Bugged ideas

Prof.dr Marcel Dicke

Farewell address upon retiring as Professor of Entomology at Wageningen University & Research on 6 June 2025

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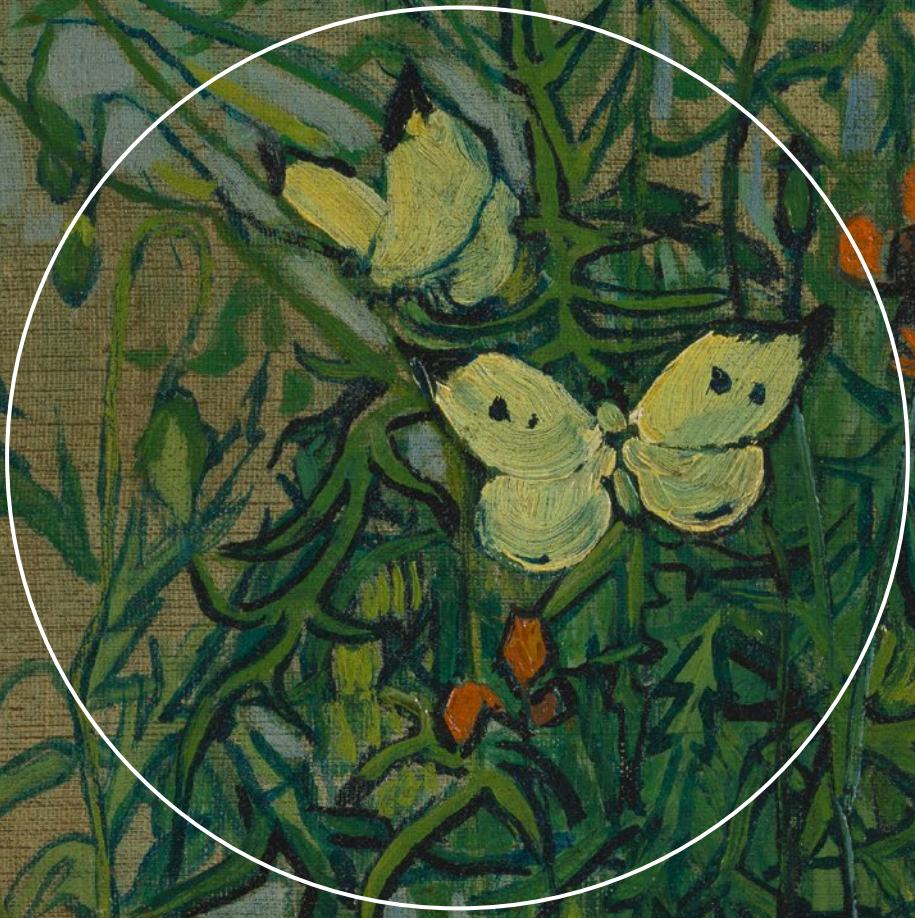

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The creatures that perform all these essential services are still all around us unnoticed in the undergrowth. Many are within a few inches of our feet wherever we tread on earth, usually unregarded. We would do well to remember them.
Life in the Undergrowth, David Attenborough (2005)[12]

We, humans, are not at the center of things, nor do we stand apart from nature. We are the rivers, the butterflies, and the plants. We are nature.
Nemonte Nenquimo (2020)[175]

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Cover picture: Vincent van Gogh (1853 – 1890), Butterflies and Poppies, 1889.
Van Gogh Museum, Amsterdam (Vincent van Gogh Foundation).
Picture back cover: Hans Smid.

Bugged ideas

Madam Rector, colleagues, family and friends

The magnificent opening of the film ‘ Once upon a time in the West’ by Sergio Leone (1968) has a several-minute-long shot of a man killing time on a rocking bench at a deserted railway platform while being bugged by a fly. The insect moves around his mouth, circles around his head and buzzes. At some point the fly sits on the bench. The man slowly draws his revolver and then with a big bang quickly catches the fly in the barrel of his revolver. He then relaxes and listens happily to the buzzing fly in the barrel. This very slow scene portrays the man’s changing moods and nicely presents how people commonly perceive insects: the animals bug us when they are free-flying but all is fine when we contain them, control them, remove them.

Insects and biodiversity

Insects are a highly diverse class of organisms, representing a wide variety of colours, shapes, sizes, locations of sensory organs. The smallest known insect is a parasitic wasp measuring just 0.139 mm in size[169], which is smaller than some unicellular organisms such as Paramecium. The largest known insect is a walking stick of 64 cm in length[9]. Insects often seem like aliens to us and indeed some movies about aliens have taken inspiration from the biology of insects. For instance, in Ridley Scott's film *Alien* (1979), clear reference is made to the life cycle of parasitic wasps. Insects are the most amazing creatures on our planet. They represent the most species-rich group of macroscopic organisms[264] and display biodiversity in its full and magnificent beauty. Yet, we have only discovered just over one million insect species so far: it is expected that there are ca. 5-6 million species altogether[215] so there are four to five million species to go to fully document insect diversity.

Insects are a successful group on Earth

These critters are truly fascinating. In fact, their dazzling biology makes it seem that the number of species is twice as large as the actual number. More than 80% of all insect species exhibit full metamorphosis. During this process, the phenotype of the individual undergoes a complete makeover, which means that an adult and its offspring have entirely different appearances (Figure 1). The parents and offspring use different food sources, they live in different habitats where they interact with different species. In short, in insects with full metamorphosis, parents and their offspring have different ecologies and occupy different niches. This is one reason why insects are so successful on Earth.

Figure 1: More than 80 percent of all insect species undergo complete metamorphosis. From left to right: Sevenspot ladybird beetle, Coccinella septempunctata, *adult (top) and larva (bottom), pictures by Alvesgaspar, Wikimedia; common house mosquito,* Culex pipiens, *adult (top) and larvae (bottom), pictures by Hans Smid; yellow mealworm beetle,* Tenebrio molitor, *adult (top) and larva (bottom), pictures by Hans Smid.*

Another special feature of insect biology is that they were the first organisms to colonise the air by developing wings to allow flying. Most insect species can fly when they become adults and this allows them to disperse over long distances. Some insect species such as the Monarch butterfly (*Danaus plexippus*) or the painted lady (*Vanessa cardui*) can migrate over very long distances, up to a few thousand kilometers[200, 201, 216]. This ability allows them to live in very different parts of their range.

Insects may also engage in very remarkable ecological interactions. For instance, caterpillars of the large cabbage white butterfly, *Pieris brassicae*, hatch from their eggs and start to feed on the plant on which their mother had deposited the eggs. They may then be attacked by parasitic wasps – so-called parasitoids – such as *Cotesia glomerata*[165, 212, 213]. Females of this wasp inject a few dozen of their eggs in each caterpillar and the wasp larvae that hatch from these eggs will feed on the host's tissues within the caterpillar. Another wasp species, the so-called hyperparasitoid *Baryscapus galactopus*, may parasitise the wasp larvae that feed within the caterpillar, by laying eggs in them[108]. These eggs will hatch and yield hyperparasitoid larvae that feed in the parasitoid larvae that feed in the caterpillar that feeds on the plant. After the parasitoid larvae egress from the caterpillar to pupate the hyperparasitoids emerge from these parasitoid pupae. These intricate interactions resemble Russian dolls.

Mindboggling diversity can be also found *within* some insect species. For instance, a worker and a soldier of the ant *Pheidologeton diversus* are so different in size that the worker is much smaller than the head of a soldier, even though they are sisters and share the same genetic background[170].

Inspiration for artists

Insects have already long fascinated people. In the 17th century a wide diversity of artists painted insects[69] and the artist Jan van Kessel made a beautiful painting representing a wide diversity of insects (plus a spider and a few amphibians) (Figure 2). It is remarkable that the artist even designed a new species as if the observed diversity inspired him to think of yet other remarkable species still to be discovered. Insects have inspired artists for centuries, starting already before microscopes had been invented[69]. Albrecht Dürer made a wonderful drawing of a stag beetle in 1505 (Figure 3) and in 1889 Vincent van Gogh depicted the cabbage white butterflies that feature on the cover of this booklet. Sculptors also depicted insects and spiders in their work[69]. Even fashion designers bow to the beauty of insects[199].

The Dutch artist Dries Verhoeven took a very special approach. He exhibited the installation Homo desperatus in 2014[251]. This presented 44 display cases, each with a

Figure 2: Insects and reptiles (1658) by Jan van Kessel the Elder (1626-1679), oil on copper, 39x56 cm. Oak Spring Garden Foundation, picture by https://www.osgf.org/library/, on commons.wikimedia.org

model of a location where a disaster had happened: the US prison in Guantánamo Bay on Cuba, the island Lampedusa off coast of Italy in the Mediterranean Sea, the nuclear plants in Chernobyl, Ukraine and in Fukushima, Japan and various others. In each display case he included an ant colony consisting of a queen and workers and the visitor could see the tiny ants

Figure 3: Stag beetle (1505) by Albrecht Dürer (1471-1528); drawing 14.1 x 11.4 cm. The J. Paul Getty Museum, Los Angeles, picture by the Getty Center via commons.wikimedia.org

roam around throughout the display case (Figure 4). In addition, Verhoeven placed a tiny finger camera in each case to closely observe the ants in their miniature world. The views of these 44 camera's were sequentially projected on a wall of the big hall (Figure 5). This yielded a very different perspective to the visitors: they now saw the ants very well and in quite some detail, including their shape, their behaviour and their social interactions. This allowed the visitor to connect to the animals and it influenced the public's impression of what had happened on the site. Insects have fascinated humans in various ways, but they have also been subject of quite some human violence and the perception of these creatures plays an important role in which approach is taken: fascination or violence.

Figure 4: Installation Homo desperatus by Dries Verhoeven (1976): display case representing the collapse of a building housing many garment factories, where more than 1100 people died and more than 2500 people were injured; 24 April 2013, Dhaka, Bangladesh. Noordbrabants Museum, 's Hertogenbosch, the Netherlands (2014). Picture by Marcel Dicke.

Figure 5: Projection of view via finger camera. Installation Homo desperatus by Dries Verhoeven (1976), Noordbrabants Museum, 's Hertogenbosch, the Netherlands. Picture by Marcel Dicke (2014).

My journey

When I attended high school, back in the 1970[s], my biology teacher Piet Groeneboom sparked my enthusiasm for life on our planet and he inspired my interest in the study of ecology. He also taught about the methods that were used to attempt to exterminate so-called "pests" (an anthropomorphic term) with chemical pesticides and their consequences for nature. I read the alarming book *Silent Spring* by Rachel Carson (1962)[46] on the devastating consequences of chemical pesticides for both nature and humanity. I decided that I wanted to contribute to the development of sustainable alternatives for chemical pesticides, such as biological control. Driven by this passion, I registered at Leiden University to study Biology and met with Joop van Lenteren whose guidance made a lasting impression on me. His passion, enthusiasm and aim to develop ecology-based biological control greatly influenced me. We have collaborated for decades and in 2003 I was provided the opportunity to succeed him as the chair of the Laboratory of Entomology at Wageningen University.

After completing my Biology study in Leiden, I moved to Wageningen to work under the guidance of the late Mous Sabelis. This collaboration resulted in the fascinating discovery that bean plants respond to spider-mite herbivory with the production of novel volatile chemicals that attract predatory mites that prey on the spider mites: the bean plants attracted the enemy of their own enemy. Plants appeared to be in charge of their defence by enlisting helpers and we coined this the 'plants-cry-for-help' strategy[78]. The collaboration with Maarten Posthumus and Teris van Beek at the Laboratory of Organic

Chemistry was crucial in this[77, 79, 219, 235]. Although initially international colleagues were sceptical about the suggestion that plants produced the predator-attracting compounds, the notion that 'plants cry for help' eventually was widely accepted[70, 172, 228] and even made it to the cover of the influential plant science journal *Trends in Plant Science* in 2003. The identification of the chemicals produced by Lima bean plants in response to feeding by the two-spotted spider mite[79] was the beginning of a long-lasting collaboration on chemical analysis of cues involved in plant-insect interactions with Maarten Posthumus and Teris van Beek. We investigated so-called herbivore-induced plant volatiles for various plant-arthropod interactions[36, 63, 98, 141, 166, 167, 173, 217-220, 235, 249, 259].

Common approach to tritrophic interactions

Also at the Laboratory of Entomology a new and exciting journey started. Together with Louise Vet and Joop van Loon we were three new members of the Laboratory of Entomology and we decided to work on a collective theme, the ecology and evolution of tritrophic interactions, each bringing in our own expertise. We selected a common tritrophic research system consisting of cabbage plants, caterpillars, butterflies, and parasitic wasps and started a very fruitful long-lasting collaboration in which many PhD candidates, postdocs, and guest workers participated[1-3, 34-37, 52, 54, 55, 59-62, 86-88, 101, 103, 112, 120-122, 132, 134, 142-145, 159-163, 176, 179-186, 188-198, 208, 226, 231-233, 258, 261, 263, 265, 266]. After ca 10 years Louise became the director of the Netherlands Institute of Ecology and showcased ecological research to highlight the value of biodiversity with a passion and charm such as only she can do. Joop and I continued our collaboration at Entomology until today. The value of this collaboration cannot be over-estimated and I am very grateful to Joop for his trust, friendship, and deep insights into the biology, physiology, and ecology of insects.

It turned out that the "simple" start of feeding by a caterpillar changes the phenotype of a plant extensively. As a result the interactions of the plant with other organisms changed both aboveground and belowground (Figure 6)[74]. Moreover, not only interactions between plants and insects, but also interactions among insects, that are mediated by the plant, changed[211]. For instance, when a herbivore attacks the leaves of a plant, this affects flower feeders[203, 204] and an insect feeding on the roots may influence caterpillars on the leaves and vice versa[121, 122]. When a parasitic wasp attacks a caterpillar that feeds on the plant this influences the interaction of the caterpillar with the plant, leading to a modulation of the blend of herbivore-induced plant volatiles resulting in the attraction of another wasp (a hyperparasitoid) that attacks the wasp larvae in the caterpillar[57, 58, 76, 267]. These insights in plant-insect biology shed light on population dynamics and community dynamics of insects associated with plants at different trophic levels[211].

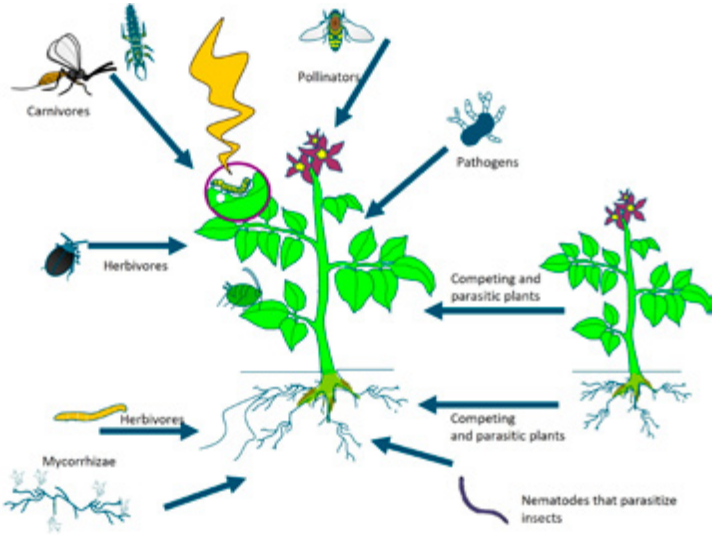

Figure 6: Effects of feeding by an herbivorous caterpillar on the interactions of a plant with other members of the plant-associated community. Modified from Dicke & Baldwin (2010)[74].

Microorganisms

Organisms are well known to harbour an enormous diversity of microbial cells and are nowadays considered to be so-called holobionts, or integrated ecological units through symbiosis[30]. It has been estimated 50 years ago that humans harbour 10 times more microbial cells than human cells[164], although more recent estimates reach a value of ca 1.5 to 2.5[207]. Microbes have important effects on the macrobial organisms they are associated with[127, 147]. For plants the ratio seems even more extreme[25]. Knowledge on the effects of insect-associated microbes is rapidly growing[67, 93-95, 148, 268]. It is becoming very clear that the microbes associated with plants and insects also influence the interactions between plants and insects[66, 191]. To really understand the ecology of plants and insects we need to have insight into the effects of microbes, such as bacteria and fungi, on these ecological interactions. For instance, taking microbes into account now shows that plants that are attacked on the leaves also cry for help belowground and attract beneficial microbes that assist in plant defence against pathogens and insect herbivores[11, 23, 24, 45, 64, 94, 104, 111, 168, 230]. So, a healthy soil with beneficial microbes is important for plant health and the plant can recruit these allies to its roots[45, 104, 168]. This research has been initiated as blue-sky academic research. Parts of it branched off into applied projects in collaboration with private industry active in plant breeding and biological control[27, 28, 32, 33, 59, 60, 62, 105, 115, 117, 118,

Figure 7: Enjoying delicious insect dishes prepared by chef Joseph Yoon (on the right), Wageningen, the Netherlands; 21 September 2024, Picture by Hans Smid.

[125, 126, 131-140, 222-226, 237, 257]. The bottom line is that plants are not helpless. They "know" how to survive and thrive and how to enlist the help of friends. Understanding how plants do this is important to develop sustainable agriculture where we support plants to defend themselves[33, 61, 62, 67, 68, 75, 80, 138, 155, 225, 257].

Crop production for feed versus food

When addressing crop production, common sense is that we grow crops to feed ourselves. However, in reality this is not quite true. The majority of crops goes to our livestock to produce meat: ca 70% of all agricultural land is used for livestock production[214]. Yet, also here knowledge of insects is very relevant. Therefore, I will shift gears here and move to insects as food and feed. My colleague Arnold van Huis has brought insects internationally into the spotlight as a sustainable source of protein, a valuable alternative to meat derived from conventional livestock[238, 245]. It has been a tremendous pleasure to be able to benefit

Figure 8: Broiler chick feeding on live black soldier fly larva. Picture by Jeroen Bouman.

from Arnold's vision during so many years: in research, teaching, outreach, events, and much more. You were a valuable soundboard for me and we discussed disciplinary and interdisciplinary science, management, outreach. Thank you very much. One of our activities was writing *Het Insectenkookboek*[241], which was later published in revised version in English as *The Insect Cookbook – Food for a Sustainable Planet*[242]. This book contains background information, nutritional data, interviews with a variety of individuals concerned with healthy food for the global population, such as René Redzepi of the prize-winning Danish restaurant *Noma* (five times voted the best restaurant of the world in The World's 50 Best Restaurants). For this book we benefitted a lot from the enthusiastic collaboration with chef Henk van Gurp at Rijn IJssel, Wageningen, who developed the recipes for the cookbook and prepared insect snacks for many demonstrations. We have been able to meet with two very special ambassadors for insects as food and feed: Princess Máxima and the late Kofi Annan, the former Secretary General of the United Nations. Rudy Rabbinge has played a vital role in making these two visits happen. Insects are currently produced both as food for humans and as feed for our livestock with a focus on circularity and sustainability. Both humans and animals enjoy a well-prepared meal with insects (Figures 7 and 8) [4, 17, 97, 123, 205, 239, 240, 242-245, 262].

Linking production of insects for food and feed with sustainable crop production

One of the most interesting aspects of my research has been that we could connect the production of insects as food and feed with tritrophic interactions and crop production. When producing insects for food and feed in a circular way by using residual streams from food production there is a residual stream consisting of moulting skins and insect faeces or 'frass' (Figure 9). This is a valuable resource for crop production[21]. When adding either of these to the soil this influences the composition of the community of soil microbes with positive consequences for crop growth, resilience of the crop to pests, and for crop yield[20-22, 92, 227, 232, 233, 254-256].

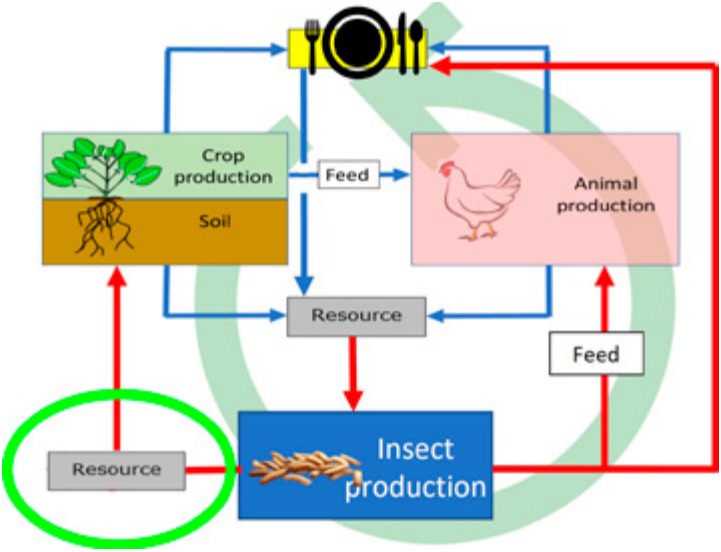

Figure 9: Insects in circular food production. The production of food leads to residual streams that can be used as a resource to rear insects for food and feed. The production of insects results in a residual stream that can be used as soil amendment to promote crop production and crop resilience (modified from Dicke, 2018[72]).

Our research on edible insects involved working with smallholder farmers in Kenya[49-51] and Colombia[15, 16, 18, 19, 73] on the one hand and with large companies in Europe[152, 153, 205] on the other hand. These projects involved much more than only natural sciences such as entomology, ecology, immunology, and toxicology, but also social sciences such as business economics, consumer behaviour, sociology, and ethics[4, 205]. Thus, we worked in interdisciplinary teams addressing value chains including various stakeholders, such as insect producers, regulatory organisations, banks, NGO's etc[81-83, 129, 130, 205]. For me these projects were very stimulating and I learned a lot. The project in Colombia, *Insects for Peace*, initiated and coordinated by Karol Barragán Fonseca is very close to my heart[14]. This project helps those who signed the peace agreement reintegrate into Colombian society that has suffered from more than 50 years of armed conflict[14, 18].

We recently collaborated with a Chinese team on the macro-aspects of producing insects for food and feed. A scenario study with our Chinese colleagues – among whom my former PhD student Feng Zhu - showed that the agricultural sector of an enormous country like China, with almost a fifth of the total human population may become climate neutral and independent of soy imports by (1) producing less livestock, (2) producing insects in a circular way for food

and feed, (3) replacing meat by insects that are produced in a circular way and (4) using insects instead of soybeans as feed for the limited number of livestock[13]. So, even small bugs can spark profound change (Figure 10).

Reducing the use of chemical pesticides

It is time to change gears again. Back to my motivation to contribute to the reduction of insecticide use. This, unfortunately, is not a good-news story yet: since 1990 pesticide use has doubled globally and insecticide use in the Netherlands increased (Figure 11)[177]. New generations of insecticides were developed[29, 41, 102]. This is truly bugging me. Many insecticides are now coated on seeds and then they disperse throughout the plant during development, being present in the sap stream, bringing the chemicals to leaves, roots, and stem[29, 40, 41]. Aphids and other insects that feed on the phloem sap ingest the compounds and excrete them in their fluid poop, which we call honeydew, a very sweet substance. Honeydew is an important food source for a diversity of beneficial insects such as bees, predators, and parasitic wasps[39, 89]. When beneficial insects feed from contaminated honeydew produced by the phloem-sap-feeding insects this leads to mortality[38-41]. This has been demonstrated by my former PhD student Miguel Calvo-Agudo for two crops, four systemic insecticides, three honeydew producers, and five beneficial insects[41]. These data show how systemic insecticides from the seeds disperse into the environment with negative consequences for beneficial insects.

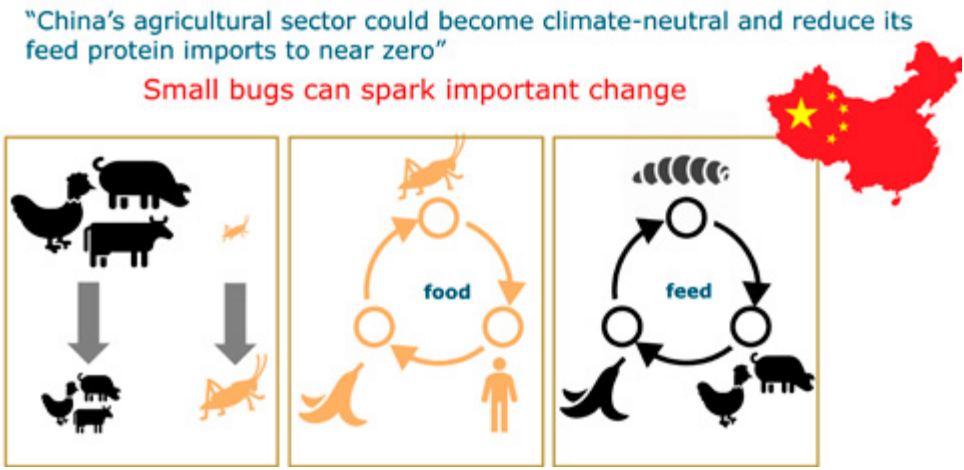

Figure 10: Scenario study shows that a food system that includes insects as food and feed may reduce feed protein imports to near zero and mitigates climate effects considerably in China (Bai et al. 2023[13]).

Non-target effects of chemical pesticides

A recent large-scale analysis shows that extensive negative effects of insecticides have been recorded for animals, plants, and microorganisms[253]. Calling such compounds insecticides – i.e. compounds that kill insects – therefore is an incomplete description. Similarly, fungicides and herbicides negatively affect animals, plants, and microorganisms[253].

Insecticides are found in various body parts of birds[5, 8, 65, 178, 221] as well as body parts of humans[6, 48, 156, 221]. They are even found in our brains[150, 156]. Knowing that all insecticides are neurotoxins this is worrying. Certainly in the light of the rapid increase of neurodegenerative diseases such as Parkinson and Alzheimer[26, 84, 90], and the association of pesticide use and the incidence of Parkinson that has been established in France[116].

Moreover, experimental studies on birds show that exposure of birds to individual insecticides influences the behaviour, reproduction and general health status of birds[85, 171]. This matches with studies that show that bird decline is stronger in areas with higher levels of insecticides such as neonicotinoids in the surface water[107]. For obvious reasons, experimental studies on humans have not been carried out. Yet, circumstantial evidence grows and for specific pesticides the United Nations Environment Programme, Food and Agricultural Organisation and World Health Organisation recommend to ban them because of the risks linked to Parkinson Disease[229]. This recommendation has been implemented in various countries. EU pesticide legislation (Directive 91/414/EEC,

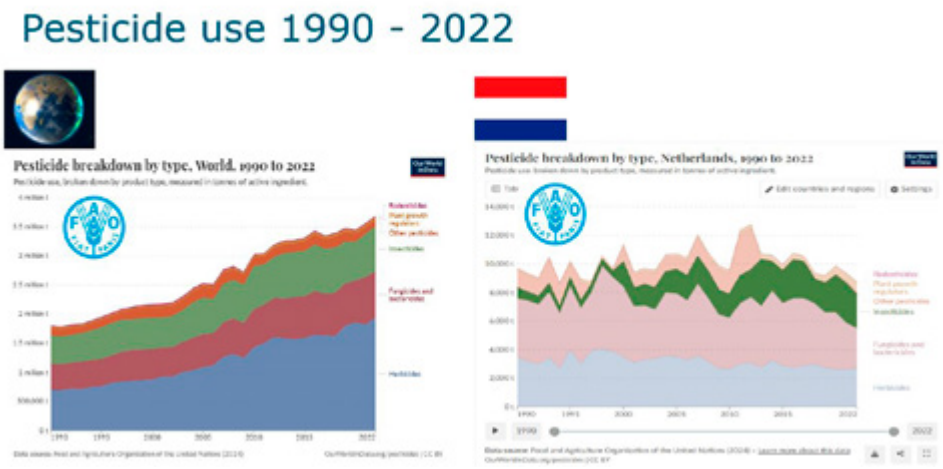

Figure 11: Pesticide use, breakdown by type 1990 to 2022, (left) World, (right) the Netherlands. Courtesy of Our World in Data, based upon data from Food and Agriculture Organisation of the United Nations (2024).

Figure 12: Graphic made for an awareness campaign for Natuurbeschermingsjaar 1970 by Klaas Ooms: bye bye birds, bye bye fish, bye bye flowers, bye bye people.

1993–2008) led to the withdrawal of 704 active substances, leaving 276 currently approved. Of the active substances withdrawn many were identified as being toxic to humans[119]. Pesticides are introduced on the market as solutions to pest problems but time and again they are taken off the market due to risks for human and environmental health[119]. Already back in 1962 Rachel Carson[46] wrote: "Future historians may well be amazed by our distorted sense of proportion. How could intelligent beings seek to control a few unwanted species by a method that contaminated the entire environment and brought the threat of disease and death even to their own kind". There is no better way to describe it (Figure 12).

Passive smoking

Now you may wonder: so, it is in our own hands, we can choose to buy food that is not contaminated with pesticides, so what is the problem? Unfortunately it is not that simple. Pesticides are everywhere: in the soil, in the dust at home and in the air that we breathe[113, 146, 174]. Just like with passive smoking we are exposed to airborne pesticides. Studies in Germany show that more than one hundred pesticides float in the air, up to 33 in a single sample[96, 146] and so we inhale pesticides on a daily basis. Some might trivialise this by saying that the amounts are too low to cause problems, but although this might hold for individual compounds, we are continuously exposed to a cocktail of 10-30 compounds. A study investigated the effect of a combination of nine compounds that are commonly found in air samples in Germany: seven herbicides, aimed at killing weeds, and two fungicides, aimed at killing fungi[96]. Individually, these nine pesticides did not affect the survival of the fruit fly *Drosophila melanogaster*, when tested at environmentally relevant concentrations. However, when they were offered as a cocktail to the fruit flies this strongly impacted the reproduction of the flies, leading to a 67% reduction[96]. And mind you: none of them was labelled as an insecticide!

Why *do* we use chemical pesticides in crop production?

The common answer to this question is the continuously repeated mantra that "we need pesticides to be able to feed the world". This justification is made over and over again[10],

[110]. For instance, already in 1971, Norman Borlaug, the father of the green revolution, which resulted in the development of high-yielding varieties of cereals, particularly wheat and rice, made very strong statements criticising those who warned about pesticides[110]. He said: "If agriculture is denied the use of DDT because of unwise legislation that is now being promoted by a powerful group of hysterical lobbyists who are provoking fear by predicting doom for the world through chemical poisoning, then the world will be doomed not by chemical poisoning but from starvation." He qualified Rachel Carson's book *Silent Spring* as "the vicious hysterical propaganda campaign against the use of agricultural chemicals"[110]. He further said about her book: "It was a diabolic, vitriolic, bitter, one-sided attack on the use of pesticides, especially insecticides and weed killers"[110]. There has been a strong lobby from those that make a business of selling pesticides. This has been extensively described by Robert Van den Bosch in 1978 in his book *The Pesticide Conspiracy*[236] in which he presents his own experiences and those of his colleagues on how pesticide use was promoted and enhanced. A common thread of the story is that insects are said to threaten our crops, our animals, our lives and that we need to control, to eliminate them. The book *A loud lobby for a silent spring*[109] elaborates how the agrochemical industry has continued their lobbying campaigns in recent years. It focusses on the tactics of the pesticide industry to undermine the Farm to Fork strategy of the European Union that aimed at a 50% reduction in risk and use of pesticides in the European Union.

'We need pesticides to feed the world'

So the mantra is that we need pesticides to feed the world. But is this really true? The argument is that if we do not use pesticides we loose on average ca 10-30% yield[31]. And indeed, the use of pesticides does lead to a higher yield in the crops that we use today. However, we need to remember that these crops were developed to be used in an agricultural setting that is based upon chemical pesticides. Norman Borlaug was quite clear on that[110]. But we should see this in the context of the fact that 70% of the agricultural land is currently employed to feed our livestock for the production of meat. So, reducing livestock production can make up for the yield reduction of crop production without chemical pesticides. And switching to a more plant-based diet is a healthy choice for consumers in the Global North[100, 202]. In other words, pollution of the planet is not a necessity but a matter of choice. That is good news, because it means that we can make the difference[210]. Scenario studies by colleagues at Wageningen University & Research show that circularity – in combination with a choice for a healthy, more plant-based diet – can result in EU self-sufficiency in food production with a 71% reduction of land use for agriculture. This land may then be used for producing food for a very large number of people outside of the EU[250].

We need to rethink our food system. The current system is based upon pesticides. For instance, if breeding for higher yield leads to reduced resistance this is compensated for by the use of pesticides, agronomic practices such as large monocultures are facilitated by pesticide use and agricultural economics commonly takes pesticides into the equation. A recent French study highlights the overuse of pesticides: 42% reduction of pesticide use was estimated to be possible without yield loss or profitability loss on 59% of 1000 farms investigated[151].

So, pesticides harm biodiversity[253] and human health[229]. Public health costs and many other costs are paid by society[7]. This is not sustainable. Moreover, yield reduction can be limited by developing a systems approach for sustainable crop production that includes input from plant breeding, biological control, agronomics, economics, etc.[53] We have many tools available and various programmes at various scales are underway to use these tools to develop sustainable approaches to crop production (Figure 13)[56, 91, 99, 106, 114, 124, 229, 234]. A main characteristic is that these programmes do not work *for* farmers but work *with* farmers. The technical building blocks for such developments are there and integrating them requires support from politics, banks, consumers, public health organisations, NGO's etc. First and foremost, it is important to develop such innovations by working with

Figure 13: Various national and international programmes that work with farmers to integrate various tools to develop food production systems that do not rely on pesticides.

farmers. Furthermore, a responsible government is expected to support such activities because this is good for public health, for nature, and for governmental finances.

Breaking free from established paradigms

There is more good news. We can break free from paradigms, although we often need a crisis for that. Let me give you an enlightening example that is presented every year in our course on Biological Control of Insects by guest speaker Karel Bolckmans from Biobest (Belgium). In Dutch greenhouses, an integrated system to protect crops through biological control has been developed by growers, researchers, and biocontrol companies during decades[248]. This started with the use of the predatory mite *Phytoseiulus persimilis* (Figure 14) to control two-spotted spider mite populations (*Tetranychus urticae*), followed by the use of the parasitic wasp *Encarsia formosa* to control the greenhouse whitefly *Trialeurodes vaporariorum*. New pests needed to be controlled and new biological control agents were introduced over the years. This resulted in an integrated pest management system based upon ecology[43, 187]. In the Spanish horticultural area of Almeria growers continued to use chemical control and this was gradually more and more difficult to do[43]. However, when the companies that produced the natural enemies used in integrated pest management in the Netherlands presented this option to the growers in Almeria, the growers were not convinced that it could solve their problem. They continued with the use of chemical pesticides at a steadily increasing intensity. When at some moment Greenpeace reported that pesticide residues exceeded the allowed levels considerably, German supermarkets considered to stop buying from Spanish growers. This caused a crisis among the Almerian growers. As a result the growers contacted the biocontrol companies, because they now wanted to give their integrated pest management option a try[42, 43, 128, 247]. The most salient outcome of this was that after a few years of implementing this, the Spanish growers concluded that the effectiveness of biocontrol was superior to chemical control. The take-home message here is that a crisis can yield something good.

Figure 14: Predatory mite Phytoseiulus persimilis, *feeding on a two-spotted spider mite (*Tetranychus urticae*). Picture by Hans Smid.*

The art of lobbying

This brings me back to Dries Verhoeven whose installation Homo desperatus (Figures 4 and 5)[251] showed that anything that we do not connect to, we do not seem to care for. This inspires me to highlight the importance of the ecosystem services of insects. These include their role in natural pest control, the removal of organic matter such as manure and cadavers, the pollination of more than 70% of all plant species, and providing food to a very large number of animals[71, 158]. An important message is that insects make this planet inhabitable for humans. In this context, it is important to stress the excellent alternatives for pesticides. As Joop van Lenteren already stressed in his farewell lecture back in 2010[246]: we need a much stronger lobby for sustainable crop protection without pesticides. The limited attention to the art of lobbying is a gap in our teaching programme.

Legacy

I see many more signs of hope. It has been a great privilege for me that I have been able to work with a fantastic team of staff, PhD candidates, postdocs, and guests at the Laboratory of Entomology at Wageningen University. We collaborated on various fundamental as well as applied aspects of insects to understand their biology and to develop sustainable ways of producing food by taking insects into the equation as living organisms and similarly also for finding alternatives for the management of insects that transmit diseases. The PhD theses of all PhD candidates that I supervised at Wageningen University are available

Figure 15: Former PhD laureates, postdocs and guest scientists are currently active in countries across six continents.

online at the library of our university[252]. It is heartwarming that a large proportion of my PhD laureates are present in this room today, arriving from four continents to Wageningen. Upon graduation, these PhD laureates have moved forward and now work in academia, private business, NGO's, educational organisations, governmental organisations. They work on biological control, plant breeding, agronomy, education, policy making, and societal development and many more topics to develop a world in which insects are respected and valued. These PhD laureates as well as the postdoctoral fellows and guest workers are active on six continents (Figure 15). Four of them have highlighted their research in the symposium *Insects, inspiration and impact*, that we had earlier this afternoon in this hall (Figure 16). Apart from working with PhD candidates, working with BSc and MSc students has been and still is deeply rewarding. Their fresh perspective and eager engagement spark hope and provide valuable progress.

Figure 16: Poster of the symposium Insects, inspiration and impact, *organised on the occasion of the farewell address by Marcel Dicke*

Promoting the ecological value of insects

At the same time, it remains important to continue improving the image of insects as being beautiful, wonderful, and vital organisms on our planet, and why not begin with one of the most detested group of insects of all: cockroaches? If someone calls you a cockroach, terrible things may happen as human history has shown in the past decades until this very day[157, 260]. Yet, cockroaches are beautiful animals that exploit a niche created by humans, i.e. places where we provide food remains that they readily use. Cockroaches feature positively in art. For instance, my database on insects in art, comprising ca 5000 entries, contains more than 50 entries of works of art that feature cockroaches. The most prolific artist depicting cockroaches that I know is Catherine Chalmers[47], who aims to change our view of these beautiful

insects. Also in music cockroaches feature, such as in the folk song *La Cucaracha* that is very popular in Spain and Mexico. Yet, no one beats the Thai artist Anon Pairot who writes the most beautiful word we know with cockroaches: Love.
Together with Arnold van Huis I have had the pleasure to organise the public lecture series *Insects and Society* since 1997 in which we portray how intimately insects are integrated into our society[149]. The topic really permeates every level of society, including e.g. medical care, food, literature, art, archaeology, psychology, technology. Every edition of the lecture series is advertised with a beautiful poster designed by our Entomology colleague Hans Smid (Figure 17). This lecture series commonly attracts a large audience of both students and non-students.

Figure 17: Poster to advertise the 2019 edition of the lecture series Insects and Society *(© Hans Smid).*

In 2006 the Entomology team transformed Wageningen to the City of Insects in a week-long festival (Figure 18) after we had won the Academic Year Prize in the *Battle of the Universities*. The success of this festival was the result of the enthusiastic collaboration with various groups in town, including the local cinema, theatre, hotel school, daycare centres,

retailers, restaurants, artists, musicians[44, 206]. This festival extended the importance of insects to all corners of the world when news agency Reuters broadcasted a short news item about the festival. In addition, last September we organised the successful event *Feeding the Future* in Theatre Junushoff with the national consortium InsectFeed[209]. The impact of these popular activities has far-reaching and long-lasting effects.

Figure 18: Festival Wageningen – City of Insects, organised by the Entomology team from 18 – 23 September 2006.

The impossible is possible

As I prepared for this farewell lecture, one thing became clear: the pesticide issue still bugs me. Friends asked whether my story will end on a hopeful note and yes, ever being the optimistic realist, I believe change is not only possible, but within our reach. To quote John Lennon and Yoko Ono: "I may be dreaming but I am not the only one"[154]. When I arrived in Wageningen in 1983 it was common for employees and students to smoke in the buildings of the university and in public buildings in general, something that I disliked a lot as a non-smoker. Had anyone back then told us that in 2020 smoking was not only forbidden in the buildings of Wageningen University & Research but even on the campus as a whole and in public spaces in general, only very few would have believed him. But here we are in smoke-free buildings on a fully smokefree campus already since the summer of 2020!

Laboratory of Entomology

In this farewell address I have already mentioned several colleagues who have played an important role in my development as a scientist. Moreover, it has been a true pleasure to work with the team of the Laboratory of Entomology throughout all these years at Wageningen University. It is a diverse team, an eager team, a collaborative team and I would like to thank all members of the team throughout the past 40+ years for being such a stimulating community. I am very pleased that the team moves on under the inspired leadership of one of my best PhD students, Bregje Wertheim. I myself will continue to

promote the importance and beauty of insects, will continue my involvement in *Insects for Peace* in Colombia and will continue to plea for pesticide-free agriculture. Next year will be a special year because the Laboratory of Entomology celebrates its 100th anniversary.

Final words of thanks

At the very end there is one person who needs to be mentioned: during the past 40+ years, Alida has been my soundboard, my joy in the many bright days, my support in a few dark days. She was my critical audience at the try-outs of many of my oral presentations, especially those for a wide audience, including this one. Together we will continue our survey of insects in art, where art meets science.

The very last words are for our six-legged hosts on this planet: you are beautiful, you are diverse and our life on this planet is possible because of you: thank you so much! And be aware: anyone who does *not* like insects is on the wrong planet (Figure 19).

Figure 19: Insects are omnipresent and provide vital ecosystem services to planet Earth (picture courtesy of Apostolos Pekas).

You may say I'm a dreamer
But I'm not the only one
Imagine – John Lennon and Yoko Ono (1971)[154]

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About the author

Marcel Dicke (1957) grew up at the edge of Rotterdam where he discovered nature, had a vegetable garden and was inspired by his biology teacher Piet Groeneboom to engage in the study of life, with a focus on ecology. He selected the University of Leiden to study Biology with a second major in Chemistry and obtained his MSc degree cum laude. He was inspired by research on insect ecology and biological control by Professor Joop van Lenteren. Chemical ecology of interactions between insects was one of his main thesis topics. He moved to Wageningen University in 1983 and obtained his PhD degree cum laude on a thesis on the chemical ecology of tritrophic interactions of plants, herbivores and predators, supervised by Professors Joop van Lenteren and Mous Sabelis.

His PhD research yielded the important result that plants respond to arthropod herbivory with the production of a bouquet of volatiles that attract the natural enemies of the herbivores. This has been the basis for a growing research field on multitrophic interactions (interactions between organisms from different trophic levels) above and belowground also including microbes) that is being integrated with the field of plant-microbe interactions. This has resulted in various national and international research programmes.

Marcel was appointed full professor in 1997 and served as Chair of Entomology at Wageningen University & Research for 22 years since 2003. The Entomology team comprises ca. 70 employees, usually representing 20-25 nationalities at the same time. The team executes an integrated teaching (BSc till PhD and Wageningen Academy) and research programme (fundamental disciplinary science, multidisciplinary science and interdisciplinary and transdisciplinary science). The team collaborates in different entomological topics as well as across science groups and with stakeholders.

He was a visiting professor at different international universities including Cornell University in the USA and Hangzhou University in China and he is an elected member of the Royal Netherlands Academy of Sciences (KNAW) and of the Royal Holland Society of Sciences and Humanities (KHMW).

Among the various awards for his work are the Eureka Prize for Science Communication (the Netherlands), the Rank Prize for Nutrition (United Kingdom) and the Belgacom Prize awarded by the Royal Belgian Academy of Sciences (Belgium). With the Entomology team he won the Academic Year Prize (2006, the Netherlands) for their idea to promote science through the festival *Wageningen – City of Insects*. He was the first employee of Wageningen

University to be awarded the Spinoza award (2007), the highest award in Dutch academia, for the scientific work that he conducted with his team.

Writing is one of his passions. He published more than 550 peer-reviewed scientific papers with his team and more than 90 popular scientific papers. In addition he published four books: a text book with his colleagues Professor Louis Schoonhoven and Professor Joop van Loon, a cookbook with his colleague Professor Arnold van Huis and chef Henk van Gurp as well as two popular scientific books. His work is very well cited.

At present, a total of 115 PhD students have completed their thesis with Marcel as one of their supervisors. Throughout his career, teamwork has been important and in research and management he aims to build bridges and teams. The Entomology team has made important contributions to Wageningen University & Research and the Plant Sciences Group via research and teaching collaborations with colleagues in all Sciences Groups.

Marcel enjoys transferring his knowledge about the ecology and impact of insects to a wide audience of colleagues, students, and the general public. His TED talk entitled 'Why not eat insects' has been watched more than 1.7 million times. Together with his colleague Professor Arnold van Huis he organises the biannual lecture series 'Insects and Society' that attract a large group of students and laypersons. In 2006 he organised with his team the week-long science festival 'Wageningen - city of insects' that attracted more than 20,000 visitors. Marcel has presented scientific insights in numerous interviews on television, radio and the written media.

Prof.dr Marcel Dicke

'Insects are everywhere, in our language ('busy as a bee' or 'butterflies in my stomach') and in nature where they play a vital role in the web of life. They pollinate the majority of our crops and serve as an excellent source of animal protein to many organisms. Still, they are often only seen as pests, leading to decades of insecticide use despite clear harm of these chemicals to ecosystems, our environment, and our health. However, excellent opportunities for sustainable food production, not based upon insecticides or pesticides in general, is possible. The view that we need pesticides to feed the world is challenged in this farewell address.'