing substances which suppress the plant's defences.

NEMATODES are a highly diverse group of minuscule worms which are found in the soil in very large numbers. Just one handful of soil can contain as many as a thousand specimens. Most of the 27,000 nematode species described feed on bacteria and other microorganisms. More than 4,000 species use plants as their food source, but only 20 to 25 of these are harmful in agriculture and horticulture. They pierce roots with their needle-like stylet and discharge saliva into the plant cells. The saliva contains effectors which, as mentioned above, suppress the plant's natural defences. The nematodes take over and manipulate the plant into producing food cells, which feed them and provide materials for their further development. Egg-filled nodules or cysts appear on the roots, which hatch and reinfect plants after a period of hibernation.

PARASITIC PLANTS live as parasites on other plants. These, too, belong to a large, highly diverse group. In total there are around 4,800 species, widespread throughout the plant kingdom, which have discovered the parasitic lifestyle independently of one another. A feature they all have in common is that after germination they attach themselves to a root or stem and then produce nutrient-absorbing outgrowths to exchange nutrients and effectors. Like bacteria, fungi, oomycetes and nematodes, parasitic plants use effectors to suppress the host plant's defence system. The strength of parasitic plants lies in the profusion of flowers and the enormous quantity of seeds they produce – up to as many as one hundred thousand per plant. The seeds can survive in the soil for decades. As soon as there is a suitable host close by, germination is triggered by a chemical substance secreted by the host plant. Then the infection begins: the host is sucked dry, weakens and dies. In Africa in particular, *Striga* and *Rhamphicarpa* species have a disastrous impact on maize and rice crops, with yield losses of as much as 70 percent. The soil in large parts of the continent is infested with seeds of these parasites, which have the ominous-sounding common names of witchweed and vampireweed.

Striga parasitises the roots of plants.

Plant pathogens and pests give chase sooner or later

Many of the agricultural crops grown on a large scale in the Netherlands originate from somewhere else. You would expect these plants to be safe from their former attackers here. But the reality is different. Sooner or later, their pathogens and pests show up here too, and globalisation only exacerbates this risk.

PROF. ANDRÉ DRENTH

These days, consumers want to know where their food comes from, but something they spend less time thinking about is the origin of the crops that produce all that food for us. All agricultural crops have a country – or more precisely a region – of origin. Those are the areas where they belong, where they have adapted to the environment. The potato, tomato and broad bean, for example, originate from South America; maize from Central America; the apple from Central Asia; and almost all of our cereals from the Middle East. The local population turned the wild versions of the plants into food crops in a process of cross-breeding and selection.

In the 15th century, explorers set out to bring spices from the Far East to Europe. This led to a large-scale global exchange of plants, often under the direction of botanical gardens which were being established in large numbers at the time. This intercontinental spreading of plants during the colonial period is also known as the Columbian Exchange, after the explorer Columbus.

Crops planted in their region of origin were exposed to many different pathogens and pests, such as fungi, oomycetes, viruses and insects. These adapted as they evolved, often developing a strong preference for certain crops, which became their host plants. As a result, they can significantly reduce the yields of these crops. When grown outside their region of origin, the crops are no longer troubled by these pests, so yields improve. Even now, centuries after the Columbian Exchange, many of our food and commercial crops still benefit from the absence of their original attackers. However, a crop in a new area is sometimes susceptible to local pathogens, such as fire blight in apples and pears in America, downy mildew in maize in Asia and leaf blotch on barley in Europe.

The greatest diversity of plants, animals, insects and fungi is found in the tropics. There, an individual crop has to contend with as many as five to ten times more pathogens and pests than the same crop in a temperate climate. Growers in temperate zones grow crops from the tropics in a moderate climate and often only in the summer, with a winter period of rest in which there are no host plants, so these pathogens and pests are much less successful there.

Coffee rust

Thanks to the invigorating effect of caffeine, coffee has been a popular stimulant for centuries. The coffee plant originates from Ethiopia. During the colonial era, the Dutch introduced the coffee plant into Indonesia, where they started cultivating it on a large scale. In 1867, the coffee plantations in the former British colony of Ceylon (now Sri Lanka) were affected for the first time by *Hemileia vastatrix*, a fungus from Ethiopia which causes coffee rust. The leaves were so badly affected that bean production collapsed. The British switched to tea. To evade coffee rust, a large part of coffee production was moved to Central and South America. Coffee rust arrived in Brazil in 1970, going on to spread throughout the continent within ten years. Successful resistance breeding in coffee has recently been reversed by the rapid evolution of this fungus.

A West Javanese farmer harvesting coffee beans.

Following in their footsteps

Pathogens and pests can, and do, follow in the footsteps of their favourite crops. A classic example is *Phytophthora infestans*. Three hundred years after the potato came to Europe from South America, the causal agent of potato late blight followed the crop, causing the Irish Potato Famine. Other examples are apple scab from Central Asia and rust fungi in cereals which originate from the Middle East. Some fungal diseases come from related host plants, such as Dutch elm disease, which came to Europe from Asia.

The enormous increase in international trade and tourism has made it much easier for pathogens and pests to spread across the globe, putting the health of our plants under ever greater pressure. Banana cultivation is kept going only with a great deal of effort, for example.

The influence of pathogens and pests can be kept under control in various ways. For fungal diseases, the solution is often a combination of short-term applications of crop protection products to limit damage, and long-term resistance breeding. Pathogens and pests are genetically highly adaptable, so plant breeders and producers of crop protection products need to keep a close eye on the populations of these aggressors. Prevention is extremely important for bacterial and viral diseases. One safeguard is the use of plant material that is certified free from pests and diseases. So the problem is never actually solved, but together scientists and growers always try to stay one step ahead of the pathogens and pests.

Saving the banana

DORIET WILLEMEN MSC

Chinese banana plantation severely affected by *Fusarium* wilt – or Panama disease – caused by *Fusarium* TR4.

There's little evidence of the problem in Western supermarkets, where the shelves are still well stocked with bananas. But it's only a matter of time before the effects of two devastating fungal diseases in banana cultivation are felt here too. Unless someone can come up with a solution soon...

The banana is having a hard time. Plantations are being affected worldwide. To start with, there is the notorious wilt or Panama disease, which is caused by several *Fusarium* species. A new, more virulent variant emerged in Asia in the 1960s: Tropical Race 4, or TR4. Despite frantic attempts to keep it in check, efforts to stop it spreading to plantations in Africa have been unsuccessful. This TR4 variant has also recently been found in South America. A major problem is that at least half of the total banana acreage consists of susceptible Cavendish bananas destined for export. It's easy for a disease to spread in such a global monoculture. Entire plantations are being destroyed, and the soil remains unsuitable for growing bananas for many decades. And yet bananas are the main source of food for more than 400 million people in the tropics.

As if that were not enough, the banana is also suffering from a leaf-spot disease with the ominous-sounding name of Black Sigatoka, caused by the fungus *Mycosphaerella fijiensis*. To get healthy bananas onto supermarket shelves, plantations can be sprayed with crop protection products anywhere between 25 and 70 times a year. But the fungus that causes Black Sigatoka is becoming increasingly resistant to these chemicals. Continuing to use these expensive, polluting compounds is therefore not an option.

In response to this, researchers are working on developing resistant banana varieties using wild relatives with genes that make the plant resistant to these pathogens. So there is still hope that we can save the banana.

Insects: friend and foe

DR. MARTINE KOS AND PROF. MARCEL DICKE

With about one million described species, insects are the most diverse group of organisms living on our planet: they make up more than half of all species known today. As pollinators, insects play an essential role in plant reproduction and dispersal. In return, plants are an important source of food for insects. They are on the menu for about half of the one million insect species described. Remarkably, only about five thousand of these, i.e. half a percent of all insect species, are regarded as serious pests for humans. Yet despite the intensive use of pesticides, insect pests are responsible for destroying almost one fifth of the world's crop production. In nature, on the other hand, pests are the exception. How is that possible?

The Colorado potato beetle *Leptinotarsa decemlineata* is particularly fond of the leaves and flowers of plants in the nightshade family, such as potato and tomato.

SOS signal

In nature, plants are very good at defending themselves against insects that prey on them. The first line of defence for plants is a *direct* one. This is the do-it-yourself method of physical defence with thorns, hairs or thick, leathery leaves which insects find difficult to penetrate with their mouth-parts, or chemical defence, for example with toxic repellents. These include the bitter taste of Brussels sprouts and mustard: what you are tasting are the defence substances – glucosinolates – that plants in the cabbage family such as Brussels sprouts, cauliflower, kale and mustard plants produce to defend themselves against insects.

Plants also defend themselves *indirectly* by attracting the natural enemies of herbivorous insects. After all, your enemy's enemy is your friend! When plants are bitten into, they produce aromatic compounds which parasitic wasps, predatory mites and other natural predators use to locate their prey. These volatile substances form a kind of SOS signal which the plant emits to summon natural reinforcements.

Plants can't move away to escape hungry herbivores, but they have many ingenious defence tactics. Even within one plant species, some varieties are more proficient at deploying these defence options than others. If we bear this in mind, we can select varieties with good defence strategies for food production and thereby reduce the use of pesticides.

On the trail of pathogens and pests

DR. IRIS STULEMEIJER AND DR. GERARD VAN LEEUWEN

To come up with effective ways of controlling pathogens and pests, you first have to detect and identify them. This is done on the basis of scientific knowledge, experience and research. Identification is challenging, because the first step, symptom recognition, requires expertise from different fields. Symptoms are not only caused by pathogens and pests; they can just as easily be the result of conditions such as the weather, a nutrient deficiency or environmental pollution. Pathogens and pests may also be present in plants that appear healthy, posing a threat to other crops, that will develop symptoms. For general plant health, detection and identification are an essential part of preventing the spread of known pathogens and pests and identifying new ones at an early stage. Every pathogen and pest requires different measures. We describe five examples below.

Even sniffer dogs are used to track down pathogens and pests.

VIRUS IN LILIES

Strawberry latent ringspot virus (SLRSV) can occur in many different fruits and ornamental crops, including lilies. It causes leaf spot and stunted growth in various fruit crops. Infected lilies appear healthy to the eye, but when infected bulbs are planted, they can put other crops at risk. This is because the virus is transmitted by two species of nematode which pass on the virus to other plant species, including other fruit crops such as grapes and soft fruit, via the soil. Therefore, before bulbs are exported, they undergo rigorous checks to ensure they are virus-free using antibodies (proteins which react specifically to the presence of the virus). As vegetative propagation of lilies helps to maintain the virus, it is crucial to select healthy lilies for propagation. This is now done with a newly developed molecular test which detects all SLRSV variants in lily bulbs.

BACTERIUM IN ROSES

The highly infectious bacterium *Ralstonia solanacearum* causes brown rot in potatoes and has quarantine status in the EU. This means that any plants infected with it and all nearby plants must be cleared. In 2015, various symptoms such as blackened, necrotic stems and yellowing, wilting leaves were observed in roses. The symptoms were very similar to those of brown rot in potatoes. Once the pathogen was isolated from the affected roses and the DNA identified, the culprit

was revealed to be a tropical variant of *Ralstonia solanacearum* which naturally thrives in heated greenhouses. It was also discovered that susceptibility in different rose cultivars varies and that the bacterium may be present without causing any symptoms. Since these bacteria can survive in soil, water and plant residues, the disease can easily spread undetected. The greenhouse in question therefore had to be cleared, very thoroughly cleaned and disinfected. No new attacks of this tropical variant of *Ralstonia solanacearum* have been observed in rose greenhouses recently.

CHESTNUT BLIGHT

Cryphonectria parasitica is a fungus which causes blight in sweet chestnuts. A striking feature of the aggressive form of this disease is the reddish-orange pigmentation on the bark. The fungus mainly occurs in southern European countries but has also been found in northern Europe. Thanks to timely detection and removal of diseased trees, it has so far been possible to keep the disease under control in northern Europe. It is therefore very important to check closely for the presence of this fungus when transporting young trees from southern to northern Europe. However, checking for symptoms is not enough on its own as there are less aggressive strains of *Cryphonectria parasitica* which cause virtually no symptoms. This is due to a virus which infects the fungus. This discovery is being exploited in Italy and elsewhere to control chestnut blight biologically. Fortunately, these days we have sensitive DNA techniques which can detect all strains of the fungus.

LONGHORNED BEETLE

There are many thousands of species of longhorned beetle (*Cerambycidae* family), a number of which pose a threat to coniferous and deciduous trees in parks and forests. Females lay eggs under the bark of trees and shrubs with their ovipositor. When the larvae hatch, they live off the plant's vascular and woody tissue and burrow under the bark or deep into the wood of the trunk. When the beetles emerge, they eat their way out of the wood and the bark and fly away. The larvae and beetles cause a lot of damage, especially when they are present in large numbers. They can also spread other pathogens and pests such as the pine wood nematode, which attacks conifers. Consignments of living trees and goods with wood packaging arriving from outside Europe are therefore strictly monitored, and targeted searches for longhorned beetles are performed at high-risk sites using traps, attractants and even sniffer dogs. Over the past 10 years in the Netherlands, dozens of trees have had to be felled in Almere and Winterswijk following two outbreaks of the Asian longhorned beetle and likewise in Honselersdijk and Boskoop after two outbreaks of a closely related species, the East Asian longhorned beetle. These actions were necessary to prevent the pest from establishing and spreading further across the country. And they succeeded: since then, no further destructive longhorned beetles have been found.

POTATO CYST NEMATODE

Potato plants are susceptible to two species of potato cyst nematode, *Globodera pallida* and *Globodera rostochiensis*. Affected potato plants suffer stunted growth and can die. These pests are classified as a quarantine pest in the EU. Large numbers of cysts measuring around one millimetre in diameter, each containing hundreds of nematode eggs, form on the roots of affected plants. The cysts can survive for many years in the soil,

forming a source of infection for a subsequent potato crop. They can also infect new fields, for example by hitching a ride in soil residues stuck to machinery or in non-susceptible crops replanted elsewhere. Therefore, before planting certain crops, farmers are required to establish that their fields are free from this nematode. This is done by taking soil samples which are rinsed and checked for cysts containing live eggs under a microscope. Only resistant table potato varieties may be grown in infected fields, as nematodes are unable to multiply on these plants.

To sum up, therefore, plant disease experts employ a wide range of techniques to detect and identify pathogens and pests. Developments never stand still. New molecular technologies are emerging. Next Generation Sequencing, for example, theoretically enables all the genetic material of bacteria, nematodes, fungi, oomycetes and viruses in a plant to be identified in a single analysis. However, before this technology can be deployed, the necessary IT infrastructure and expertise need to be in place. Moreover, the reliability of the analysis must also be demonstrated, because, above all, a diagnosis must be correct.

Dipsticks, which are relatively inexpensive and quick, are a popular aid. They look like pregnancy tests

How the modern plant doctor works

DR. PETER BONANTS

To identify as many pathogens as possible, the agricultural and horticultural sectors ideally want to use targeted, sensitive, robust and rapid tests that don't cost the earth. Tests used in the past were often based on properties that could be seen under a microscope, such as shape or growth. In the 1970s, tests were developed based on antibodies – substances that adhere to specific proteins of the pathogen. The 1990s saw the emergence of DNA testing, which was added to the toolbox. Based on the genetic characteristics of the pathogen, special tests were developed which targeted a specific part of the DNA of one single organism. A commonly used variant of these is the TaqMan PCR, a DNA test that not only visualises but also quantifies the presence of a particular pathogen in the sample. Many tests can only be carried out in a laboratory, such as the ELISA test, which can trace specific bacteria and viruses relatively inexpensively. For diagnosis, the samples are sent to inspection services or specialist laboratories. Other methods have been developed for carrying out monitoring an on site in the field or greenhouse. The LAMP method is a DNA test which can detect pathogens such as a virus in whitefly within half an hour on a simple portable device. Dipsticks, which are relatively inexpensive and quick and look like pregnancy tests, are also popular: you can see whether a crop is infected with viruses or bacteria within 10 minutes.

To improve the effectiveness and efficiency of diagnosis, new methods are being developed which enable multiple pathogens to be detected simultaneously. The Luminex system is one example. This platform uses colour-coded beads precoated with specific antibodies or pieces of DNA

A laboratory technician uses LAMP, a rapid DNA test, to analyse whether an orchid leaf is affected with the bacterium Acidovorax cattleyae. The result is known within 30 minutes.

and enables up to 100 different pathogens to be analysed simultaneously in one sample.

Most molecular techniques depend on the availability of genetic information. This DNA consists of four building blocks (A, C, G and T) which has a fixed sequence in each organism: the DNA sequence. Whereas in the 1980s it was only possible to determine several hundred building blocks per day, with Next Generation Sequencing 6 trillion building blocks can be sequenced in 48 hours. Scientists are encouraged to store this information in publicly accessible databases. These contain the genetic information of a vast number of different organisms, including known pathogens and pests and even different strains of individual pathogens. If you have the DNA information of a suspected pathogen, you can compare it with the DNA sequences in public databases and quickly identify the culprit. You can also find out where the pathogen has been found before and whether it is a new or known strain. All in all, we have an enormous toolbox of methods for detecting pathogens at our disposal.

Biblical plague

DORIET WILLEMEN MSC

An African farmer watches helplessly as locusts devour her crops.

Plagues of locusts have ravaged the world for thousands of years. Their devastating impact is even described in the Old Testament: *'They came in swarms and settled over the whole country. They covered the ground until it was black with them; they ate everything [...] including all the fruit on the trees. Not a green thing was left on any tree or plant in all the land of Egypt.'*

And it's true: picky eaters these creatures are not. Many insects are limited to one or two plant species, but the desert locust, *Schistocerca gregaria,* eats everything in its path, leaving behind a desolate landscape stripped completely bare. Watch a video of the recent locust plague in East Africa to get an idea of the full extent of the problem. A swarm is 60 kilometres long, 40 kilometres wide and averages 40 to 80 million animals per square kilometre. How can you go about tackling a locust swarm of that size? Spraying it with chemicals from the ground is a hopeless task. So it has to be sprayed from the air – with all the inherent additional risks for humans and animals. As an individual farmer, you are powerless. In Ethiopia and Somalia, the insects destroyed around 700 square kilometres of agricultural crops and pasture in one season, threatening people and livestock with famine. The UN Food and Agriculture Organisation (FAO) advises people on the ground to catch the locusts and dry them so that they at least have something to eat in subsequent months. Thanks to their high protein content, the insects are highly nutritious.

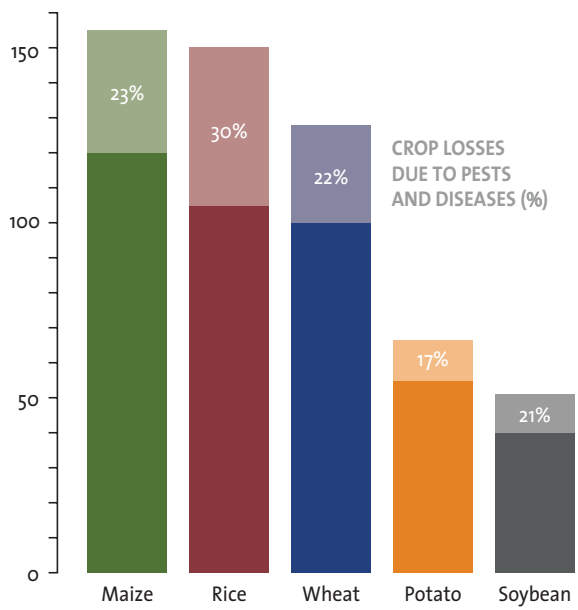
In addition, research is underway into an environmentally friendly strategy for tackling locust swarms using the parasitic fungus *Metarhizium anisopliae*. Fungal spores are sprayed onto the crop and germinate when they come into contact with the insect. The emerging hyphae then penetrate the cuticle of the locust and enter the body, where they excrete toxins which kill it. The decaying body turns green from the many spores that grow on it. These spores can then infect other locusts and, hopefully, curb the plague.

The toll of pests and diseases in agriculture

PROF. ANDY NELSON

We take food for granted: for two generations at least, most of the Western world has not been faced with famine. For two generations at least, too, the majority of those who live in the West have no farmers among their immediate kin. We have become disconnected from agriculture. But things are very different in the non-Western world, where food is often scarce and sometimes lacking completely, and where agriculture still is a major activity. Yet, in both worlds, plants are threatened by pests and diseases taking their toll. We seldom realise that this is happening to all crops, all over the world.

GLOBAL PRODUCTION PER CAPITA (KG) OF FIVE MAJOR FOOD CROPS



Pests and diseases are having a negative impact on food production worldwide: they often lead to crop losses – losses in quantity and/or quality of harvests – whether in small-scale, diverse, traditional agriculture or in intensive systems with large-scale, genetically uniform monocultures.

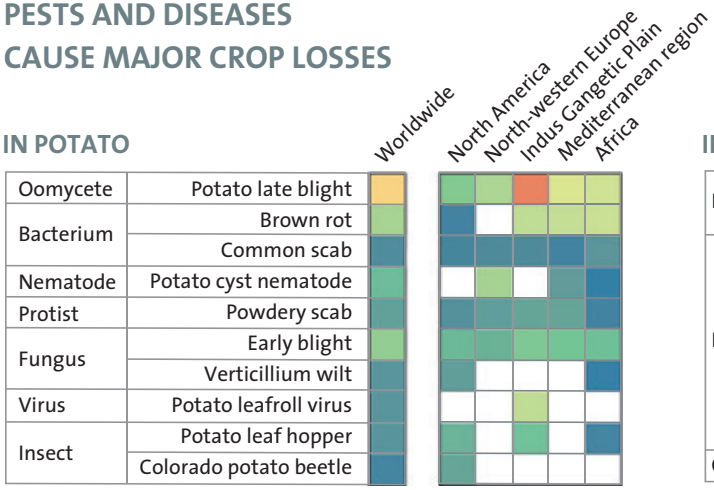
Scientists agree that pests and diseases are an important cause of crop losses and form a threat to food security. Nonetheless, this is difficult to back up with hard figures, for two reasons. One is the sheer biological diversity of pathogens and pests: these can be viruses, bacteria, fungi, oomycetes, nematodes, insects, molluscs, rodents or parasitic plants. This diversity makes it difficult to ascribe a crop loss to a single pathogen or pest. The other reason is ecological: pathogens and pests are integral parts of the human-made agrosystems – in fact, pathogens and pests have been domesticated at the same time as crop plants, over millennia. As a result, the effects of pathogens and pests in agriculture are very hard to disentangle from the complex web of interactions among factors at play within agroecosystems.

In 2016, the *International Society for Plant Pathology* (ISPP) decided that a survey on pathogen and pest losses in crops should be conducted. This worldwide online survey was conducted between 1 November 2016 and 31 January 2017, reaching over 2,500 members of the ISPP, along with nearly 100 crop health experts from many scientific organisations worldwide.

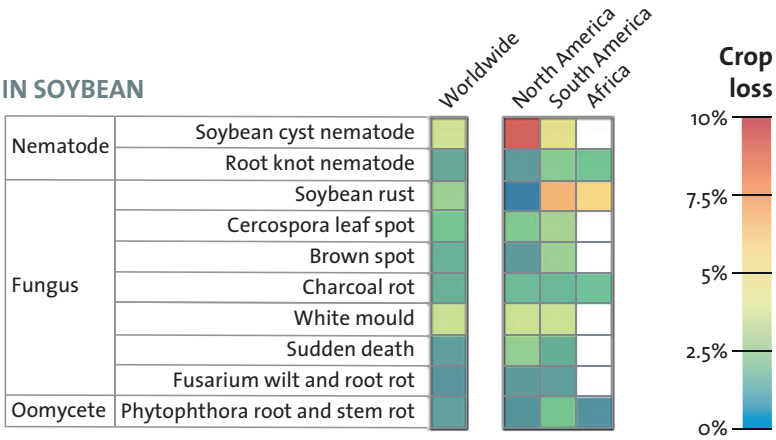
Using a simple online questionnaire, we collected almost 1,000 responses from experts on five major food crops (wheat, rice, maize, soybean and potato) in 67 countries. We chose these five crops since together they provide about 50 percent of the global human calorie intake. The 67 countries represent 84 percent of the global production of these five crops.

PESTS AND DISEASES CAUSE MAJOR CROP LOSSES

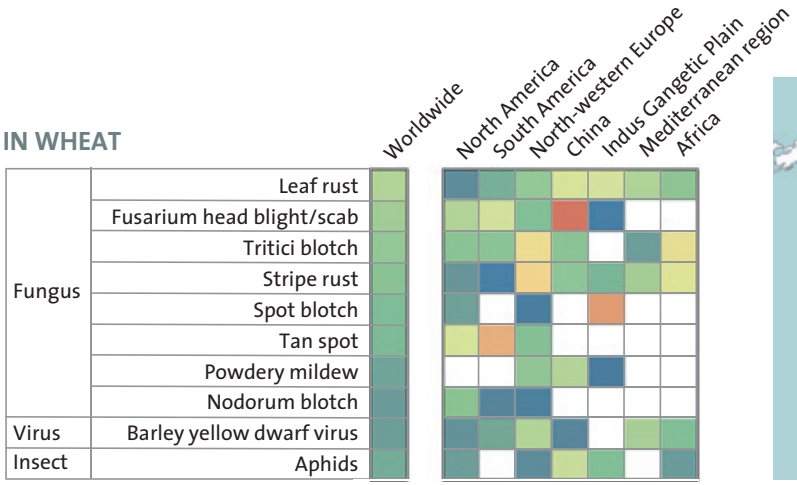
IN POTATO



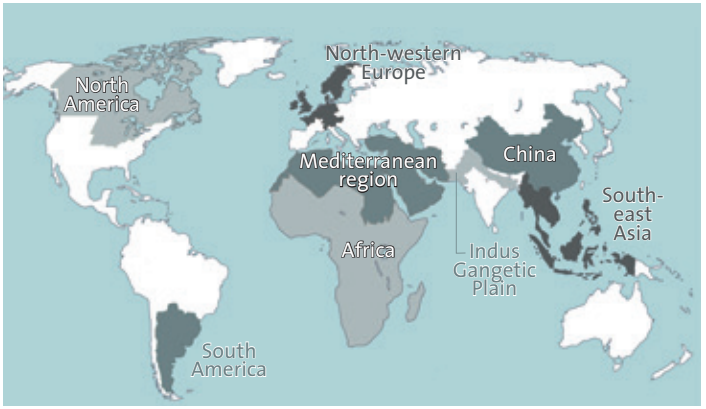
IN SOYBEAN



IN WHEAT



Regions where the five main food crops are grown: wheat, rice, maize, soybean and potato



Pests and diseases in wheat, potato and soybean which cause the highest yield losses worldwide. The heat maps show the percentage yield losses per crop, which pathogen or pest was responsible for them, and how this varies per region. The world map shows eight regions where the five main food crops are grown.

Ethiopian farmers harvest teff, or Abyssinian lovegrass. The small seeds are used to make flat cakes, porridge or beer.

The highest losses occur in food-deficit regions with fast-growing populations

The study documents the extent of losses associated with 137 pathogens and pests. At a global scale, we estimate that the range of losses are 10–28% in wheat, 25–41% in rice, 20–41% in maize, 8–21% in potato and 11–32% in soybean. The study also ascribes loss estimates to individual pathogens and pests for these five crops globally.

Our results highlight differences in the impact of pests and diseases on crops in different regions. The highest losses occur in food-deficit regions with fast-growing populations, and frequently as a result of emerging or re-emerging pests and diseases in these regions.

This quantification of crop losses in five major food crops provides a measure of past advances and a benchmark for future progress in crop health management. Our results provide a basis for further research and policy prioritisation of crop health management. Some pathogens and pests occur chronically – meaning they occur regularly and over large areas. For these pathogens and pests, efforts are needed to deliver more efficient and sustainable management tools, such as developing resistant varieties. New pathogens and pests emerge and existing ones re-emerge regularly and are associated with recent large increases in yield losses. Urgent action is needed to contain these outbreaks so that the epidemic can be brought to a halt. Efforts to generate long term solutions, preferably involving varietal resistance, need to be undertaken rapidly.

Famine and migration

DORIET WILLEMEN MSC

The famine caused by potato late blight claimed many victims in Ireland, such as this family from Killarney.

Many different potato diseases exist, but one of them is by far the most common: potato late blight. This is one of the most serious plant diseases, both in the past and the present day. Europe experienced its first bout of potato late blight in 1845, when it spread throughout Western Europe, completely destroying the potato harvest. Hardest hit was Ireland, where a large proportion of the population depended heavily on this one crop. One and a half million Irish people eventually starved to death, and another million emigrated, mainly to the United States.
The culprit responsible for this disaster was the fungus-like pathogen *Phytophthora infestans*, which, translated literally, means 'infectious plant destroyer'. An appropriate name, given the fatal impact on the victims and its rapid spread from plant to plant and from field to field. Only an expensive combination of control methods is effective against this pathogen, which severely affects tomatoes as well as potatoes. Potato blight is found all over the world and is particularly problematic in all temperate regions with a humid climate, especially in wet years. This is because *P. infestans* belongs to the oomycetes, a group of water moulds that thrive in a damp environment. Diseases caused by *Phytophthora* also occur in other plants. *P. ramorum* is notorious for causing the death of many different trees and shrubs. This pathogen was first found in oaks in California over 20 years ago, where it was named 'sudden oak death'.

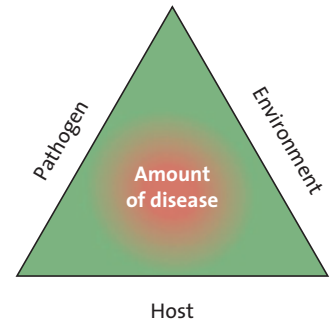
In the Netherlands, *P. ramorum* has been found on beech, American oak and on popular garden shrubs such as rhododendron and yew. Naturalised rhododendrons in woods fall prey to it because the plants can remain wet for long periods of time in the sheltered shade and moisture is essential for infection by water moulds. To prevent *P. ramorum* from spreading in the Netherlands, a joint effort is needed on the part of tree breeders, gardeners, nature conservation organisations, municipalities and private land and garden owners.

Better storage

DR. SUZAN GABRIËLS AND PROF. ERNST WOLTERING

We've all been there: you pick up an orange out of the fruit basket and there's a blueish powdery coating on the skin. These are the spores of *Penicillium*, the fungus that will have will have already penetrated far into the rotting orange by then. When you pick up the orange, the spores fly around. To prevent the fungus from spreading, it's best to throw away all the spoilt fruit. This is annoying for consumers and can sometimes be disastrous for the fruit and vegetable sector. Millions of tonnes can be lost in transport and storage in this way. After harvesting, most fruit and vegetables are stored for various lengths of time before being sent to the shops. Europe produces 60 million tonnes of fruit and imports 10 million tonnes, with a total value of €30 billion, according to data from GroentenFruit Huis, the Dutch fruit and vegetable sector interest group. But as many as 30 to 40 percent of these products are lost post-harvest for a variety of reasons, the biggest culprits being pathogenic fungi.

Storage is essential for products that can't be grown all year round. Apples and pears can be kept in good condition for ten to eleven months at a low temperature (0–1°C) and with low oxygen levels (1–2 percent). Storage at room temperature increases the risk of spoilage. Spoilage is not only brought about by infection with pathogens but also occurs as a result of ageing or over-ripening. Infection only happens if the pathogen is present, the fruit is susceptible and the environmental conditions are right.



Storage diseases can be prevented by growing resistant varieties, by implementing hygiene measures – often in combination with chemical crop protection products and treatment with hot water or UV radiation – and with cool storage conditions with low oxygen levels, which slows down infections and ripening and preserves the quality of the fruit.

Long-term storage is becoming increasingly important due to climate change. Droughts and floods have a negative impact on the quality of harvested products, for example. In addition, the number of permitted chemical crop protection products is shrinking. What will be needed in the future, therefore, are sustainable measures such as biological controls, further exploitation of resistance breeding and effective spoilage monitoring. The latter can be done using sensors that detect volatile substances to determine the right storage strategy.

Left: This rotting apple is infected with the oomycete *Phytophthora cactorum*, which is related to the bête noire of the potato, *Phytophthora infestans*.

Right: Conference pear with side rot, brown spots caused by the fungus *Cadophora luteo-olivacea*.

Does plant diversity reduce the risk

PROF. LIESJE MOMMER

Ever since 1950, ecologists have suspected that biodiversity protects plants against pathogens and pests. Ecosystems with a wide range of plant species, such as natural grasslands or tropical rainforests, seem to be less troubled by pests and diseases than agricultural systems in which entire fields contain the same variety of a single crop. In arable fields or on golf courses, you can sometimes see bare patches where a disease has taken hold and the plants have withered or stopped growing. You never see patches like these in a natural, species-rich ecosystem. Of course, diseased plants could be being overwhelmed by healthy ones, but ecologists think there is more to it than that. They suspect that biodiversity reduces the risk of plant pathogens and pests.

Since 1990, global attention has increasingly been focused on the negative effects of species loss on the functioning of ecosystems. Ecologists have started running trials to monitor the effects of biodiversity on plant growth. They are carrying out biodiversity trials in which they create vegetations with different combinations of species. They usually work with grassland species (grasses and herbaceous plants) as these are easier to handle than trees. One of their findings is that species-rich vegetations generally grow better than species-poor ones. Ecologists initially believed that the various plant species seemed to make better and more efficient use of the available resources together than they would on their own, but recently it has become clear that diseases also play a major role. Plant diversity seems to give

diseases less of an opportunity to take hold. This was revealed in a study of the presence of leaf fungi on plants in a biodiversity experiment. Although more species of plant pathogenic fungi were found in the species-rich plots than in the monocultures, fewer leaves were affected per plant overall in the species-rich plots.

Dilution effects

Much attention is being paid to these 'dilution effects' of plant diversity on pathogenic soil organisms because they are notoriously difficult to control, especially with the range of permitted crop

# of disease?

Ecologists at work in a biodiversity experiment in Wageningen. They harvest the plants every summer, enabling them to monitor the effects over several years.

protection products continuing to shrink. What do ecologists think is going on? Plants have an impact on the soil through their roots. Not only do they absorb essential nutrients, they also control soil organisms. If plant species remain in the same place in the soil for a long time, the number of plant pathogens there will increase. This effect is known as 'negative plant-soil feedback'. To prevent the build-up of pathogens, farmers rotate their crops every season. Various studies have shown that species diversity reduces negative plant-soil feedback. There are fewer soil-borne diseases in species-rich systems than in monocultures. We just don't yet know exactly how this works. Biodiversity in the soil is enormous: every hectare contains many billions of organisms belonging to thousands of species, and we don't know what most of them do. Generally speaking, most of the bad guys in the soil are fungi and nematodes, but among and within these groups of organisms there are big differences in life cycles which can cause differences in the dilution effects of biodiversity. One study which opened this 'black box' found that 26 pathogenic soil fungi decreased in density as plant diversity increased. But there are other studies in which numbers of nematodes were seen to grow with increasing biodiversity. So it is clearly not only species richness that is key, but also species composition. In theory, plant diversity can only lead to a dilution of diseases if the density of the susceptible host decreases. Plants of the same species are generally farther apart in mixed vegetation than in a monoculture, so soil-borne diseases spread more slowly, though only if the other species are not host plants for the disease.

Therefore, we seem to be able to directly reduce disease pressure by choosing plant species that are not hosts to the most notorious pathogens. But there is more going on below ground. Plants can affect the soil in another way: they excrete compounds through their roots which can inhibit the growth of pathogenic fungi. These compounds can also attract specific bacteria or other microorganisms which then compete with or attack the pathogens. Ecologists believe that species-rich vegetations can boost this natural arsenal of 'good guys', making the soil more resilient to many kinds of diseases.

If we understand how diversity in natural ecosystems reduces the risk of disease, we can apply the same principles to agricultural systems and make our food crops less vulnerable to diseases. The first step in this direction is strip cropping. Farmers and scientists are investigating whether diseases occur less frequently if different crops are grown in strips alongside one another in a field. Time will tell.

How can you outsmart plant pathogens and pests? Put up barricades and don’t give them a chance.

2 Prevention is better

Prevention is the operative word in plant health: how can we stay one step ahead of diseases, and how can we prevent crops from being attacked? One way of doing this is by adapting the plant's environment: making sure the barriers that keep out the pests are high enough. We can also build barricades into plants by selecting and breeding for resistance. Yet another way is to get plants off to a good start and protect them against intruders by pre-treating the seed. And nowadays we also have apps that sound the alarm when conditions become conducive to pathogens.

Arming crops with a resilient environment

DR. WALTER ROSSING

Cultural practices aimed at increasing plants' resistance to pests and diseases are attracting ever more interest. Creating distance between plants of the same species – think of it as agricultural social distancing – can also help keep crops healthy.

A poor living or working environment can make people sick and reduces their life expectancy. Medicines may take symptoms away but they don't deal with causes. The same applies to plants and agricultural crops: the environment they are grown in has a significant impact on their health. Farmers combine climate factors and crop and soil properties in the best possible way to maximise yields. You can't grow coconuts in Western Europe, for example, because coconut palms can't survive in the temperatures there. Heavy clay is unsuitable for root crops, as the structure and density of the soil causes roots to fork and split instead of growing nice and straight. And growing potatoes without pesticides, as is done on organic farms, is a risky undertaking in areas where a lot of potatoes are grown because of the high risk from air-borne plant pathogens. The choice of growing site and crop type determines how much effort a farmer has to put in to grow a good product – in other words, how much labour, machinery, fuel, fertilisers and pesticides are needed.

After the Second World War, a form of agriculture developed in the industrialised world which relies primarily on tactical adjustment through

the use of labour, capital and energy. This form of agriculture focuses far less on strategic choices, in other words preventing problems by maximising the use of natural processes and conditions. Dependence on external inputs such as artificial fertilisers and chemical pesticides makes conventional agriculture comparable to an industrial process in which inputs are converted into outputs, with the soil as the substrate. It is now clear that there are several major issues with this model: a major deterioration in soil quality worldwide, with more than a quarter of the world's soils already severely degraded; nitrogen and phosphate surpluses; a significant contribution to greenhouse gas emissions; and biodiversity loss, associated with a decline in pollinators and natural predators. Scientific reports reveal that this method of farming is no longer sustainable, and this is increasingly reflected in the policy papers of national and international organisations, the Dutch Ministry of Agriculture, Nature Management and Food Quality among them. Alternative models of food production make much greater use of strategic choices based around cultural practices.

'Good guys' and 'bad guys'

Cultural practices cover all cultivation measures that are carried out to increase plants' resistance to pests and diseases. An important measure is crop rotation, the practice of growing different types of crops in a field across a sequence of growing seasons. Different plant species make different demands on their environment and benefit it in different ways. By balancing crop requirements and beneficial influences across growing seasons, farmers can help create an environment that is favourable for growing crops. There are several different reasons for practising crop rotation. It boosts the reuse of nutrients; growing crops with different root depths – onions are more superficially rooted than cereals, for example – improves the soil structure; and it helps suppress pests and diseases. Ecologically smart crop rotation over time interrupts the build-up of plant pathogens and pests that spread by feeding on specific crops and mobilises soil microorganisms that live on plant pathogens and pests. This creates a balance between the 'good guys' and the 'bad guys', which benefits the farmer.

Mixed crops

Growing different types of crops in the available space – each crop in the rotation is grown on a different field each year – can also suppress pests and diseases as it encourages biodiversity in the soil and on the plants. The size of the plots also plays a role. It has recently been discovered that landscapes with smaller fields have greater biodiversity than those with large ones. Mixed cropping systems, in which different crops or different varieties of the same crop are sown or planted together, are less troubled by pests and diseases. Combinations of peas and wheat, for example, can yield up to 20 percent more: they share the nutrients in the soil, and plant pathogens can't spread so easily – a form of social distancing in arable farming. In wheat, potatoes and rice, it has been found that plots with mixed varieties that differ in their arsenal of resistance genes have lower disease pressure than plots on which only one single variety is grown. Mixed crops can also be used as ecological traps: caterpillars that attack cabbage plants find some varieties more attractive than others, so planting one or two plants of the attractive variety protects the others.

Intelligent use of cultural practices to produce healthy food with a minimum of external inputs is central to organic farming. In the rich part of the world, there are laws governing the criteria organic farming must meet in order for products to be sold as organic. The use of synthetic pesticides and artificial fertilisers is prohibited, for example. To nonetheless ensure good returns, organic farm-

Mixed cropping of peanuts *Arachis hypogaea* and the miracle tree *Moringa oleifera*, which provides both edible fruits and ingredients for herbal medicines.

ers are constantly exploring new strategies based on natural processes. As mentioned above, one successful approach is to ensure diversity in the crops grown. Another method that has attracted attention in recent years is agroforestry, or the combination of trees and annual crops. In this method, the trees benefit the crops in different ways: they provide shade, protection against the wind and shelter for organisms that suppress pests and diseases in the crops.

Strip cropping

Another source of inspiration – mentioned in the Dutch minister of agriculture's recently published policy vision – is strip cropping. This system involves growing two or more species of plants in alternating strips that are wide enough for the farmer to work with modern agricultural machinery but narrow enough to benefit from the biological effects of spatial diversity. Strip cropping has been popular in other countries for some time, partly to prevent erosion. It has been found to have beneficial effects in the Netherlands, too, including increasing biodiversity and reducing disease pressure compared with fields in which a single crop is grown. In organic potato cultivation, for example, yields can total as much as 50 tonnes per hectare, representing a 25 percent increase over full-field potato production systems. In addition, this system boosts numbers of farmland birds, and farmers who have experimented with it claim that it makes their work more enjoyable and satisfying.

There is still much to be discovered in terms of which crops make good neighbours, how wide the strips should be and how much diversity is enough. The inspiration for this comes from nature itself, where individual species grow together in smaller and larger groups. Could this form of agriculture be an option as robotisation progresses and machines are getting smaller? What is certain is that whereas cultural practices were an afterthought in plant disease textbooks 40 years ago, they now occupy a prominent place in the design of cultivation systems in which farmers use natural processes to produce food and feed.

Powdery or downy – can you tell your mildews apart?

DORIET WILLEMEN MSC

Grape leaf affected by downy mildew *Plasmopara viticola*.

It's a familiar sight: that white fuzzy mould on the leaves of oak trees or roses. Mildew is the general name for an enormous group of diseases that manifest themselves as a thin white powdery layer on plants. It is found on a vast array of plant species all over the world. The pathogen is usually named after the type of plant it affects: apple powdery mildew, rose powdery mildew, wheat powdery mildew, and so on. Almost every plant species has its own mildew fungus, which feeds on substances it extracts from the plant cells. As the fungal hyphae cover the leaves, the plant receives less sunlight and grows more slowly. In apple, the powdery mildew *Podosphaera leucotricha* affects shoots and buds, producing deformed fruits with rough skin. In cereal crops, the mildew fungus *Erysiphe graminis* can cause yield losses of as much as 25 percent.

The above diseases are all examples of powdery mildew, in which the white mould grows across the top of the leaf. Besides this, there is another large group of mildew diseases called downy mildew, in which the fuzzy growth usually appears on the underside of the leaf. In this case, the hyphae grow between the leaf cells. Downy mildew diseases are caused by water moulds (oomycetes). A particularly notorious example is the downy mildew *Plasmopara viticola,* which attacks grapes. In the late 19th century, it was discovered that spraying with a mixture of copper sulphate and lime helped to control this and other fungal diseases. Known as Bordeaux mixture, this was the most important chemical crop protection product until the Second World War.

Downy mildew is a much-feared disease in the Dutch horticulture and protected cropping sectors. An infection with *Bremia lactucae* in lettuce or *Peronospora farinosa* in spinach has disastrous consequences for the production of these leafy vegetables. A desperate search is currently under way for lettuce and spinach varieties that are resistant to mildew. A major problem is that downy mildew regularly develops new variants that break through the defences put up by a resistant plant. In 2018, a major research project set out to learn more about this and to identify new resistances that could be used to develop mildew-resistant lettuce and spinach varieties.

Thwarting pathogens and pests with resistance genes

DR. JAN-KEES GOUD

New resistance genes can also be broken again

THE AIM of plant breeding is to improve the genetic properties of plants. This is done by selecting and crossing suitable parent plants in the hope of finding a specimen among their offspring that combines the best characteristics of both parents. All the composite characteristics of a plant – known as the phenotype – are determined by the plant's genes – the genotype – as well as environmental influences.

The environment has virtually no influence over some characteristics such as flower colour. These are qualitative characteristics which are governed by a single or several genes and are often easy to observe on one plant. Other characteristics are strongly influenced by the environment, such as germination rate, growth and yields. These quantitative characteristics are usually determined by a large number of genes, each having a minor effect. Selecting the best plants for these characteristics requires several genetically identical plants and an environment that can be kept as equal constant as possible.

Defence against pathogens and pests

Plants are attractive sources of food for a wide range of plant pathogens and pests. And yet most plants don't seem to suffer that much. This is all down to evolution: over time, the plants have developed barriers such as growing a thicker waxy layer on leaves, producing substances that are toxic or repellent to pests, or activating a hypersensitive response to keep the pest out. All these defence mechanisms have a genetic basis, so they can be used for breeding. But plant pathogens and pests can also adapt genetically and can bypass the lines of defence by mutating, thereby creating an arms race between pathogen or pest and breeder.

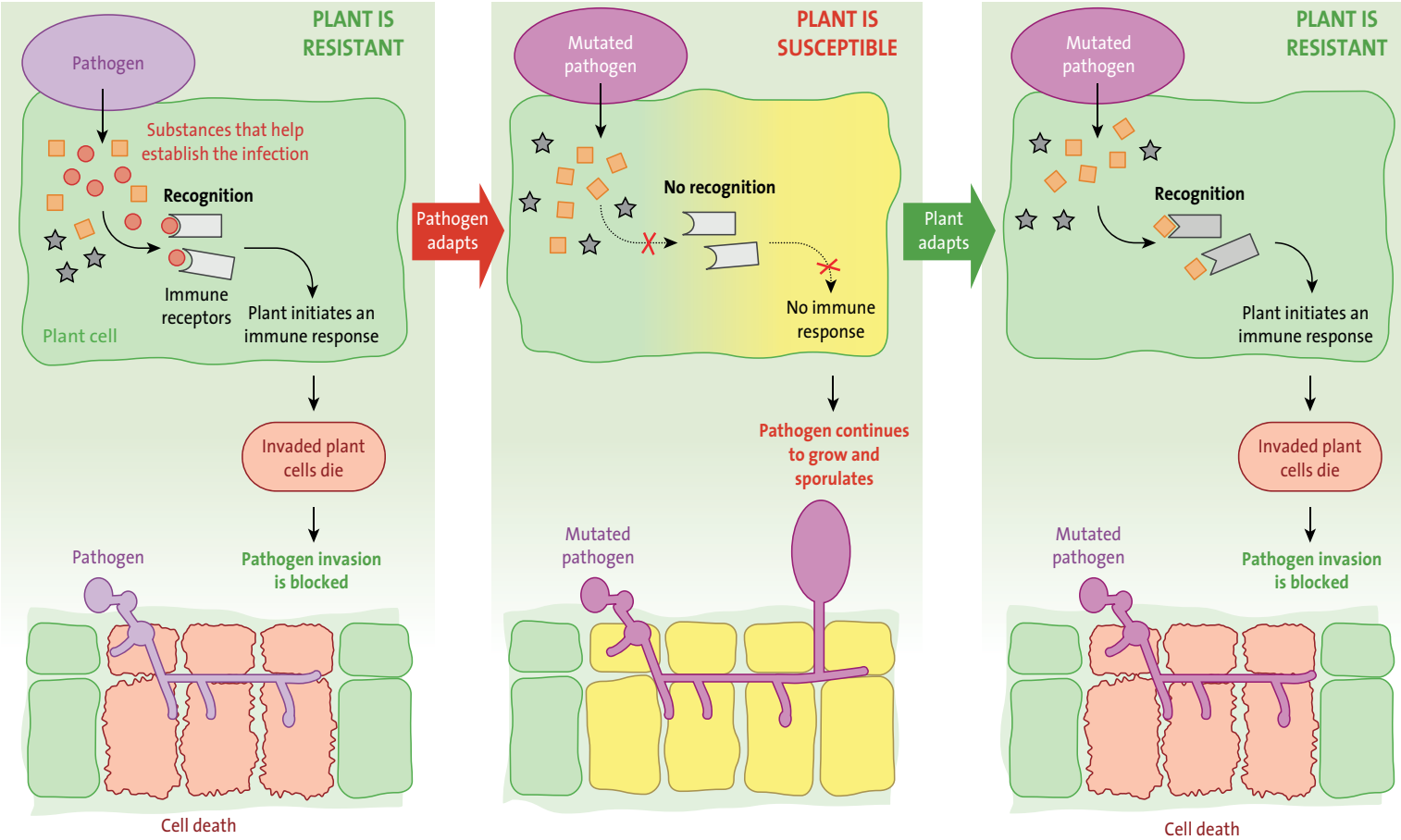
The hypersensitive response is a highly effective and typically complete form of resistance, especially against pathogens that specialise in one single plant species. The response is triggered as soon as the plant recognises its attacker. To infect plants, specialised pathogens use an arsenal of substances known as effectors, which they introduce into the plant to suppress its natural defences. When a plant recognises one of these effectors, it reacts by quickly killing off the infected plant cells. The plant can easily survive without those few cells, and the pathogen dies. The plant recognises effectors by using immune receptors: proteins in the cell membrane or in the cell itself which trigger a defence response when the alarm is raised. The genes that code for the immune receptors are called resistance genes and usually work against one particular pathogen.

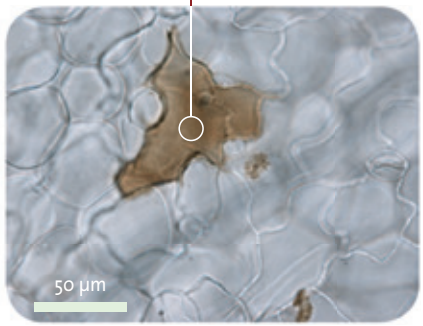
Arms race

The immune response is therefore triggered by specific effectors. If a variant of the pathogen emerges that has slightly altered or completely replaced its effector, the reaction will not occur and the plant's resistance will be broken. Plants can adapt their own arsenal of immune receptors so that they recognise the altered or new effector and can once again develop resistance. These new resistance genes can also be broken again, and so the arms race continues.

Breaking resistance can happen quickly. Microorganisms adapt easily because they reproduce very fast and can often quickly tolerate DNA mutations. Due to selection pressure, the one mutant that is able to infect the target will soon dominate the entire population. However, adaptation in plants is a much slower process and only takes place – without human intervention – in natural settings, where wild plant species co-evolve with their specialised pests and pathogens. That is

ARMS RACE BETWEEN PLANT AND PATHOGEN





A hypersensitive response on a resistant plant

Potato late blight on a susceptible plant

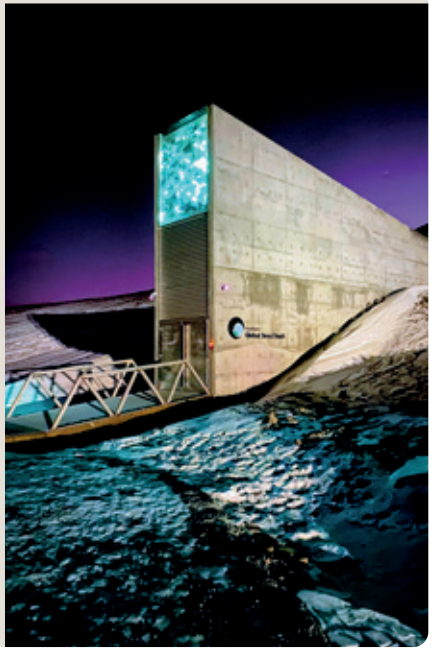
The pathogen produces many different substances that help it to infect the plant. These are detected by the plant's immune receptors, which initiate an immune response. If the pathogen has adapted by mutation, the plant no longer recognises the substances it produces and becomes susceptible. Through natural adaptation or breeding, the plant acquires new immune receptors and becomes resistant.

why the wild relatives of cultivated plants are real treasure troves for plant breeders, as they often possess the desired resistance genes. Because of the all-or-nothing nature of the hypersensitive response, the larger the area on which the resistant crop is grown, the more likely the plant pathogen will be to break the resistance. One solution to this is to 'stack' resistance genes, for example by simultaneously introducing three resistance genes into a variety. After all, the chances of the pathogen mutating its DNA at three points in exactly the right way at the same time are very small.

Besides resistance based on the hypersensitive response, which is usually determined by a single gene, there are other resistance mechanisms which depend on the activity of multiple genes. Known as quantitative resistance, this is effective against all strains of the pathogen. Each individual gene only has a minor effect, but when properly coordinated they form a substantial barrier. This may not result in complete resistance, but the disease progresses less rapidly and there is less risk of the resistance being broken than when it is based on the hypersensitive response.

Maintaining biodiversity in the field and in gene banks

Resistance genes are very common in old varieties and wild relatives of our cultivated crops. It is crucial to conserve this plant biodiversity. One way of doing this is to protect the locations where wild relatives occur. The alternative is to collect seeds of old varieties and wild species and store them in gene banks. The information is shared in a public database, making the seeds accessible to researchers and breeders. The Centre for Genetic Resources, the Netherlands, specialises in vegetable seeds. A backup copy of the seed collection can be kept in another gene bank such as the Global Seed Vault in Spitsbergen. The Spitsbergen facility houses the most important seeds from all the world's gene banks.



Classical breeding

Over the centuries, humans have genetically improved beneficial plants by successively cross-breeding them and then selecting the best specimens with no prior knowledge of the principles of heredity. Today we know that the genome, which is made up of DNA, forms the blueprint of an organism, and that all cellular and biochemical processes are controlled by genes – pieces of DNA that code for proteins.

In classical breeding, plant breeders cross plants with good characteristics. Crossing is particularly beneficial when the two parent plants complement each other's characteristics, for example in terms of yields, flavour, quality or disease resistance. In many crops, the first cross is followed by self-fertilisation of the offspring. In the next generation an array of new combinations of characteristics are then seen. The breeder obtains a pure line by allowing selected plants to self-fertilise in each subsequent generation. With the right selection, the plant develops resistance to a range of species of pathogens and pests.

Plant breeders regularly look for new resistances, often in wild relatives in the crop's area of origin or in gene banks (see box). They then cross the wild plant with a good quality, high-yielding modern variety. Resistance selection must be carried out with great care. At every stage, the breeder must check which plants are susceptible and which are not, and must avoid accidentally crossing a selected plant with a susceptible one which escaped the

pathogen by chance. It is therefore important to ensure that all plants are exposed to the pathogen and that the conditions are such that the disease can develop optimally.

Bringing together a large number of genes for quantitative resistance in one plant – in other words, building up a substantial barrier – can be done by repeatedly carrying out cross-breeding and removing the most susceptible plants each time. Over a number of generations, the genes that have a minor effect individually will accumulate, often resulting in surprisingly good overall resistance which is not easy to break.

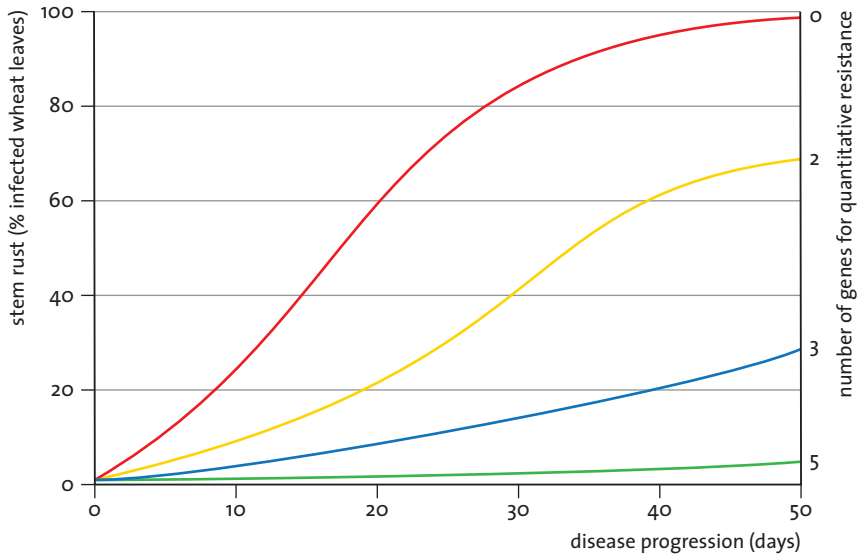
Faster selection

Marker-assisted breeding is a technique that is widely used today. Markers are variations in DNA which happen to be linked to a gene. Selecting plants with the right combination of markers indirectly selects for resistance. This is particularly useful as a replacement for labour-intensive disease tests, or in the case of quantitative resistance, because it allows resistance to be predicted on the basis of one seedling instead of several genetically identical plants. As we discover more about the genome of plants and the patterns in the DNA code of resistance genes in the future, we will be able to select directly for these genes.

Selecting from the variety list

Plant breeding produces genetically improved varieties for the farmer or grower to use. Variety lists contain descriptions of the characteristics of each variety and how resistant they are to major pests and diseases. This enables the grower to choose the varieties that are the most suitable for their land and that will meet their customers' or consumers' needs. Varieties that are resistant to pests and diseases have the major advantage of needing no, or only very little, disease control.

The more resistance genes there are in wheat, the less it is affected by the fungal disease stem rust.



Seed with a jacket

EDITORIAL BOARD

THE PRODUCTION of starting material is essential for agriculture: you need seed to grow wheat, rapeseed or flax, and you need seed potatoes to grow potatoes. Starting material must be of the highest quality, which is not as easy as it sounds: disease-causing fungi, bacteria and viruses can lurk in the seed and propagating material and can quickly make plants sick. Things can go wrong even while the starting material is in storage. In response to these threats, various methods have been developed to improve seed and propagating material, such as the following:

- Selection methods to clean up starting material: removing weed seeds, for example, or removing poor quality seed and propagating material. These days this is done using advanced X-ray techniques.
- Priming: pre-treating seeds to get them germinating simultaneously. This makes the crop more suitable for use with precision farming techniques.
- Coating: coating seed with chemical or biological crop protection products or growth stimulants. Some coatings are designed to prevent predation: they are dyed an unnatural colour so that birds will not recognise them as seed.
- Pelleting: covering seed with a coating so that it can be sown more easily and more uniformly. Seeding machines can only handle pelleted seed.

Seeds are often dyed so that birds do not recognise them.

The upside of plant diseases

DORIET WILLEMEN MSC

Semper Augustus, the flamed tulip, was worth a fortune in the 17th century. At the time, it was not known that this patterning was caused by a plant virus.

Plant diseases are not only harmful; they can also be attractive and even beneficial. Distinctive growth abnormalities and unusual discolorations on fruits or leaves can often be astonishing. Take flamed tulips at the time of tulip mania in the Low Countries in the 17th century, for example. For a brief period of time the bulbs were worth a fortune: as much as a whole year's salary or even the price of an Amsterdam canal house. What they didn't know back then was that this characteristic pattern on the petals was caused by a plant virus. Today, poinsettias are deliberately infected with a pathogen to improve their appearance. The pathogen in question is a phytoplasma, a bacterium with no cell walls. This microorganism disrupts the hormone balance in the plant, causing it to branch freely and keeping it more compact with fuller blooms. This is a perfect example of how a pathogen is used for economic gain.

Humans make clever use of pathogens in other situations, too. In tomato cultivation, young plants are deliberately infected with a weak variant of Pepino Mosaic Virus (PepMV) to protect them against the more aggressive strain of the virus. Known as cross-protection, this is a similar process to vaccination in humans.

Some fungi that plague farmers can be a treat for gourmets. For example, grapes affected by *Botrytis cinerea* produce an exclusive wine. And in Mexico, *huitlacoche* – corn cobs infected with corn smut (*Ustilago maydis*) – is considered a delicacy.

Mistletoe has a romantic image, but it is actually nothing more than a pesky tree parasite. This evergreen plant, *Viscum album,* whose name derives from an old English word for 'birdlime' due to the sticky properties of its berries, is nowadays grown on apple trees for sale as a Christmas decoration. When a sticky mistletoe berry lands on a branch, the seed can take hold in the bark and grow into a plant. Mistletoe does not form roots itself but infects its host and lives off the sap.

Apps with gut feeling

EDITORIAL BOARD

THE ADVANCE of robots, artificial intelligence and big data is unstoppable, including in agriculture and horticulture. Picking robots that harvest sweet peppers and tomatoes are cutting labour costs. High-tech self-driving sprayers are reducing the use of crop protection products in fruit cultivation, and drones with sensitive cameras are helping to detect signs of disease in the field at an early stage. During planting, sowing, fertilising or spraying, farmers are increasingly relying on the control systems in their tractor cabs rather than on gut feeling.

Precision agriculture is based on big data, which farmers need help to get the most out of. That help comes in the form of agricultural and horticultural platforms that collect and integrate a wide range of information. An example is the Dutch Akkerweb, in which all agricultural fields in the Netherlands have been mapped using satellite images. The system also records all meteorological and field-related data, including crops grown in each field every year and the yields and fertilisers applied. Farmers use this information to determine their business strategy. Akkerweb provides a range of apps that help prevent diseases and crop losses. We explain some of them below.

Apps help the modern farmer to practise precision farming. During planting, sowing, fertilising or spraying, farmers increasingly rely on the control systems in their tractor cabs rather than on gut feeling.

Potato late blight, which is caused by *Phytophthora infestans*, can completely destroy a susceptible crop in damp conditions in as little as two weeks – that is how quickly the epidemic takes hold. Preventive control with crop protection products is essential, but only if the weather conditions are conducive to an infection. The *Phytophthora* app recommends whether and when to spray and which product to use. This can be quite convoluted because the products are much less effective when it rains.

The NemaDecide app focuses on nematodes. It not only recommends which crops to grow when certain nematode infections are present but also which varieties are the most suitable. The app calculates the impact of a nematode infestation in the field in a few years' time and therefore the damage it will cause. Farmers can choose from a range of options, allowing them to pick the best strategy themselves.

There are various early warning services available based on accurate local weather forecasts. These are indispensable for fruit growers because spring frosts pose a threat to harvests. Spraying the trees with a sprinkler system helps protect them against frost damage. These services are warnings in the truest sense of the word: they can wake the farmer up in the middle of the night!

Healthy grass

DR. IRENE VROEGOP

Like crops, grass is susceptible to diseases. The most common types of grass used in soccer stadiums are perennial ryegrass and smooth meadow-grass. Different grass species are used on golf courses, such as red fescue, Kentucky bluegrass, perennial ryegrass and common bentgrass. Perennial ryegrass is a species that is susceptible to a range of plant diseases, such as leaf spot, rust and snow mold. These fungal diseases spread most rapidly when the plant is stressed due to factors such as low humidity, high temperatures or a lack of nutrients. Damage to the turf caused by players can increase the risk of fungal infection.

Disease damage is a problem that has every groundsmen searching for a solution. Resistant grass varieties are often not an option for playing fields and golf courses because modern grass species have been selected for their recovery capacity and mowing height. The use of chemical crop protection agents has been ever more tightly controlled in Europe in recent years. According to the EU directive on the sustainable use of pesticides, their use should be minimised or banned entirely in areas used by large numbers of people or by vulnerable groups. This requirement therefore also applies to playing fields and golf courses. In the *Green Deal Sportvelden* (Green Deal on Playing Fields) in the Netherlands, stakeholders have agreed to stop using chemical crop protection agents on playing fields and golf courses except where absolutely necessary from 2020 onwards. Greenkeepers therefore have to find other ways to fight diseases in their grass. Taking preventive measures and monitoring various factors that impact on the diseases are an important part of this.

Continuous monitoring

Groundsmen can take action in good time by continuously monitoring the conditions in the field, such as the light levels, the relative humidity, the temperature and the wetness of the grass. For example, it is better to give small amounts of water

on an ongoing basis rather than large amounts all at once. This allows the grass to dry out more quickly, giving plant pathogens less of a chance. They can also monitor nutrient levels: diseases are more likely to occur if certain nutrients are too plentiful or in short supply. Other points to keep an eye on are the pH of the soil and ensuring that grass cuttings are removed after mowing to reduce the spread of plant pathogens.

It is also important to keep mower blades sharp to limit damage to the grass. Relative humidity and temperature also impact greatly on disease pressure, but these factors are more difficult to control on a golf course or in a sports stadium. However, special fans are now available that can improve the conditions for the grass with advanced air circulation and cooling. There are also models that predict the pressure from various grass diseases based on temperature and relative humidity. Special machines can then destroy the emerging plant pathogens with ultraviolet light. Monitoring and recording the quality of the field, the amount of precipitation and the use of nutrients and chemicals also play an important role in good grass management. Using the tools described above, the AFAS soccer stadium in Alkmaar, the Netherlands, has already been able to do away with chemical pesticides altogether. But by no means all playing fields and golf courses are that far advanced as yet.

Damage to the turf caused by players can increase the risk of fungal infection.

Pathogens sometimes break through the barricades. When that happens, the only remaining option is control. This is increasingly being done biologically: with natural predators and green chemistry.

3 What if a disease strikes?

If all efforts are focused on prevention, why do plant diseases still happen? Unfortunately, there are still a good many plant pathogens for which resistance is not available. And even where resistance does exist, plant pathogens can sometimes mutate and bypass it. In that case, the only remaining option is a direct form of control, either biological or chemical. The question of whether we can manage without chemical control is a hotly debated topic at the moment, with the Dutch government aiming to phase out the use of chemicals within ten years. This could result in sugar beet, which is under extreme pressure from all kinds of pests and diseases, disappearing from our fields altogether. Potatoes will still be around, however, although yields could plummet. Biological control (also known as biocontrol) could be an alternative, but are there enough effective green products available?

Protecting crops with chemistry

ASTRID SMIT MSC

Crop protection has become increasingly sophisticated and targeted over time. It has also become greener in recent years. This development has been going on for some time in protected cropping, but it is now also starting to gain momentum in outdoor systems. The Dutch government wants agriculture to be free from synthetic crop protection products by 2030. But is that possible?

We are used to seeing an abundance of sweet peppers, pumpkins, green beans, chicory, kale, asparagus, apples and pears on supermarket and greengrocers' shelves, all looking fresh and inviting without a single rotten or mouldy patch in sight. And you'll never see a sign saying 'Sorry, no grapes today. Mildew has destroyed the harvest.' This is because our fruit and vegetables are sourced from a global market. If one grower can't deliver, there's another that can. This large-scale production and constant supply of fruit and vegetables is also made possible thanks to high levels

Arable farmer Gerard Breunissen is using a new sprayer system. The perspex panel prevents the wind from blowing the chemicals in the wrong direction. The spray lands directly on the crop and no longer spills over into the ditch or onto the verge alongside the field.

of agricultural expertise, especially in Europe.

Farmers and growers know how to keep many pests and diseases under control. Non-organic growers rely gratefully on synthetic pesticides. In the Netherlands, 9.4 million kg of crop protection products were sold in 2018, with just under half used for controlling fungi and bacteria, a third for controlling weeds and a few percent for killing insects. The figure for the whole of Europe is 380 million kg per annum, France, Spain, Germany and Italy being the largest consumers.

If you grow large concentrations of plants of the same species in the same place, as most farmers do, you also attract their pathogens and pests. So if you don't want them to eat your crops and damage your harvest, you have to intervene. Humans have been trying to control these aggressors ever since the dawn of agriculture around 12,000 years ago. The Chinese were already sprinkling lime and wood ash over harvested produce to combat pathogens three thousand years ago; in the Roman era, farmers would use sulphur and bitumen to kill leaf-roller moth larvae in vineyards; and a few centuries ago, farmers would spray nicotine from tobacco or pyrethrins from chrysanthemums to keep aphids and other sucking insects at bay.

Bordeaux mixture

'Chemical control of plant diseases did not appear on the scene until the end of the 19th century, though,' says Jolanda Wijsmuller of Bayer Crop Science. Back then, it was discovered by chance that the 'Bordeaux mixture' – a mixture of copper salts and lime – was an excellent way of protecting grapes against mildew. This mixture was later found to be very effective against potato late blight as well. 'From that point on, the chemical industry, particularly in Germany, started to develop a range of broad-spectrum synthetic compounds to control pests and diseases in crops.'

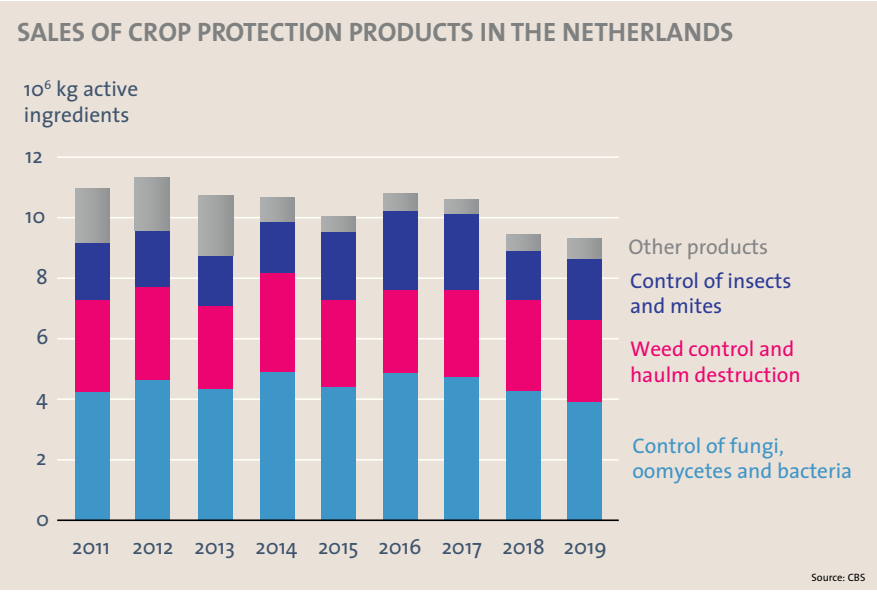
For example, from 1910 onwards various mercury compounds came on the market, which enabled farmers to prevent seeds of wheat, barley, rye and other cereals from becoming infected with fungi. The 1930s saw the development of new fungicides such as dithiocarbamates and captan compounds. These, too, proved to be extremely effective in nipping fungal spores in the bud, such as scab in apples and pears and downy mildew in onions. 'These products are still in use today,' Wijsmuller says. 'The fungi don't get much chance to build up resistance because the products have such a broad-spectrum effect. They attack the fungi at several basic points.'

Broad-spectrum products

The pre- and post-Second World War periods also saw the launch of broad-spectrum crop protection products such as 2,4-D (2,4-dichlorohenoxyacetic acid) and MCPA (2-methyl, 4-chlorophenoxyacetic acid) for weed control. These compounds stimulate plant growth, causing the unwanted weed to bolt and die. The advent of these products reduced or even eliminated the need to hoe, delivering sub-

stantial labour savings for farmers. Products based on glyphosate and glufosinate were introduced in the early 1970s. These destroy the above-ground green parts of the plant; glyphosate even penetrates into the roots. The first soil herbicides that prevent weeds from germinating originate from that time. Farmers still use 2,4-D, MCPA, glyphosate and various soil herbicides to control weeds today.

To tackle insect pests, in the pre- and post-war years the chemical industry developed broad-spectrum insecticides such as chlorinated hydrocarbons. One of these was DDT, but this proved so harmful to the environment – it is highly resistant to environmental degradation – that it was banned in the early 1970s. Pyrethroids (the synthetic variant of pyrethrins), carbamates and phosphoric esters took over the market, to be joined in the 1990s by neonicotinoids. However, the European Union has now prohibited the use of the latter in certain crops because of their links to bee mortality.



Targeted products

Other, more targeted chemical crop protection agents, so-called systemic compounds, came onto the market in the 1950s. Rather than blanket killing all fungi or insects, these only destroy certain species of fungi or particular life stages of insects. These more targeted compounds can be used effectively alongside natural predators, the form of biological control that has emerged in protected cropping and fruit growing since the 1970s. If you are using a naturally occurring parasitic wasp to get rid of aphids in fruit crops but you also have a problem with caterpillars, for example, you can use selective agents that only kill the caterpillars.

The disadvantage of these targeted compounds is that pests can more easily develop resistance to them. Even minimal genetic changes in the pathogen can sometimes be enough to have that effect. 'Active substances from the triazole and SDHI group of fungicides, both of which are widely used in agriculture and horticulture to control diseases such as powdery mildew, have given rise to numerous forms of resistance over the years,' Wijsmuller says.

The late 1980s saw the emergence of integrated crop protection – the smart and economical use of chemical compounds. Rather than spraying preventively, this involved first observing how a pest or disease develops and then using early warning models to monitor whether the threshold for economic damage is being exceeded. Since 2014, all European farmers and growers have been required to follow the basic principles of integrated crop protection.

Over the past two decades, more and more crop protection products of natural origin have come onto the market, including viruses, bacteria, fungi and plant extracts. And yet this 'green chemistry' still only accounts for a very small share of the total market, says Wijsmuller. Just 5 to 7 percent of sales of crop protection products in the Netherlands

consist of green chemistry; the rest is still synthetic compounds.

Despite this, the Dutch Ministry of Agriculture, Nature and Food Quality wants agriculture to stop using chemical crop protection agents by 2030. 'The pressure is very high,' Wijsmuller says. 'Pesticides are evaluated every ten years, and some are dropped every time.' The switch to biological control and green chemistry in greenhouses has been relatively successful, she believes. However, it is much more difficult in outdoor cropping systems. 'If you aren't allowed to use herbicides any more, how do you get rid of weeds without incurring huge costs? And green chemistry is less robust than the synthetic versions. Farmers can't rely on that alone.' She therefore finds the ministry's plans extremely ambitious. 'It only gives us ten more seasons to explore alternatives. That's really not very long. I don't think it will be enough,' she says.

Fungal, viral and bacterial diseases can also be kept in check using natural predators

Biological control: using what nature offers

DR. JÜRGEN KÖHL AND PROF. GERBEN MESSELINK

To keep producing enough food, we need to protect our crops from damage caused by plant diseases. We also need to reduce the number of chemicals we use even further to minimise the risk to humans, animals and the environment. In protected cropping systems, the use of chemical crop protection products against harmful insects and mites has been greatly reduced by the widespread use of cultivated natural predators. These include arthropods such as predatory mites, predatory bugs and parasitic wasps, but also nematodes that parasitise insects or microorganisms that infect and eventually kill insects and mites. This form of biological control has been used successfully against a wide range of pests since the 1970s. Besides insect pests, natural predators are also used to control fungal, viral and bacterial diseases. Known as microbial antagonists, the natural enemies of these pathogens are usually also bacteria, fungi and viruses. They can be identified by studying nature carefully and selecting the most effective enemies.

Many types of microorganisms live in the soil, on plants and in dead organic matter. They communicate with each other via chemical compounds. They work together in communities to break down food sources or compete with their neighbours for food and space, sometimes using inhibiting substances to achieve their aims. Microorganisms that use other microorganisms as a source of food, known as hyperparasites, generally make good candidates for biological control, but the same is true of benign microorganisms that trigger the immune system of plants and therefore indirectly inhibit plant pathogens and pests.

These microorganisms are isolated from the

soil or from plants or crop residues and tested for their properties. This is done by first observing the extent to which they suppress plant pathogens and then by checking whether their ecological properties are appropriate for the intended uses. For example, for leaf applications in outdoor cropping systems, they must also be UV tolerant and resistant to cold and drought. Before they can be used commercially, they must also be tested to ensure they are safe for humans, animals and the environment, of course.

There are other requirements that must also be met. Take a microbial product containing fungal spores or bacteria marketed as dried powder, granules or seed coatings, for example. The microorganisms are grown by the manufacturer in large bioreactors and then processed into a product. These microorganisms will only be suitable for commercial use if they can be produced in large quantities and have a shelf life of at least several months. The development of these biological agents usually entails testing several hundreds or even thousands of candidates step by step in order to arrive at a product that is effective in practice.

How do microorganisms protect plants?

Microbial crop protection products rely on bacteria or fungi that use a wide range of mechanisms to protect plants from pathogens. One important mode of action involves priming the plant's defences using induced resistance. The beneficial microorganisms produce small amounts of special substances called microbe-associated molecular patterns (MAMPs) which are absorbed into the plant via the roots or leaves and induce immune responses. The plant then produces substances which inhibit the pathogen as soon as it enters, strengthening physical barriers such as cell walls as well.

These microorganisms can also alter the local conditions in which plant pathogens grow. They consume sugars or specific nutrients such as iron, making them unavailable to the plant pathogens, which are then out-competed. These two important modes of action – induced resistance and competition – involve no direct interaction between the natural predator and the plant pathogen. Hyperparasites, on the other hand, do interact directly with the pathogen: they live on and in pathogenic fungi, kill them and consume the nutrients released from the host cells. Many microorganisms use small amounts of toxins to defend their niche against other microorganisms. This method is also deployed in biological crop protection in which bacteria and fungi secrete small quantities of inhibiting substances as they interact with the pathogen. These substances then break down rapidly in the environment.

According to the regulations, microbial products that control diseases are crop protection agents and are therefore subject to authorisation. The European Union and the Dutch authorities (the Dutch Board for the Authorisation of Plant Protection Products and Biocides, *Ctgb*) assess the properties of microorganisms, such as natural spread, life cycle or mode of action. They also check for any relationship with microorganisms that can infect humans or animals and how high the risk is of this happening. In addition, they assess the potential for production of unwanted substances. Finally,

The mottled arum aphid *Neomyzus circumflexus* is a pest in greenhouses where it attacks sweet peppers and ornamental plants such as chrysanthemums and fuchsias. It can be controlled using the parasitic wasp *Aphidius ervi*.

Sugar beet: a hairy situation

DORIET WILLEMEN MSC

Rhizomania, a viral disease, causes bearding on sugar beet.

Sugar beet is not something that generally attracts much attention. But what people may not realise is how important healthy sugar beet crops are for products such as biscuits, sweets and chocolate. Another little-known fact is that sugar beet cultivation is under considerable pressure. More and more crop protection agents are no longer authorised for use, and other ways are having to be found to keep harmful pathogens at bay.

Nematodes are minuscule worms. Some species are particularly partial to sugar beet. One species of concern is the white beet cyst nematode *Heterodera schachtii.* After hatching, the juveniles penetrate the roots and feed on root cells. This reduces water absorption, causing the beet plants to wilt, especially on dry days. After a while, small cysts around 1 mm in diameter form on the roots. These cysts are the bodies of swollen females, which expand outwards through the plant tissue. They are full of eggs which can survive in the soil for several years if the conditions are right. It is possible to reduce the nematode population in infected fields by as much as 80 to 90 percent by planting a cover crop. This works as follows. The cover crop (white mustard or oilseed radish) excretes substances that lure the nematodes out of the cysts, after which they starve because they cannot feed on the roots of the cover crop.

Rhizomania is a viral disease of sugar beet which causes the normally spherical, bald roots to become pointed and grow a mass of thin hair roots, giving them a bearded appearance. Unusually, this virus is transmitted by a soil fungus, whereas the majority of plant viruses are transmitted by insects. A virus transmitted to sugar beet by an insect is beet yellows virus. The green peach aphid passes on this virus when it sucks plant sap from beet leaves – similarly to the way the malaria mosquito infects people. Once there is a virus infection in a field, it spreads very quickly when there are aphids present. The yellowing disease caused by this virus can be limited by closely monitoring the beet plants from the start and controlling the aphids at an early stage. Despite this, this virus cost European growers €7 million in 2019 alone.

The parasitic fungus *Verticillium biguttatum* penetrates the pathogenic fungus *Rhizoctonia solani* and is a suitable candidate for biological control.

multi-year field trials have to be carried out to demonstrate the efficacy of the microbial product. Details of which crops these products are suitable for and which diseases they can be used against are given on the label. The mode of administration and the application rate are also determined. The authorisation procedure can take many years and is therefore expensive.

Biological control industry

Microbial biocontrol agents are produced by specialist companies. There are more than two hundred such companies worldwide, most of which are small and medium-sized enterprises, although multinationals are also now recognising the potential of these products. Many of these companies are members of the International Biocontrol Manufacturers Association (IBMA), whose aim is to further develop the commercial use of biocontrol agents. The annual IBMA conference attracts more than a thousand participants. The world market for biocontrol agents, which now accounts for about five percent of the entire crop protection market, is growing by about 16 percent per year. The use of these agents is therefore expected to rise in the future. Biocontrol agents are already much more widely used in greenhouse cultivation than in outdoor cropping systems. Some greenhouse growers use them almost exclusively now.

However, in Brazil farmers are already using many microbial agents in outdoor cropping systems across an area of as much as seven million hectares. Europe is expected to follow suit, as chemical crop protection agents become further restricted in the near future – over the next ten years in the Netherlands – and robust agricultural systems with high disease resistance are developed. This will require the development of new microbial agents on an ongoing basis.

Microbial biocontrol agents can go some way to replacing chemicals in conventional cropping systems. This will reduce residues in food and lessen the risk of pathogens developing resistance to chemicals. Future resilient and sustainable cropping systems will use a combination of preventive measures such as disease resistance of crops, crop rotation and the use of natural buffers created by natural predators. The microorganisms around the root play a key role in this. Where there is a risk of certain diseases occurring in a cropping system, microbial agents can be applied preventively or correctively. Selective microbial agents complement the buffering by the microbiome that is naturally present. Broad-spectrum chemicals, on the other hand, can disrupt it. Selective microbial agents will therefore be a particularly valuable element in future cropping systems.

A ‘vaccine’ for the elm

DR. JOEKE POSTMA

The elm is a beautiful and versatile tree which makes an important contribution to biodiversity. Almost seventy species of caterpillars feed on the elm, and butterflies and moths such as the white-letter hairstreak and the white-spotted pinion are fully specialised on it. Since elms are resistant to wind, recover easily from root damage and are relatively insensitive to air pollution, they make ideal avenue and street trees. The Netherlands once had an abundance of elms, with an estimated 1.5 million trees, mainly along roads and canals, in cities and in coastal regions.

Dutch elm disease arrived in the Netherlands just over a hundred years ago, in 1919. Professor Johanna Westerdijk of the Phytopathological Laboratory in Baarn started investigating the cause. It was the fact that the disease was successfully identified in the Netherlands that gave it its common name. The cause turned out to be a fungus, *Ophiostoma ulmi*, which is spread by the elm bark beetle using an ingenious strategy. The beetle lays its eggs under the bark of weakened or recently dead elm trees. The emerging larvae feed on the inner bark (phloem) and eat their way out after pupating. The young beetles fly out in search of young bark on healthy trees, thereby transmitting the fungal spores from diseased or dead elms to healthy ones in a highly efficient way. When a tree becomes infected, branches at the top of the tree wither first, but eventually the whole tree dies and becomes a breeding ground for new beetles, thus completing the circle.

The elm population in several European countries was reduced by up to 40 percent by this first outbreak of Dutch elm disease. From 1960 onwards new clones were planted that were expected to be sufficiently resistant. However, a new, more aggressive fungus (*Ophiostoma novo-ulmi*) from America appeared in Europe in 1972, resulting in mature elms being wiped out almost everywhere in Europe.

To prevent the elm from disappearing from the landscape altogether, the Netherlands implemented a strict, government-coordinated policy between 1977 and 1991. This involved removing affected and dead trees and promptly debarking dead wood, reducing the number of elm beetle breeding sites and therefore preventing the disease from spreading. As a result, the percentage of new annual infections dropped from over 10 to 1 percent. However, this policy was abandoned in 1991 and the national annual loss rate rose again to 10-15 percent. Exceptions were the City of Amsterdam and, from 2005, the Friesland Elm Watch Foundation (Iepenwacht), both of which continued to pursue the old policy.

Injections with ‘vaccine’

In 1992, a biocontrol agent became available which, when properly applied and repeated annually, protects healthy elms. It contains spores of the fungus *Verticillium albo-atrum*, which activate the tree’s immune system on injection. This mechanism is known as ‘induced resistance’. Like a flu vaccine in humans, it has to be administered before the tree becomes infected. Trees must be

Elm with Dutch elm disease. The branches die as the vascular tissue becomes blocked. New shoots also wither rapidly. Botanical illustration from Utrecht University, 1941, used by Professor of Plant Pathology Johanna Westerdijk.

injected against Dutch elm disease every spring to protect the new sapwood. This treatment, which plays a particularly important role in protecting urban elms, is expensive and labour intensive. But clearing diseased trees and planting new ones is many times more costly. Around 25,000 elms are injected with this compound in the Netherlands every year. As a result, the loss rate is now below 0.1 percent. The Dutch-produced vaccine is also being used in several other countries. Unfortunately, it doesn't work if the infection enters via roots that come into contact with diseased trees.

A third control strategy is planting resistant varieties. However, developing these in trees is a long-winded process. Research into the development of resistant elm varieties first began in the first half of the 20th century. Large-scale, long-term cross-breeding and selection programmes have been carried out in the Netherlands and the USA in particular. These are now bearing fruit: a growing number of resistant elm varieties are becoming available.

With the combination of control strategies and the availability of resistant varieties, the elm once again has a bright future. Amsterdam, which is home to 31,000 elm trees, plays host to the annual Springsnow Festival, which marks the beautiful natural phenomenon of elm seeds whirling through the streets like spring snow. Dutch Butterfly Conservation is also reporting a positive effect on biodiversity: the white-letter hairstreak, which had retreated to just a few sites in Limburg, has now also been spotted in Nijmegen, Eindhoven, Winterswijk and even Amsterdam!

Like many of us humans, plant pathogens and pests are frequent fliers. Globalisation has caused a massive uptick in the spread of plant diseases. What can we do about this?

4 Monitoring plant health

Most of us may not be aware of this, but plant health is monitored right across the globe. There is an International Plant Protection Convention as well as covenants both inside and outside Europe, meaning that no plants may be traded without a certificate or passport. The aim of these measures is to prevent plant pathogens and pests from hitching a ride and creating new victims. Where they do manage to fall through the net of international rules, tough measures are applied to prevent further infection, such as control and quarantine. Plant health protection is very similar to public health protection.

How is plant health organised globally?

JUST AS a new form of flu or coronavirus can spread around the world, so too can plant pathogens and pests. How do countries work together to prevent this, and how can individual countries protect themselves?

DR. NICO HORN

There are thousands of pests and diseases that threaten plants the world over. Pests include insects that feed on plants; diseases can be caused by fungi, oomycetes, bacteria, viruses and nematodes. Most plant pathogens and pests have only a limited distribution, perhaps because the plant they feed off only grows in certain areas or because they have a preference for high temperatures and therefore only survive in the tropics. Others may not yet have had the chance to spread around the globe. Moreover, certain pathogens or pests may only be found in one part of the world and do not cause problems there because the plants they live on have become accustomed to them and have adapted.

When plant pathogens or pests spread to another part of the world where the plants are not adapted to them, this can cause enormous damage and the problem can spread rapidly. Compare this to when Europeans arrived in the Americas, bringing with them diseases such as smallpox, measles and flu to which the local population

had no immunity. Take the pine wood nematode, *Bursaphelenchus xylophilus*, for example, which originated in North America. Local pine trees are barely affected by it at all. But when the nematode spread through Japan and parts of Europe, it caused massive mortality of pine trees.

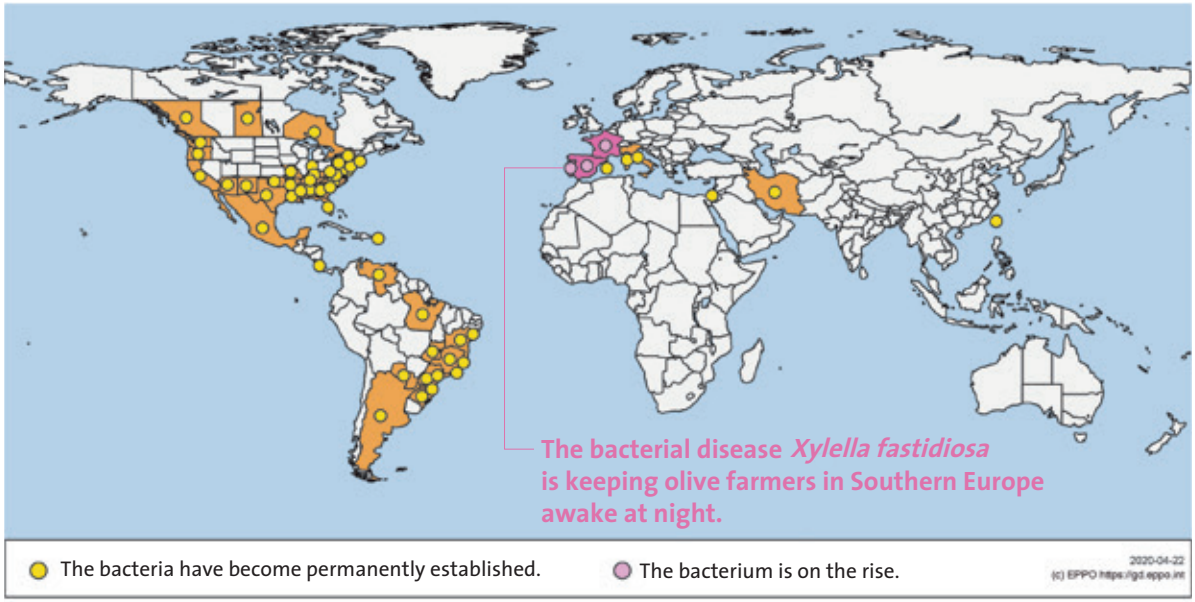
The extent to which plant pathogens and pests can spread under their own steam is limited. Humans spread them over much greater distances by trading and moving plants around. The last few decades have seen a dramatic rise in the spread of plant pathogens and pests due to the increase in international trade in plants such as exotic fruits and vegetables, cut flowers, seeds, cuttings, trees and wood. All these plants and plant products can harbour pathogens and pests.

In 1951, the International Plant Protection Convention was drawn up by a number of countries with the aim of collaborating on phytosanitary measures to protect plants against pathogens and pests. Revised in 1997, this convention has now been signed by more than 180 countries, including the USA, the UK and the European Union, and is recognised by the World Trade Organisation. The aim of the convention is to ensure international collaboration on protecting plants worldwide against the spread of plant pathogens and pests in order to maintain food security and biodiversity while allowing international trade in plants and plant products to take place. Countries are only permitted to impose health requirements on plant imports if they are scientifically substantiated.

Plant health certificate

One of the ways to guarantee plant health worldwide is to use plant health certificates. By issuing

The last few decades have seen a dramatic rise in the spread of plant pathogens and pests due to the increase in trade in plants.



Distribution of *Xylella fastidiosa* around the world. This bacterium can occur on 200 different crops. Olive plantations in Southern Europe are currently under serious threat from it.

these, exporting countries declare that the plants and plant products they export comply with the health requirements of the importing country. Each importing country has its own legal requirements for plant imports: it may require plants to be inspected and free from specific pathogens or pests prior to import, or it may require them to undergo field inspections or laboratory testing as well.

Besides the trade in plants and plant products, pathogens and pests can also spread around the world in other ways. One important source of plant pathogens and pests is wood packaging materials (crates, pallets) used for transporting items such as car parts, computers or toys. The wood may contain insects and nematodes that can attack trees. Since the 1990s there have been a number of outbreaks of new pests and diseases in Europe that can be traced back to wood packaging materials, such as the pine wood nematode and the Asian longhorned beetle. At that time, a standardised method of treatment was agreed worldwide in the International Plant Protection Convention. Individual countries can make this treatment mandatory in order to prevent the spread of pests and diseases in wood packaging. However, providing a plant health certificate for every pallet and crate was not considered feasible, so it was agreed that a special mark could be applied to wood packaging materials.

Plant health certificates, formally known as phytosanitary certificates, have been in existence for over a hundred years. In the Netherlands, the first ones were issued in 1899 to declare that plants being exported from Boskoop to the USA were free from grape phylloxera. Now, hundreds of thousands of certificates are issued annually in the Netherlands and millions worldwide. Despite the many security features used on these certificates, fraud is clearly on the rise, especially since the advent of high-quality colour photocopiers and printers. With this in mind, electronic versions of the plant health certificates have now been developed which are more fraudproof and are globally harmonised under the International Plant Protection Convention.

Bringing home plants, seeds, fruits or flowers from other countries increases the risk of spreading plant pathogens and pests

The European and Mediterranean Plant Protection Organization (EPPO) has produced a series of posters that warn travellers about the risks of bringing plants from other countries.

Bringing home plants, seeds, fruits or flowers from other countries also increases the risk of spreading plant pathogens and pests. What is more, there has been a sharp rise in plants being traded online. Customers ordering these plants may not know where they come from or whether they are free from new pests or diseases. This subject is being discussed within the International Plant Protection Convention, as countries cannot solve this on their own. Many countries have undertaken to severely limit opportunities for people to take plants, seeds, fruits or flowers with them when they travel. Checks on parcels – the way internet orders enter the country – will also be stepped up.

International Year of Plant Health

The UN declared 2020 the International Year of Plant Health. The main objective of this year was to raise awareness of the importance of plant health. Protecting plant health is in everyone's interest, and we can all do our bit. Members of the public can take more care when ordering plants online and stop bringing plants home from other countries. Politicians can recognise the importance of protecting plant health and make more funds available for it. Ultimately, plants are essential for our food supply and biodiversity.

The International Plant Protection Convention also contains agreements on regional cooperation. The European and Mediterranean Plant Protection Organization (EPPO) was founded in 1951. It has 52 member countries in Europe, North Africa and Central Asia. EPPO provides its members with advice, makes proposals for harmonising implementation and carries out risk analyses to support the control of high-risk pests and diseases. It also develops educational materials that can be used to raise awareness in all countries. In addition, EPPO provides a platform on which plant health experts can cooperate, network and share experiences, allowing the limited number of experts in this field to join forces. The spread of plant pathogens and pests can only be effectively tackled if countries cooperate globally and regionally and if policymakers, experts and members of the public all do their bit.

The side effects of globalisation

PROF. JELLE REUMER

It's the elephant in the room: plants and animals being carted around the globe. As mentioned at various points in this publication, the blessings of globalisation also have a downside, the coronavirus pandemic being a bitter example of this. Plants, animals and diseases have been transported from place to place since time immemorial. With the Romans came the rat and the plague, and Columbus brought us potatoes, maize and syphilis. Modern planes bring green beans from Senegal, asparagus from Peru and roses from Kenya, with the result that we expect to be able to buy just about anything at any time of year. But pathogens can often hitch a ride.

Tiger mosquitoes – stowaways on lucky bamboo, an ornamental plant from China – are potentially dangerous to humans because they can transmit diseases. But plant pathogens and pests, too, can spread unnoticed, become established somewhere and do great harm. In October 2018, for example, the Netherlands Food and Consumer Product Safety Authority reported a finding of the mite *Tetranychus mexicanus* on ornamental plants (*Beaucarnea recurvata*, the ponytail palm, a popular house plant) in a greenhouse in Drimmelen. The mites suck out the contents of cells in the leaves, causing them to discolour and rendering the plants unsaleable. As their name suggests, the mites originated from Central America and did not get here by themselves.

This publication is teeming with examples of plant diseases that have reached our shores through transport, from the citrus longhorned beetle *Anoplophora chinensis* to the olive tree-destroying bacterium *Xylella fastidiosa* (see Deep Dive – A treacherous souvenir). What they all have in common is that rather than being natural introductions that can be put down to an act of God, they are all the result of movements via human modes of transport. Fungi, mites, insects, viruses – the global transport of food and ornamental plants, and even of packaging materials such as cardboard or wooden pallets, can lead to unnoticed but often very harmful parallel imports. We would do well to place greater emphasis on foodstuffs and ornamental plants with a local or regional origin and to curb unbridled imports and exports of these commodities.

An as yet unknown gall midge is attacking the African lily *Agapanthus* in the UK. Will this insect also reach Dutch shores?

Pathogens and pests in quarantine

DR. DIRK JAN VAN DER GAAG

Outbreaks of new plant pests and diseases occur regularly in Europe. One example of a pest that was previously unknown to our shores is the box-tree moth, which has already devoured many a box hedge in gardens across the continent. The European Union has passed legislation to keep new pests and diseases out. This may not always succeed, but without it we would probably have far more pests and diseases, given that there are so many different plant pathogens and pests in the world that can be introduced with all kinds of imported plants and plant products.

One of the components of EU legislation is a list of quarantine pests: harmful organisms that are either not yet present or not widely distributed within the EU. There are currently about 175 species and groups of organisms on the list. They are included if they cause unacceptable damage when introduced and if measures exist to prevent their introduction or further spread. When a quarantine pest is identified, member states are obliged to notify it and put measures in place to control it.

There are currently about 175 species and groups of organisms on the EU quarantine pest list

Risk

Organisms can only be added to the list of EU quarantine pests once their risk has been assessed. The assessment looks at how the organism can enter the EU – with imports of certain plants or fruit, for example – and how great the risk is of this happening. It also estimates whether the European climate is conducive to the organism becoming established in the EU and how much damage it would cause here if it did so. Measures to mitigate the risk of the organism being introduced are then identified and evaluated.

An EU-wide risk assessment is very time-consuming to perform. Very few were done before 2005, but that has changed in recent years. Given the potential threat to food production, the European Food Safety Authority (EFSA), which was established in 2002, has started to conduct risk assessments relating to plant health. EFSA also conducts risk assessments for pests and diseases that affect ornamental plants. EFSA's efforts have led to a significant rise in the number of risk assessments being produced in the last five to ten years. The European and Mediterranean Plant Protection Organization (EPPO) also conducts risk assessments. The form these take mean that they are also suitable for use in the EU. In addition, individual member states can conduct EU-wide risk assessments. The Netherlands Food and Consumer Product Safety Authority (NVWA) has produced several risk assessments for the EU, including for the pepper weevil (see box).

An EU working group issues recommendations on amending or extending the regulations. These could include tightening up import requirements, for example, or adding a new pest to the quarantine list. A committee made up of representatives of all member states then votes on the recommendations and the outcome of the vote is incorporated into EU legislation.

If a harmful pest that is new to the EU or still has a restricted distribution range is identified, a quick scan is carried out by experts from NVWA National Reference Centre and BuRO, an independent NVWA body.

Based on the outcome, a decision is made as to whether official measures are needed. If it is decided that they are, the NVWA informs the European Commission and other member states of its decision so that emergency measures can be taken against the pest. Other systems involve systematically searching for reports of new threats in the literature and on websites, potentially leading to

Pepper weevil

The pepper weevil *(Anthonomus eugenii)* was first found in a sweet pepper greenhouse in the Netherlands in 2012. This organism was new to the EU, having previously only been known in Central and North America and French Polynesia. The beetle attacks the fruits, causing them to drop off or rendering them unsaleable. Following a quick scan, the Netherlands Food and Consumer Product Safety Authority (NVWA) took measures to eradicate the organism. Contaminated farms were instructed to clear their crops. The NVWA then carried out an in-depth risk assessment for the whole of the EU. As a result, it was assigned quarantine status in October 2014. When a member state finds the beetle, it is now required by law to implement control measures.

quick scans being performed and new organisms ultimately being added to the EU quarantine pest list.

New threats

The bacterium *Xylella fastidiosa* and the emerald ash borer, *Agrilus planipennis* are among the pests on the EU quarantine list that pose a major threat to the Netherlands. The bacterium is present in several locations in southern Europe and is causing serious damage to olive trees. It can also be found on more than two hundred other species of plants. The bacterium is unlikely to cause much damage in the Dutch climate, but the measures the Netherlands would have to take if an outbreak were to be discovered could have significant economic consequences. If a case cannot be traced directly back to recently imported plants, a buffer zone around the site of infestation must be demarcated and plants in that zone that are capable of spreading the disease may no longer be traded. If the bacterium were to be found in an arboricultural area with a large concentration of businesses, for example, it would have major economic consequences for the arboriculture sector.

The emerald ash borer poses a very different threat. This species could potentially do a lot of harm in the Netherlands. The beetle originates from East Asia, where it causes very few problems because the ash species there are not particularly susceptible to it. However, American and European ash trees are extremely susceptible: after it arrived in North America, probably in the 1990s, it killed tens of millions of ash trees there. The beetle has also been introduced in the vicinity of Moscow and is moving west, having been found in Ukraine in 2019. It is expected that the beetle will eventually make its way into the EU and will then be hard to stop. Attempts to eradicate or slow down this plant predator in North America have been unsuccessful.

Besides known threats, there are also unknown ones. In 2014, for example, an undescribed species of gall midge was found on *Agapanthus* (African lily) in the UK. The gall midge attacks the flower buds, which then fail to open. During an official survey in the UK in 2015, the gall midge was found to be present in many locations. No official measures have been taken there and the species does not yet have EU quarantine status. There have been no reports of the pest on mainland Europe as yet, but it is likely that it will cross over to the European mainland at some point.

Boxing not so clever

DORIET WILLEMEN MSC

The caterpillars of the box-tree moth can strip a box hedge completely bare.

box hedges are a familiar sight in gardens everywhere. Some gardeners like to grow larger specimens and clip them into different shapes. These evergreen shrubs are also popular in royal gardens, such as those at Versailles. Wait, did we say 'evergreen'? Sadly, in recent years this shrub has struggled to live up to its species name *(Buxus sempervirens*, meaning 'evergreen box').

The leaves are poisonous to humans and most other animals, but the larvae of the box-tree moth *(Cydalima perspectalis*) thrive on it. They eat, moult and poop on these shrubs until they pupate into adult moths. The plants they live on develop patches of dieback, with bare branches covered in white webbing. Repeated attacks year on year will severely weaken the plants.

However, after several years of infestation it seems that the natural balance starts to slowly recover. Great tits and other birds are welcome assistants in the fight against the plague of caterpillars. Moreover, there is ultimately little left for the larvae to eat once all the box plants have been stripped or replaced by other shrub species. So the box-tree moth seems to be retreating somewhat.

But so are professional box growers: their numbers have more than halved over the past decade.

Sadly, the box-tree moth is not the only reason box plants have to be fearful. They are also under threat from box blight, caused by the fungus *Cylindrocladium buxicola*. Box blight causes dark brown spots on the leaves, desiccation and, ultimately, plant death. Gardeners affected by this are in good company, however. The box hedges in the garden of Het Loo palace in the Netherlands have also been seriously affected since 2009. In 2013, the fungal infestation there was so bad that it was decided to remove 27 km of hedges and replace them with 90,000 Japanese holly bushes *(Ilex crenata*) – a job that took two years. *Ilex* is resistant to this fungus and is fortunately not on the box-tree moth's menu.

Crop protection products – illegal unless authorised

DR. TONNIE ENGELS

Approved substances and authorised products are reassessed every ten years

As the name suggests, crop protection products are agents used to control and prevent pests, diseases and weeds in crops. A crop protection product contains one or more active substances, the compounds responsible for the product's action against harmful organisms. It also contains adjuvants and additives to ensure stability, safe and efficient application and effectiveness.

However, getting a crop protection product to market involves a lot more than simply launching it and selling it. No crop protection products are legal until they are authorised. So how does that work? Crop protection products and their active substances undergo rigorous assessment for their safety for humans, animals and the environment. This is done in two steps. Firstly, the active substance is assessed at the European level and either approved or rejected. If it is approved, the member states then assess the end product and decide whether or not to authorise it. Information on approved substances and authorised products is generally reviewed every ten years based on the latest scientific findings.

The European Commission will only approve an active substance after a thorough and comprehensive scientific assessment to ensure that it is safe for use. A complete dossier containing the results of studies that meet EU requirements must be submitted. This must cover physico-chemical properties, toxicity to humans and ecosystems, residues, efficacy and behaviour in soil, water and air. Each dossier is evaluated by the member states' national authorities and by the European Food and Consumer Safety Authority (EFSA). Once an active substance has been approved, the manufacturer can apply to the European member states for authorisation of a product based on this active substance. The member states will assess the dossier and then make a decision on whether or not to authorise it. The authorisation will only apply to the crops specified in the product's legal requirements for use.

Not the same in all member states

Why are some products permitted in Belgium and Germany, for example, but not in the Netherlands? The European Regulation on Plant Protection Products applies to all EU member states, but agricultural or environmental conditions are not the same in every country. Member states therefore have the opportunity to designate specific national elements. To maintain harmonisation, the Dutch Board for the Authorisation of Plant Protection Products and Biocides (Ctgb) aims to adhere as closely as possible to the EU-wide arrangements and therefore generally adopts authorisations issued by other EU member states. One specific national element that the Netherlands pays close attention to in its assessment is water. The country is water-rich and has more ditches and surface waters than many other EU countries. The Ctgb therefore asks for additional data indicating that very little if any of the product will end up in ditches and other surface waters. In addition, the Netherlands takes a number of technical issues into account to allow for specific agricultural practices in the country. For example, potatoes are grown in such large numbers in the Netherlands and the population of *Phytophthora infestans*, the microorganism causing potato late blight, is so diverse that tests must be carried out to prove that a product is effective under Dutch conditions.

In the EU, active substances for crop protection products are generally approved for a period of ten years. Thereafter, the substances must be

A semi-automatic robot sprays chrysanthemums in a greenhouse with a crop protection product.

reassessed to ensure they comply with the latest requirements. Every time the approval of an active substance is renewed, the authorised products based on that substance must be reassessed. As requirements are tightened up over the years, the authorisations of a large number of products expire. It is estimated that 30 to 60 percent of the products available today will disappear over the next few years. As a result, a large number of crops are likely to run into difficulties because pests and diseases will no longer be able to be controlled effectively.

Risk versus hazard

The stricter requirements are partly the result of a shift in the method of assessment: the emphasis is now less on the risks and more on the intrinsic hazards in substances and products. What is the difference? Take a crocodile, for example. A crocodile in your garden is dangerous. But if that crocodile is surrounded by a high metal fence, the risk of the crocodile hurting you is zero. Until recently, the main focus was on the fence. As a result, many substances gained authorisation by being made subject to certain restrictions. Now the focus has shifted to the crocodile itself – in other words, the hazard intrinsic to the product. As a result, fewer substances, and therefore fewer products, come onto the market.

The Dutch government is currently promoting the use of 'green' products: crop protection products with a natural origin, such as microorganisms, viruses, plant extracts and pheromones. But the existing regulations were originally designed for chemicals and cannot be applied directly to green products, resulting in delays in obtaining authorisations. What is more, green products tend to be less effective than chemical products. Therefore, chemical products cannot be replaced by green products on a one-to-one basis.

Correct use

EU member states must ensure that the legal requirements for the use of authorised products are strictly adhered to. These can be found on the label and in the product leaflet. The legal requirements for use aim to ensure correct application, optimal effectiveness and minimal impact on the environment. They state which crops the product has been authorised for use on, how it should be applied safely and in what concentrations. In addition, spraying equipment is subject to compulsory inspections, and farmers and growers are required to clean the empty packaging of crop protection products using suitable equipment.

The user of a crop protection product is responsible and liable for its correct use. In the Netherlands, the NVWA is the body responsible for enforcing the rules. It checks that products are applied correctly and that no illegal products are being used. Inspectors carry out physical and administrative checks. They can also take samples of the crop, the soil or the harvested product. In particular, the inspectors check that the farmer or grower is following the requirements for use and inspect their stocks of crop protection products, their certificate of professional competence (see box) and their compliance with the administrative obligations. The Netherlands therefore makes every effort to ensure that the use of crop protection products does not have an adverse effect on people, animals and the environment.

An NVWA inspector checks the packaging of products at a wholesaler.

Certificate of professional competence

Crop protection products are subject to strict rules designed to protect people and the environment. Anyone who works with or provides advice on crop protection products in the Netherlands must be in possession of a certificate of professional competence issued by the Dutch Accreditations Office (*Bureau Erkenningen*). Farmers, growers and contract sprayers must have a certificate for the application of crop protection products (a sprayer licence); transport operators and managers of retail outlets must have a distribution certificate; and crop consultants must have a certificate for providing advice on crop protection products. To ensure that everyone with a certificate of professional competence is in possession of up-to-date product and regulatory information, all holders of such certificates must attend refresher courses on a regular basis.

A treacherous souvenir

DORIET WILLEMEN MSC

For these olive trees in Southern Italy, the consequences of an infection with the bacterium *Xylella fastidiosa* are disastrous.

Olive groves in Southern Europe are being decimated by a bacterium. Around 21 million olive trees have died and entire orchards have been destroyed. With Italy bracing itself for the loss of half of its harvest and olive oil production, the EU is taking measures to prevent the further spread of *Xylella fastidiosa*. Whether this will succeed remains to be seen. The bacterium has also been found in Spain and France. There are no chemical or biological crop protection products available to control *Xylella* and it is unlikely that any will become available soon. The only way to fight the disease is to prevent new infections. Drastic measures are therefore being taken: affected trees are being destroyed and trees in a wide radius around an infestation are also coming under the axe. Creating these buffer zones sometimes means that healthy, centuries-old olive trees have to be cut down, which is proving highly controversial.

Unfortunately, the bacterium can not only infect olive trees but more than 300 other plant species besides, including weeds such as nettles and a wide range of garden and bedding plants. For this reason, the authorities are attempting to impress upon people how important it is not to bring home lavender or other plants as a souvenir of a holiday in the Mediterranean, even if they look healthy, since even these can be a source of infection. Whether a plant becomes diseased depends partly on the temperature. To complicate matters further, this bacterium is also spread by insects, including the meadow froghopper.

On the American continent, *Xylella* has been causing major problems in Californian grape cultivation for over a century. Almond and peach trees in southern US states have also succumbed, as have citrus orchards in Brazil.

Plant health is not a game! Or is it?

DR. BART VAN DE VOSSENBERG

There's no doubt that plant health is an important issue that affects us all. And yet very few people are aware of it. How do you inform the general public about subjects they don't come into contact with in their daily lives?

Serious gaming could provide an answer. Serious games are physical or digital games designed primarily for a purpose other than entertainment, such as communicating a message, education or finding out more about a particular subject. In the world of plant health, serious gaming is still very much in its infancy and there are no official releases by game manufacturers. But there are initiatives under way to create games that address specific plant health issues.

Player gets to be the bad guy

As part of the International Year of Plant Health, the Royal Netherlands Society of Plant Pathology (KNPV) has commissioned a board game called *Plant Pest Invasion*. It covers many different facets of plant pathogens and pests: how they spread across the globe, the factors that influence them and the countermeasures taken by governments. The players assume the role of the pests – the bad guys – and have to adjust their characteristics to invade as many regions in the world as possible. Differences in climate can stop the spread of pests and diseases. The players have to make adjustments to their pests so that they can enter different climate zones. The method of spread is also an important characteristic that can be adjusted. Spreading naturally by crossing borders into neighbouring countries is relatively slow, but once a pest can travel by air or sea, things can ramp up a gear. Pests that feed on a wide range of plant species (host plants) have an advantage over fussy eaters. Players can broaden their pest's range of hosts, making it easier to infiltrate new regions. But just as in real life, there's no such thing as a free lunch. In every round, a phytosanitary inspection is carried out in which pests are detected and eradicated. In the end, quarantine measures can be put in place and entire countries can be shut down. A large version of this game has been successfully used at public events and as part of themed lessons in secondary schools.

So is plant health a game? It can be!

The board game Plant Pest Invasion teaches people in a playful way how plant pests can spread around the world and how they can be kept in check.

Plants need a valid passport too

DR. RENSKE LANDEWEERT

THE CULTIVATION and sale of plant products is an important economic activity in the European Union. Dutch ornamental plant cultivation represents an export value of more than € 9 billion and is therefore an important player in the economy of the EU. The ornamental plant industry does a flourishing trade in flower bulbs, seeds, pot plants, trees and shrubs. Large quantities of cuttings, seeds and seedlings are also shipped around the world for the production of food crops.

The risk of harmful organisms hitching a ride with these plants lurks omnipresent in the background. EU regulations are therefore designed to minimise the spread of these plant pathogens and pests. Under these regulations, products travelling from or to a country outside the EU must be accompanied by a phytosanitary certificate, and plant passports are compulsory within the EU. These documents guarantee that the plants were grown in controlled conditions and are free from harmful organisms. If a problem does arise, the potential source of the plant pathogen or pest is easier to trace.

A plant passport is easy to identify by its fixed layout. It can often be found on the pots of plants sold in retail outlets.

Branding

A plant passport is a form of branding that is prominently displayed on each trading unit. It is easy to identify by its fixed layout. It contains the EU flag, the botanical name of the plant and the unique phytosanitary registration number of the company placing the plants on the market. The passport also often contains a batch number or tracing code and always states the country in which the plant was grown. The two-letter country code makes it easy for the consumer to see whether the plants have been grown in their home country or abroad.

All plants that can be planted, replanted or remain planted, such as cuttings and propagating material, pot and house plants and garden and container plants, must have a passport. This document guarantees that the company placing them on the market is audited by an inspection authority and that it is familiar with the prevention and control of plant pathogens and pests. Products without a plant passport may not be sold to other operators in the supply chain. In the Netherlands, this is monitored by Dutch inspection authorities and the Netherlands Food and Consumer Product Safety Authority (NVWA). Retailers are exempt from the

obligation to supply a plant passport with plants they sell, although wholesalers' passports are often still visible on the pots of plants sold in retail outlets. However, plants sold via the internet must have a passport.

Illegal

Plants travelling within Europe without a passport are illegal. The unclear health status of these plants can lead to the risk of plant pathogens or pests being moved to other countries or regions in the EU. The plant passport is not yet obligatory for plants that are exchanged privately, but discussions are ongoing at European Commission level as to whether this is necessary and feasible. The EU regularly runs campaigns for hobby gardeners and the general public to raise awareness of the risks of introducing harmful organisms. It also urges citizens not to bring home seeds or cuttings as souvenirs from other European member states or from countries outside the EU.

Researchers are further expanding the plant's arsenal of weapons with high-tech genetics, drones and reinforcements in the soil.

5 Looking ahead

Scientists are looking at new ways to safeguard plant health in the future. Geneticists can arm plants ever more subtly by making small changes to their genetic make-up. Other scientists are investigating how microorganisms in the soil can come to the aid of plants. In addition, automated systems are being developed which detect and control plant pathogens and pests at an early stage. The outlook for farmers should therefore be rosy, particularly if the government ensures they get a better price for their products.

Targeted tinkering

DR. DIEUWERTJE VAN ESSE-VAN DER DOES

One of the most fundamentally important discoveries ever made in biology is DNA, the molecular material that stores all the information on the characteristics of a living being. DNA is made up of genes, each of which contains information about a small part of what needs to happen in each living being or organism. Among other things, the genes of plants contain information about the material the stem or trunk is made of, what colour the flowers are, what conditions the plant will flower in and how the plant reacts when a pathogen invades.

Like us humans, plants have genes that are responsible for recognising pathogens and mounting an appropriate defence. In plants, this defence reaction may entail producing substances that kill the pathogens or that cause the infected plant cells to die off rapidly, thus keeping the pathogen from penetrating further into the plant. It may also cause the structure of the plant's cell walls to change, making it more difficult for the pathogen to pass through. Pathogens, for their part, have genes that allow them to penetrate as far into the plant as possible without being recognised by the plant's immune system. Plants that don't have the right recognition and defence genes can therefore fall prey to the pathogen. Technological developments over the past decade have made it easier and quicker for us to unravel the genetic code of both plants and their pathogens, which also enables us to identify the relevant defence genes more quickly.

Farmers in Bangladesh are growing aubergines containing a gene from the bacterium *Bacillus thuringiensis*. The plant now makes the bacterium's crystal protein itself, so the fruits are no longer eaten by insects.

Bacterial DNA

To insert genes into plant DNA, scientists use the bacterium *Agrobacterium tumefaciens*, which has the ability to transfer a piece of its own DNA into another plant's genome. This process is known as genetic modification (GM). Scientists can insert genes of their choice into the bacterium at the location of the piece of DNA that it would normally transfer into the plant. Then, rather than transferring its own DNA to the plant, the bacterium becomes the vehicle supplying the genes which the scientists want to insert into the plant. This method enables disease resistance genes from a wild plant or a related plant variety to be incorporated into a cultivated crop that has lost these genes over time. For example, disease resistance genes from wild potato species have been inserted into cultivated potato species to protect them from the devastating late blight disease. Genes of this type can also be introduced by crossing and breeding, but that is a much more time-consuming process that can take years or even decades, depending on the crop. Moreover, some crops are unsuitable for cross-breeding, such as the banana plant. Genetic modification is fast: an existing variety can be provided with an extra gene within the space of one year. In addition, it is very easy to introduce multiple resistance genes at the same time, so that the plant remains better protected for longer and can also be protected against several different pathogens at once.

Genetically modified aubergine and papaya

Not only can scientists transfer genes from one plant to another, they can also use genetic modification to introduce genes from other organisms. This is often done using the bacterium *Bacillus thuringiensis* (Bt), which contains genes for the production of crystal proteins. Crystal proteins, which are also used in biological control, are harmful to certain groups of insects, thus making plants containing Bt genes resistant to those insects. The 'Bt brinjal' is a genetically modified aubergine (eggplant) grown and eaten in Bangladesh. It contains a Bt gene that makes it resistant to *Leucinodes orbonalis*, the eggplant fruit and shoot borer, which causes great damage in aubergines. The presence of the Bt gene allows Bengali farmers to grow this vegetable without having to spray it with large amounts of expensive and harmful pesticides.

Another option offered by genetic modification in the fight against plant diseases is the targeted inactivation of the pathogen's genes. This approach is based on a widely used mechanism called RNA interference (RNAi), which controls the activity of genes in the plant under natural conditions. It is also very effective against viruses that are totally dependent on their host plants for gene activity and replication. A gene from the virus is introduced into the plant using genetic modification. When the virus attacks the plant, the RNAi control mechanism is triggered. The plant identifies excessive activity from the gene in question and

intervenes, after which the virus can no longer replicate and the infection stops. A good example of an RNAi approach is the Rainbow papaya, a variety of papaya grown in Hawaii. This genetically modified variety is resistant to papaya ringspot virus, which decimated papaya crops in Hawaii in the second half of the 20th century. Once the Rainbow papaya was introduced in the later part of the century, papaya cultivation could resume there.

Genome editing – a recent invention

Besides genetic modification, a technique known as genome editing (GE) has been available since 2012. This entails cutting an organism's DNA at very specific places, enabling small fragments of DNA to be removed or inserted in those places. One way to do this is using the so-called CRISPR-Cas9 system. Some bacteria use this method naturally to defend themselves against invading viruses. They recognise the genetic material of the virus using the genetic code in their CRISPR (segments of bacterial DNA) and then cut it into fragments with the Cas9 enzyme they produce, thereby disabling the virus. Scientists have also used this system in plants, humans and animals to edit DNA in certain places. CRISPR DNA can be modified to recognise any DNA code, and the Cas9 enzyme then does the cutting. The advantage of this method is that it enables very subtle changes to be made to the function of existing genes, enabling a gene to be inactivated or even made to work more efficiently. The more we discover about how disease resistance genes work, the more we will be able to use these targeted changes to optimise the way the plant's immune system works.

CRISPR-Cas9 can be used to make very subtle changes to DNA. This process is also known as genome editing.

So close and yet so far

As a precautionary measure, the European Union has taken a very conservative regulatory approach to the use of these types of techniques. The rules are more flexible in other parts of the world: a range of genetically modified crops have been approved in North and South America, South Africa and Bangladesh, for example. The crops had to undergo in-depth safety studies first. Placing genetically modified crops on the market is therefore a protracted and expensive process, even though it is much faster to produce the products themselves this way than via breeding. The USA has decided that such an extensive safety study is not necessary, as research has shown that genome editing does not produce any different effects in a crop from conventional plant breeding. This makes this new technology attractive for use in improving crops. However, genome editing does not do exactly the same thing as genetic modification. These two techniques complement each other and are not interchangeable.

Molecular biology offers countless solutions for improving plant pest and disease control: for example, with the help of molecular techniques we can protect bananas from the devastating Panama disease, potatoes from potato late blight, soybeans from soybean rust, maize from insect pests and cereals from leaf and ear diseases. These solutions can deliver long-term protection and will greatly reduce the use of chemical crop protection

products. The more we use molecular techniques to identify even more genes offering protection against pathogens, the more numerous the opportunities become. However, due to the conservative regulatory approach to molecular technology, we currently have a long way to go before it is widely used in the EU.

Genetically modified crops in the EU

HUIB DE VRIEND MSC

For more than 30 years, the authorisation of genetically modified crops and their derived products has been regulated at EU level. With the exception of some techniques that have been in use for some time, no experiments may be performed with genetically modified organisms (GMOs) and these organisms may not be placed on the market without authorisation. To obtain authorisation, the GMO must have been extensively tested for safety for the environment, humans and animals.

Different rules apply to the use of GMOs in scientific research. The safety of scientific experiments in laboratories and greenhouses is monitored at national level, the procedures being laid down in national legislation. The cultivation, marketing and authorisation of GMOs and GMO products are subject to safety assessment at EU level. In addition, member states may impose restrictions on the cultivation of genetically modified (GM) crops based on considerations other than safety.

Only one GM crop is grown in the EU, mainly in Spain and Portugal: maize made resistant to the caterpillar of the harmful European corn borer by a gene from the bacterium *Bacillus thuringiensis*. For more than 20 years, a number of European member states have been blocking the authorisation of new GM crops. However, the EU has since granted import authorisation for around 60 GM crops. They are mainly grown in North and South America and are used in Europe as a raw material for cattle feed and, to a limited extent, in food.

There has been much debate in the EU about new breeding techniques, including genome editing, the modification of minute fragments of DNA. The European Commission has taken advice from scientists about the difference between genome editing and conventional breeding. The European Court of Justice, the highest judicial body in the EU, had the final word, ruling in 2018 that for now, genome editing is subject to the same authorisation requirements as other forms of genetic modification.

Decisions on authorising GM crops in the EU are ultimately taken by the responsible ministers in the member states. These decisions are therefore of a political nature. It is the responsibility of politicians to look at all socially relevant values. Over the past few decades, dozens of studies have been carried out on citizens' views on GM and its use in plants. These show that, besides the criterion of safety, citizens value the contribution made by GM crops to sustainable agriculture without chemicals, freedom of choice and a fair distribution of costs and benefits. People also believe that there should be a place for GM-free production. In addition, there is widespread concern about too much power being concentrated in major corporations, thus making farmers dependent on their seeds.

Fungi and bacteria help plants defend themselves

DR. ROELAND BERENDSEN AND DR. PETER BAKKER

PLANTS ARE inhabited by billions of bacteria, fungi and other microscopic organisms. These microorganisms live on and in the above-ground and underground parts of the plant, particularly around the root system, the part of the plant we don't usually see.

Plants are a good breeding ground for microorganisms because of the abundance of sugars and other carbon compounds they produce with the help of energy from the sun. Fixing carbon through photosynthesis is not enough to ensure normal plant growth: water and essential nutrients such as nitrogen, phosphorus, potassium and iron are also required, which plants obtain from the soil via their roots. To absorb these nutrients from the soil efficiently, plants call on the services of microorganisms. Familiar examples are mycorrhizal fungi, which provide the plant with phosphorus, nitrogen and water, and root nodules in which bacteria (rhizobia) fix nitrogen from the air in compounds that plants can use as building blocks, for example to make proteins. In return for these services, the microorganisms receive carbon compounds such as sugars. This 'compensation' can amount to as much as 30 percent of a plant's total carbon production. The density and activity of microorganisms in the layer of soil just around the plant roots, known as the rhizosphere, is between ten and a thousand times higher than in the surrounding soil further away from the influence of the roots.

Plant microbiome

The term 'rhizosphere' was coined back in 1904 by the German scientist Lorentz Hiltner. He realised that microorganisms in the rhizosphere play an important role in plant growth and health and predicted that an in-depth understanding of them would be useful for agriculture. This plant microbiome – the microbial community with all the accompanying functions associated with a plant – is also sometimes referred to as the plant's second genome. For several decades, scientists have been studying how this can be of use in agriculture. Can the fungi and bacteria in the rhizosphere help achieve a form of plant protection in which chemicals play an ever diminishing role?

According to estimates, 30 percent of the world's harvest is lost to pests and diseases. Even though plants have an advanced immune system which allows them to respond to attacks by plant pathogens and pests, they can still become diseased or be eaten because their defence responses are triggered too late or because their attackers are able to bypass or sabotage the plant's defences. Plant pathogens and pests can also spread easily in a field in which large numbers of identical susceptible plants are grown in close proximity, thus increasing the disease pressure. The microbiome could very likely play an important part as the first line of defence against the attackers in this situation. Certain microorganisms in the rhizosphere are capable of effectively suppressing some soil-borne pathogens. This may be the result of interactions between the benign microorganisms and the pathogens, such as competing for space and nutrients or producing antibiotics. Other microorganisms boost the plant's defences against intruders, a process referred to as induced systemic resistance (ISR). These microorganisms put the plant in a heightened state of readiness, enabling its immune system to respond much more quickly and effectively to an attack.

Outbreak of disease is needed first

It has been observed in a number of crops that in order to build up a soil microbiome that offers the

plant effective protection, an outbreak of disease is needed first. For example, if wheat is grown in the same field year after year, the disease take-all, caused by the fungus *Gaeumannomyces graminis,* first increases, then decreases rapidly after four to five years and finally remains at a very low level. Even if the pathogen is subsequently added to the soil artificially, the plants do not become diseased as the soil has become disease-suppressive at this site. This is due to the build-up of a high population density of the bacterium *Pseudomonas,* which produces the antibiotic 2,4-diacetylphloroglucinol, a substance that inhibits fungal growth. A similar phenomenon occurs in sugar beet. Infection with the fungus *Rhizoctonia solani* leads to the development of a consortium of microorganisms in the rhizosphere which suppresses the disease.

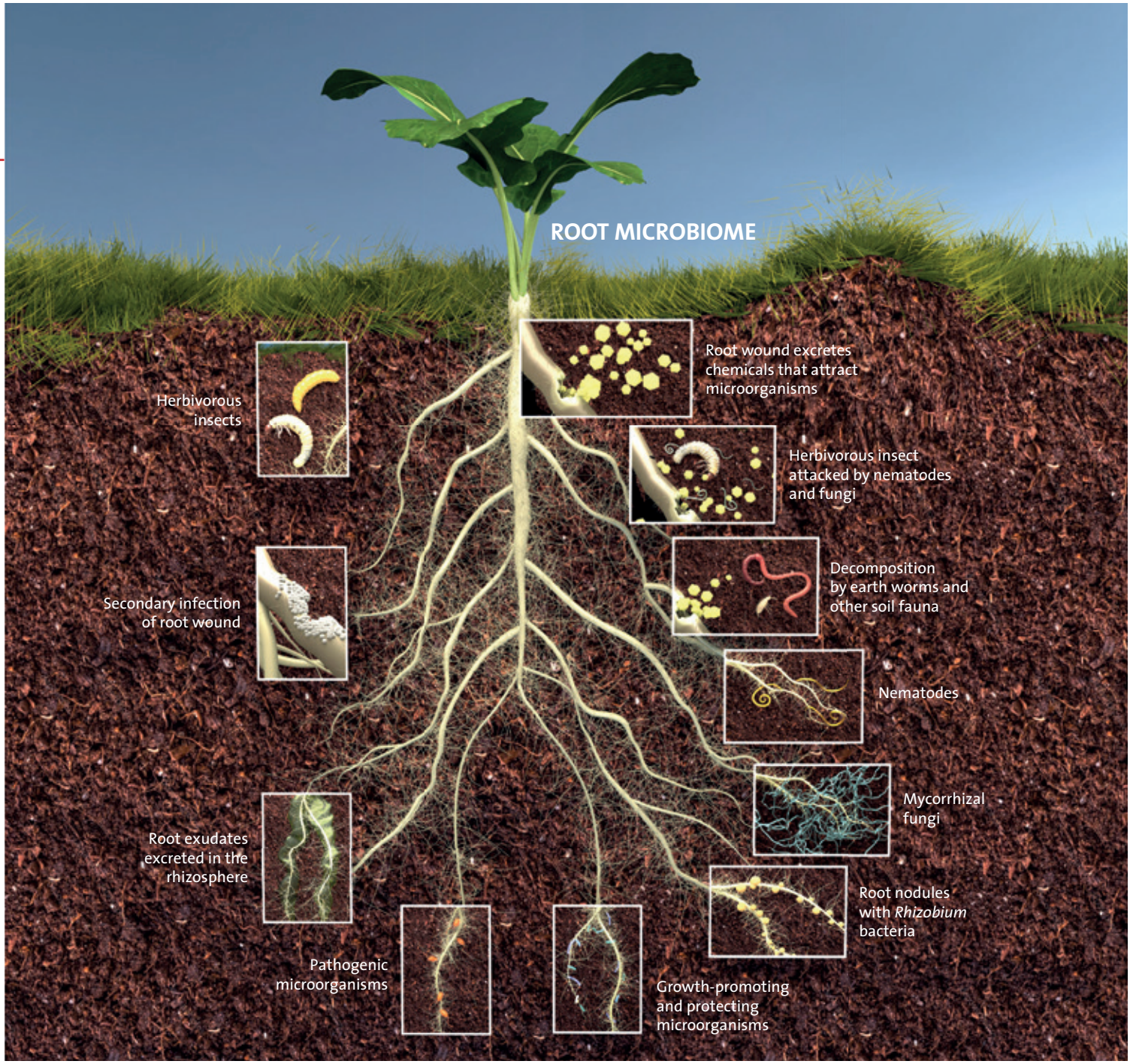
But it is not only an infection with soil-borne pathogens that can change the microbiome around the root; an infection in the leaves can do so as well. This was demonstrated in thale cress (*Arabidopsis thaliana*), a model plant used for research into interactions between plants and microbes. The composition of the microbiome around the roots changed after the leaves were infected with downy mildew. Specific microorganisms increased in number, and when they were isolated, multiplied and added back into the soil they were able to activate the immune system of the thale cress and protect it from infection with downy mildew. The study also showed something else: if plants were grown in soil that had previously been confronted with downy mildew infected plants, they were better protected against the disease. Therefore, once above-ground parts of the plant have been infected, a kind of microbial memory is created in the soil which helps to protect the next generation of plants from the pathogens that attacked the previous generation.

Friend or foe?

There are still many unanswered questions surrounding the microbiome. How does a plant know which of the millions of microorganisms are friend and which are foe? When a plant recognises a microbial foe (a pathogenic virus, bacterium or fungus), it not only activates its immune system but also temporarily inhibits its own growth, because it has to divide its energy between defence and growth. Benign bacteria and fungi are often difficult to distinguish from pathogens, and any unnecessary activation of the immune system leads to unwanted inhibition of growth. However, it has recently been discovered that many benign microorganisms in the root microbiome specifically suppress the plant's defence system, enabling the organisms to successfully colonise the plant without being inhibited by its immune system and allowing them to perform their protective function without affecting the growth of the plant and therefore the harvest.

Special substances excreted by stressed plants control the selection of specific microorganisms in the rhizosphere that help the plants defend themselves. Identifying these compounds opens up opportunities for even more targeted applications, such as selecting plant lines during breeding that excrete more of these natural substances and therefore recruit more protective bacteria from the soil. Biological crop protection products already use a limited range of biocontrol agents based on microorganisms such as mycorrhizae, rhizobia and *Trichoderma* and *Bacillus* species. These promote plant health by improving the availability and uptake of nutrients, suppressing soil-borne pathogens and boosting the plant's immune system. However, today's crops have not been selected for properties that optimise interaction with these types of beneficial microorganisms in the microbiome. A better understanding of the interaction between plant and microbiome could help us improve the

Right page
Root microbiome: Plants excrete up to 20 percent of the carbon sources they produce through photosynthesis back into the soil in the form of root exudates. These substances influence the composition of the soil microbial community close to the root in the rhizosphere. Beneficial microorganisms such as mycorrhizal fungi and nitrogen-fixing *Rhizobium* bacteria enter into a symbiotic relationship with the plant. Other growth-promoting and protective microorganisms are also attracted. Together they improve the availability and uptake of nutrients from the soil and offer protection against pests such as nematodes and plant-eating insects, as well as pathogenic fungi and bacteria.


ROOT MICROBIOME
Herbivorous insects
Root wound excretes chemicals that attract microorganisms
Herbivorous insect attacked by nematodes and fungi
Secondary infection of root wound
Decomposition by earth worms and other soil fauna
Nematodes
Mycorrhizal fungi
Root exudates excreted in the rhizosphere
Root nodules with *Rhizobium* bacteria
Pathogenic microorganisms
Growth-promoting and protecting microorganisms

relationship between our crops and their natural microbiome. Also promising are the protective microorganisms recruited by certain crops following an infection. These could potentially be developed into microbial 'personalised medicine', which could reduce the need for chemical crop protection products in the future.

Precision agriculture

RICK VAN DE ZEDDE MSC AND DR. GERRIT POLDER

DETECTING PLANT pathogens and pests is extremely important: unless you know what the plant is suffering from, you can't do anything about it. The earlier pests and diseases are identified, the easier it is to control them. Automated systems are starting to play an ever greater part in this.

Automatic detection of diseases in plants as early as possible and without damaging the plant is an approach that is gaining ever more traction in agriculture and horticulture. The basic assumption in automatic detection is that a diseased plant looks different from a healthy one. For example, leaves can have subtle colour differences, which are often invisible to the human eye but can be captured using techniques such as spectral imaging.

Hundreds of different wavelengths

A standard camera records red, green and blue light. A spectral camera uses hundreds of different wavelengths and is also able to capture information outside the spectrum visible to the human eye. In doing so, it creates an extremely detailed image of the reflection of light on plants or other

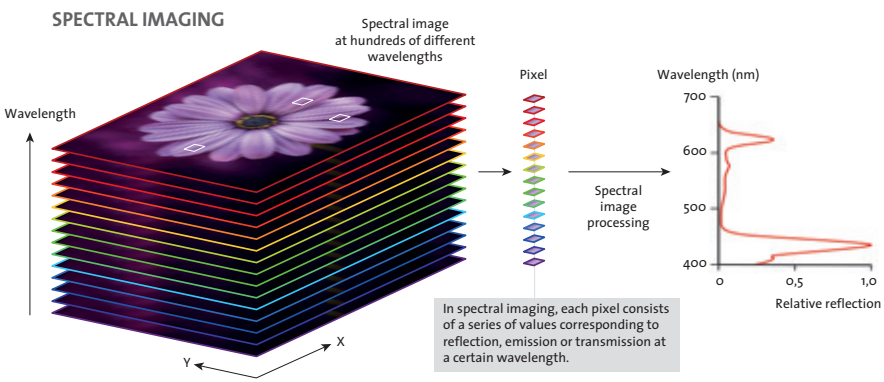
Optima

The EU's OPTIMA project is currently developing an environmentally friendly integrated pest management system. This involves the use of biological crop protection products, disease prediction models, spectral early disease detection systems and precision spraying techniques. OPTIMA will optimise prediction models for downy mildew in vineyards, apple scab in apple orchards and Alternaria leaf blight in root crops. This will allow the spread of diseases to be mapped more quickly. Advanced early detection methods based on spectral imaging and deep learning techniques are being developed to precisely localise and quantify infections.

objects, allowing minute differences in spectral properties between diseased and healthy leaves to be monitored. This provides a lot of information on plant pigments, sugars, proteins, fats and water in the leaves, for example, but also on deviations from normal patterns caused by diseases. Spectral imaging therefore has the potential to become a powerful tool in disease detection in greenhouses or on self-driving tractors.

To give a concrete example: viral and bacterial diseases are one of the biggest problems in seed potato cultivation. The bacterial disease blackleg causes around €12 million worth of damage every year. Much of the damage is due to late detection of the disease. Detecting diseased plants at an early stage with modern optical visual techniques could therefore lower costs significantly.

Laboratory experiments showed that spectral imaging clearly distinguishes between healthy and infected potato plants at an early stage. A camera set-up was then designed and installed on a tractor to detect diseased plants in the field. The results from the spectral camera turned out to be almost identical to a crop expert's score. The advantage of an automated analysis is that the crop can be examined more intensively and at much lower cost than an analysis by a crop expert.



Artificial intelligence

Automatic detection of plant diseases by robots involves the collection of a massive amount of data. Processing this data requires a lot of computing power. The wide-ranging uses of artificial intelligence and the rapid increase in computing power in other fields, such as autonomous vehicles, speech recognition and the internet, make it possible to store all this collected data and quickly perform calculations with it. New developments are also leading to the creation of self-learning systems inspired by the human brain. Like our brains, they have a generic structure which learns a new application simply by looking at examples. The main challenge is to collect representative examples to train the systems. In recent years, this methodology – also known as 'deep learning' – has proved capable of dealing flexibly with new, additional data. As a result, a system that has been thoroughly trained by one grower can also be used by others by simply showing it a few examples of plants with new, specific disease symptoms.

Cameras brought to the plants

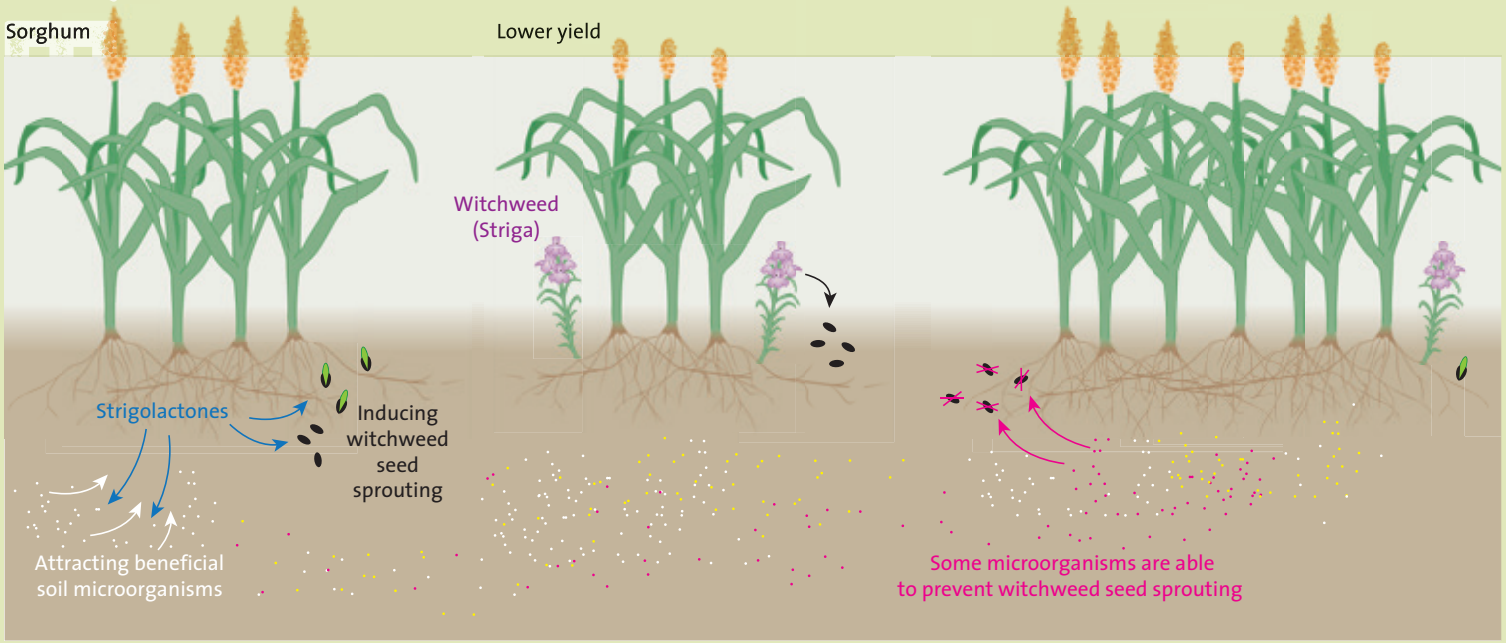
Spectral imaging can be used in protected cropping, too. For this purpose, the cameras must be brought to the plants on a vehicle or a moving gantry. Plants can also be passed in front of the cameras on conveyor belts. In both cases – 'plant-to-sensor' or 'sensor-to-plant' – the spectral camera can be integrated into a monitoring system to analyse whether there are diseased plants in the greenhouse. Technology is already being developed to recognise diseases such as botrytis, mildew and other fungal diseases in greenhouse crops such as tomatoes, cucumbers, cyclamen and gerbera. Wageningen University & Research (WUR) recently commissioned the construction of a hyper-modern greenhouse for research into the detection of plant diseases. The greenhouse is part of the Netherlands Plant Eco-Phenotyping Centre

Vampire plants

DORIET WILLEMEN MSC

In Africa and Asia, entire crops can be devastated by the parasitic weed witchweed (*Striga* species). This vampire plant grows on the roots of important food crops such as sorghum, maize, barley and rice. The parasite penetrates the host plant's vascular system and steals all the water and nutrients it needs via a special suction organ, the haustorium. The crop barely survives and yields little or nothing for the farmer. Witchweed has an unusual life cycle. There is a kind of three-way relationship between witchweed, the host plant and microorganisms in the soil. The roots of the host plant produce strigolactones, molecules that attract beneficial microorganisms to the soil surrounding the roots. The seeds of witchweed have evolved to 'eavesdrop' on these signals so that they know when a host plant is nearby. Witchweed seeds only start to germinate when strigolactones appear in the soil. This is a necessary step for the parasite, as the seedlings are completely dependent on the host plant. The weed spends its first few weeks living underground on the root of its host plant. Once it emerges above ground, it can make its own sugars by photosynthesising but continues to extract water and minerals from its victim. Witchweed produces purple flowers, after which new seeds are spread across the field. A contaminated field is unusable, posing a major problem for small subsistence farmers. An international research project funded by the Bill & Melinda Gates Foundation is searching for an effective approach. In a test set-up, more than 30 species of bacteria and fungi were found that partially suppress the germination of witchweed seeds, and investigations are currently under way to determine which genes and molecules are responsible for this suppression. It is hoped that the findings will eventually lead to a method of breaking the interaction between the parasitic witchweed and its hosts in the field.

The three-way relationship between witchweed, the host plant sorghum and microorganisms in the soil.



Jappe Franke from Wageningen University & Research uses a drone to examine the condition of various varieties of winter barley.

Drones can also recognise diseased plants

(NPEC), funded by the Dutch Research Council (NWO), and will open for use by scientists and businesses in 2021.

Drones

Drones can also recognise diseased plants. They can analyse a large area of land in one flight, enabling a disease to be quickly identified in a crop. By flying over a field several times per season, a drone can monitor the development of the crop, using a combination of colour images, spectral imaging and 3D cameras.

Drones are particularly good at monitoring green cover in a field. To detect a growth deficiency in the crop, multiple images need to be taken during the growing season. If the drone detects a growth deficiency, a specialist must go into the field to find out what is causing it. This may be a disease, but also drought or a nutrient deficiency.

In the future, farmers and growers will be able to use all of these techniques to identify the development of diseases in their fields or greenhouses at an early stage. They will then be able to deploy sprayers to tackle the diseases at the right time, in the right place and with exactly the right dosage – the essence of precision agriculture.

Ploughing ahead

ASTRID SMIT MSC

Farmers are under a lot of pressure to change their business practices to protect the environment. The government wants them to reduce the use of chemical crop protection products to control pests and diseases, but they still need to be able to produce enough to turn a profit. So is there a future for farmers in the Netherlands?

Krijn Poppe, economist at Wageningen Economic Research, is convinced that agriculture in the Netherlands has a rosy future. 'The basic conditions for farming in the Netherlands are good. The soil here is very fertile, our climate is favourable and our country's airports and seaports are among the largest in the world. In addition, our agricultural sector is determined, competitive and strong enough to take a hit.'

Scaling up

But to remain competitive, farmers will have to continue to scale up, Poppe believes. Livestock farmers achieve the lowest cost price at a herd size of 200-250, but the average size is currently 95. An arable farmer needs at least 80 hectares to do well, depending on their cropping plan, whereas the average farm size is currently 60 hectares. That is why competition for land is so tough. When an older farmer sells up, there are younger colleagues queueing up to take over the land and add it to their own farms.

Small farmers will find it tough going over the next few years unless they specialise in a niche market with short supply chains, Poppe believes. Some small farmers produce local specialities such as Texel sheep's cheese or Hoeksche chips, which consumers are happy to pay a little more for. Others combine farming with other activities such as a care farm, a windmill or a camp site. 'But that requires a different skill set, which not every farmer has,' Poppe points out.

The further increase in scale the economist is expecting is not only necessary in terms of the cost price but also for the environment. To suppress pests and diseases, arable farmers will have to work to a longer crop rotation interval than most use at the moment. So rather than growing potatoes or sugar beets on a field once every three years, they could switch to once every five years and grow wheat, grass seed, peas or another break crop in between. This rotation system depletes the soil less and allows pathogens to die out. 'In that case, you would need more land to make the same amount of money because break crops are generally not such good earners.'

That cropping plan could also include soybean, so that the Netherlands no longer needs to rely on imports from countries such as Brazil. This would also help to reduce the pressure on tropical rainforests. Poppe: 'Growing animal feed is also not particularly profitable, so it would never become a major activity. But soybean fits the bill well as a break crop.'

Precision agriculture

In addition to upscaling, Poppe also anticipates a switch to precision agriculture. This is probably an effective response to the government's desire to reduce the use of synthetic crop protection products. In precision agriculture, these products are administered in a much more targeted way and are replaced by a knowledge of ecology, with decisions being made based on data from special cameras, drones and satellites. 'We are learning more and more about how plants and soils work and interact. Farmers will soon be using this knowledge on the farm. Spraying entire fields at great distances from the plants will be replaced by a small, very targeted dose of chemicals on individual crops or weeds.'

To remain competitive, the average arable farmer will need more land in the future. Scaling up is inevitable, says agricultural economist Krijn Poppe.

The Dutch government wants farmers to abandon chemical crop protection products once and for all by 2030. Will that be feasible for them? 'I really can't say,' Poppe comments. 'But I do think it is useful to have certain products on hand as a backup to avoid too much damage. We have an Outbreak Management Team to manage coronavirus – perhaps we need one for plant diseases too, with the use of chemical crop control products as a last resort.'

Towards organic farming

In European agriculture, there are increasing moves away from chemicals towards organic farming. Poppe again: 'Organic farmers' yields are still lagging behind those on conventional farms, but they are catching up rapidly. Organic farming in the Flevopolder area in the Netherlands, for example, has become a flourishing sector over the last 30 years.' And as farmers and research institutes gain a better understanding of plants, their interactions with pathogens and the microorganisms in the soil, it won't be too long before organic yields are almost on a par with those from conventional farming, he believes.

In economic terms, farmers could even manage without any synthetic crop protection products at all, especially if all European countries adopted this approach at the same time. That would make food slightly more expensive, but the retail price of a food product is only partly determined by farm production costs, with the bulk taken up by processing, retail, marketing and transport, according to Poppe. For example, the cost price of a kilogram of potatoes or onions is only ten percent of the retail price.

And the cost price is dropping by 1 to 1.5 percent per year because farmers are producing more per hectare, Poppe adds. This decrease has benefited consumers in recent decades. As a result, consumers in the Netherlands no longer spend half their income on food, as people in many developing countries still do today, but just eight percent. The economist thinks this eight percent mark is about right and that the profits from productivity improvements should go to the farmers to give them more space to grow other things, such as break crops, more extensively. 'As an economist, I am not in favour of regulating prices. But the government can steer this in the right direction by imposing requirements on farmers: making break crops compulsory, for example, or banning certain crop protection products.'

Urban agriculture and plant diseases

DR. ESTHER VEEN, JAN EELCO JANSMA MSC, TYCHO VERMEULEN MSC AND PAULIEN VAN DE VLASAKKER MSC

URBAN FARMING – producing food in or around the city – has been popular for many years. To what extent plant diseases are, or are perceived as, a problem in urban agriculture is therefore a legitimate question. However, it is important to realise that the term 'urban agriculture' is used to describe a variety of practices, from allotments and community gardens to high-tech vertical farming in office buildings to city-centre or suburban farms. Even someone who grows food in their garden can be regarded as an urban farmer. This diversity is reflected in the extent to which plant diseases are seen as a problem.

In community gardens, growing fruit and vegetables is sometimes a means rather than an end. These gardens are often set up as a joint activity to make the community greener or to show children how food grows. The size of the harvest is generally much less of an issue. In such gardens, artificial fertilisers and synthetic crop protection products are often not used at all, and little is done to control plant diseases. This may partly be due to a lack of knowledge. According to research, plant diseases are indeed often a low priority in community gardens. Problems such as a lack of leadership, uncertainty about how long the land can continue to be used and unsupportive local residents play a greater role.

Allotment holders are often much more fanatical, however. Weeds, slugs and *Phytophthora infestans*, the cause of potato late blight, are an issue for many. To prevent potato late blight, growing potatoes is banned on some sites, or only permitted in a three- or four-year crop rotation. On others, chemical controls are permitted or even compulsory: in those locations, it is not unusual to spray potatoes as soon as the leaves start to emerge. Nonetheless, chemical crop protection products are used less often than in the past, partly because their use is subject to increasingly strict regulation.

A recent survey in Almere in the Netherlands has shed light on how non-commercial urban farmers experience plant diseases. Participants were asked about their experience of growing their own food. The question about the main problems encountered when growing food in the garden, community garden or allotment was answered by 393 respondents. Plant diseases finished in third place, after slugs and lack of time. However, a substantial majority of four out of five respondents reported that they had no problems with plant diseases.

But crop protection is very important for commercial urban agriculture initiatives, says Wageningen biologist Tycho Vermeulen, initiator of the City Vineyard in The Hague. Apart from wine sales, the City Vineyard's main income stream is from participants who rent grapevines and learn how to maintain them. To ensure a secure financial footing and for the enjoyment of participants, the production volume is important. Because participants are not on site to monitor the grapes every day, less disease-sensitive varieties and different cultural practices are used.

'To control mildew and botrytis, we try to allow the grapes to dry quickly after rain,' Vermeulen says. 'We pinch out the new shoots, remove the leaves around the clusters and mow the grass to

Plant diseases are of minor importance for community gardens.

open up the space between the vines to sun and wind. There is little we can do about downy mildew apart from carefully removing leaves to prevent an incipient infection from spreading. For fungus control, we ask a neighbouring wine grower to spray with an organic product.' Vermeulen says that apart from using nets to keep wasps away, they rarely need to control insects because there are enough natural predators in the city thanks to the many green areas that are extensively managed. But in 2017 they still had to discard 15 to 20 percent of their red grapes because of the spotted wing drosophila. 'We are therefore looking at growing a variety with a thicker skin in future. We lost a lot of the crop to a mildew infection in 2015, but our grapes have generally been free from pests and diseases. That's also because we only have a thousand square metres in an area with low disease pressure, relatively warm city air and lots of disease-free sea breezes,' Vermeulen says.

A recent development is growing vegetables in buildings, often with LED lighting. Because the environment is fully controlled, pests and diseases are rare there. If the space is not properly sealed, hawthorn flies and aphids can be an issue, however. High relative humidity combined with poor air circulation increases the risk of fungal attack. This can be avoided by carefully configuring the growing system with the right temperature, relative humidity and air circulation.

So plant diseases do occur in urban agriculture, but they are seldom seen as a problem in practice because of the small scale, the relatively high urban biodiversity, the controlled environment in buildings and the fact that the size of the harvest is not usually an issue.

Epilogue: Dancing with nature

PROF. EMER. ALLE BRUGGINK AND DIEDERIK VAN DER HOEVEN

The time when artificial was better than natural is over

WE SHOULD respect plants a little more. Over 60 percent of the carbon in the body of an average American comes from the corn plant. More than 99 percent of the organic material on our planet – fossil or living – is plant-based. For convenience, we will include microorganisms under the heading 'plant-based' for now.

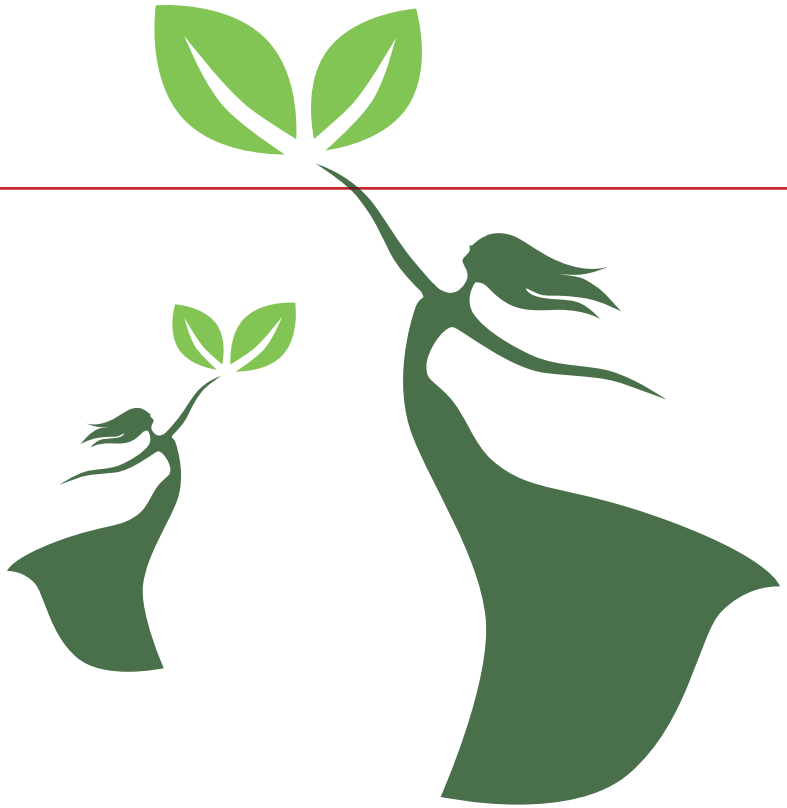
Plants are important producers of oxygen and are our source of energy, whether directly or indirectly. It is only recently that humans have been able to obtain useful amounts of energy without the intervention of plants and with greater efficiency: from the sun, wind and water. Plants are also self-sufficient. We humans ingest many different ingredients such as proteins in highly functionalised form, whereas plants make them from inorganic substances.

Moreover, plants produce their complex substances entirely waste-free. Chemists manufacture these substances with an efficiency often as low as 1 percent or less, resulting in many useless or even toxic by-products.

But even with chemically simple molecules, plants are smarter than we are. Take aspirin, one of the world's best-selling painkillers. It is based on the plant hormone salicylic acid, which almost all species of plants produce and which plays an important role in defending against plant pathogens. In their book *Brilliant Green*, Italian professor of biology Stefano Mancuso and science journalist Alessandra Viola give some superb examples of plants that have developed all kinds of clever tricks in the course of evolution. Take the acacia, for example, which adds a hint of alkaloids to its nectar to drug attracted ants so that they are constantly busy protecting the tree from hungry giraffes. Or the pitcher plant *Nepenthes rajah* from Kalimantan, Borneo, which will not release tree shrews feeding on its nectar until they have deposited their nitrogen-rich dung in the pitcher. And then there's the Cuban liana, *Marcgravia evenia*, which, when in flower, grows a disc-shaped leaf to attract passing bats relying on echolocation to pollinate it.

A little more respect, please

We should respect nature a little more. We owe much of our wellbeing to defying nature: fighting and killing unwanted life. This has enabled us to feed seven billion people and improve our health in leaps and bounds. But the time when artificial was better than natural is over and the debate on changing the way we deal with nature is hotting up. It only took us twenty years to decide which course to take to deal with the energy problem: sun, wind and water. And now things are changing fast with food. Eating less meat is becoming the norm: insects are slowly gaining acceptance as a good nutritional basis for our food, and vegetarians and flexitarians have long since ceased to be regarded as cranks. This reduces energy and raw material wastage, which in turn benefits the environment. We can genetically modify plants to make them more efficient and resistant to diseases. We are increasingly appreciating that nature uses genetic modification on a daily basis and that it is a mechanism for evolution and survival. Our



resistance to genetic modification is unnatural, to put it bluntly.

Learning from nature

Trends in scientific research are often pointers to the society of the future. And the trend of the moment is learning from nature! Our understanding of nature and how everything is interconnected is growing in leaps and bounds. This also applies to modern biotechnology, with its latest masterpiece, the acclaimed CRISPR-Cas technique which enables us to make subtle changes to genetic codes. Due to our rapidly expanding knowledge of how nature works, we are increasingly able to control pests and diseases using natural methods – an approach that is being perfected in greenhouse horticulture and is also finding increasing acceptance in arable farming. Many modern techniques come together at this point: observing the crop with spectral cameras, image analysis with artificial intelligence, DNA analyses showing the richness and importance of soil life, pest control with natural predators, and achieving higher agricultural yields by stimulating biodiversity. And learning from nature has only just begun.

We are also finding out about the mechanisms behind genetic mutations and the way nature makes its materials, from cobwebs and silk to gluing and sticking under water. Computers allow us to keep tabs on and use many different variables in our research. Or to put it in simple terms, whereas thirty years ago we would optimise our processes by varying two or three factors at a time, nowadays we can handle many more at once. Pattern recognition technologies enable us to process even more variables simultaneously. These may still be strategies that involve simplifying how nature works, but they enable us to rapidly increase our understanding and test the results of our experiments against natural developments. We hope that this will enable us to shape our future in a permanent interaction with nature. Working in tandem – much like dancing a Viennese waltz.

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Interviewees

Krijn Poppe, business developer at Wageningen Economic Research, Wageningen UR.
Jolanda Wijsmuller, Manager Biologics at Bayer Crop Science.

More information

Websites

Find out more about the International Year of Plant Health 2020 at: www.fao.org/plant-health-2020/about/en/

You can find plenty of information on plant health on the UK Department for Environment, Food & Rural Affairs (DEFRA) information portal: planthealthportal.defra.gov.uk

Accessible knowledge on plant parasites in Europe (leaf miners, galls and fungi), especially on wild plants, is available at: www.bladmineerders.nl

To find out more about pests and diseases of trees, visit: https://www.forestresearch.gov.uk/tools-and-resources/pest-and-disease-resources/

For secondary school students and teachers, there is a good range of teaching material on plant diseases at: www.saps.org.uk/saps-secondary-key-themes/1404-plant-disease

The British Society for Plant Pathology (BSPP) has an education section on its website with numerous resources at all levels: www.bspp.org.uk/education

The American Phytopathological Society website also provides a good selection of educational resources: https://www.apsnet.org/edcenter/Pages/default.aspx

Dutch government information on legislation and regulations relating to plants, plant products, pests and diseases can be found on the Netherlands Food and Consumer Product Safety Authority (NVWA) website: english.nvwa.nl

The Dutch Board for the Authorisation of Plant Protection Products and Biocides (Ctgb) assesses whether crop protection products and biocides are safe for humans, animals and the environment before they can be sold in the Netherlands: english.ctgb.nl

At the European level, the European and Mediterranean Plant Protection Organization (EPPO) and the European Food Safety Authority (EFSA) advise on and set standards for plant health: www.eppo.int and www.efsa.europa.eu

For more information about the International Plant Protection Convention (IPPC), visit www.ippc.int/en

The International Society for Plant Pathology (ISPP) (www.isppweb.org/about__ispp.asp) is an umbrella organisation of national plant pathology societies. The European Foundation for Plant Pathology (https://www.efpp.net/default.htm) has a comparable role at the European level.

The Royal Netherlands Society of Plant Pathology publishes the journal *Gewasbescherming*, which can be downloaded at: https://knpv.org/nl/menu/Gewasbescherming/Het-verenigingsblad (in Dutch)

Videos

European research into biological control: https://www.youtube.com/watch?v=OrMKHhb6jgs

International Year of Plant Health: https://www.youtube.com/playlist?list=PLzp5NgJ2-dK4cmV7gTSNPk6y6V9AAr52q

Books

'Brilliant Green – The Surprising History and Science of Plant Intelligence, Stefano Mancuso and Alessandra Viola. Published by Island Press, 2018.

'Natuurlijk! Logisch. Hoe de natuur ons steeds weer voor verrassingen stelt', Alle Bruggink en Diederik van der Hoeven. Biobased Press, Amsterdam, 2019 (in Dutch; book review in English at https://www.biobasedpress.eu/2020/01/nature-as-our-teacher).

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Jan-Kees Goud / WUR: p. 40 centre left and centre right (adapted from: Dodds and Rathjen 2010, Nature Reviews Genetics), 42 (adapted from: Dr. Ravi P. Singh / CIMMYT, Mexico)
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In this issue:

- Pathogens and their cunning ways
- Arming plants with a resilient environment and resistance genes
- Protecting crops with chemistry and biology
- Plants that are traded need a passport too
- The future: high-tech agriculture and learning from nature

With a foreword by Marjolijn Sonnema, Director General Agro at the Ministry of Agriculture, Nature and Food Quality

We take them all for granted: healthy crops in the fields, trees blossoming in the parks and beautiful ornamental plants in our greenhouses. But what we tend to forget is that they are constantly under attack from plant pathogens and insects. Incredibly, a third of all harvests are still being lost to these attackers, huge numbers of ash trees are coming under the axe, and growers have to work hard to keep their crops thriving.

Plant health is monitored constantly. This is done by staying one step ahead of the plant pathogens and pests and fighting them off when they unexpectedly crop up. Our current weapons of choice are chemicals, but biological solutions look set to take over. Learning from nature is the motto, combined with high-tech solutions such as drones that monitor crops and robots that only spray affected plants.

Globalisation is not making this any easier. Like us humans, plant pathogens and pests can also take the plane and indulge in continent-hopping. Take *Xylella*, for example, the bacterium that is causing untold damage to olive trees in Southern Europe, or Panama disease, which is threatening banana crops worldwide.

The United Nations designated 2020 as the International Year of Plant Health to raise awareness of the efforts needed to prevent plants from becoming diseased. In this booklet, experts lift the lid on what is involved. After reading it, you could well find yourself seeing the supermarket fresh produce shelves through different eyes.

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