Feature

Systemic pesticide concerns extend beyond the bees

Systemic pesticides, including the widely used neonicotinoids, have been linked to colony losses in honeybees and declines in other pollinator species. More recently, evidence has accumulated suggesting that their widespread, often prophylactic use is harming important parts of soil and water ecosystems, putting biodiversity and ecosystem services at risk. **Michael Gross** reports.

It sounded like a good idea at first. Rather than spraying toxic substances on entire fields of crops, the 'systemic' approach involves coating the seeds with the product such that the plant will take up the chemical and incorporate it into its structures. Pest species that nibble on the plant will ingest the poison, while good insects that fly past won't be affected by it.

However, what happens below ground isn't quite as neat as the initial image of pest-defeating crop plants suggested. Only around 5% of the substance reaches its destination, the cells of the plant. Around 1% gets blown off as dust, and the remainder ends up in the soil or in the water permeating the soil. Given the widespread use of systemic pesticides in the last two decades and their ability to persist in the soil for up to several years, those remaining 94% add up to a serious contamination of the ground and water. The chemicals that are causing the most concern include neonicotinoids, such as imidacloprid and clothianidin, and the unrelated substance fipronil, which targets GABA- and glutamate-gated chloride channels.

Producers have argued that the toxicity of neonicotinoids to non-target organisms is relatively low under typical field conditions, but, as research motivated by the colony collapse disorder in honeybees and the decline of bumblebees and other pollinators has shown, non-lethal effects can also disrupt the ecological balance. These findings have led the European Commission to impose a temporary ban on the use of the three neonicotinoids—imidacloprid, clothianidin and thiamethoxam—in outdoor flowering crops that are attractive to bees (Curr. Biol. (2013) *23*, R462–R464).

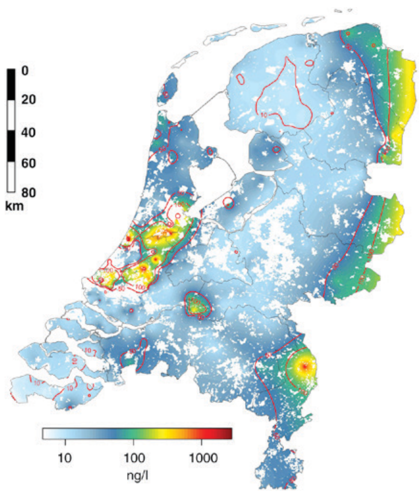
However, that collateral damage could reach much further. In the summer of 2010, Henk Tennekes from Experimental Toxicology Services Nederland at Zutphen warned that the accumulation of neonicotinoids in the environment would not only decimate useful insects but also have a knock-on effect on other species, including birds (Curr. Biol. (2011) *21*, R137–R139). At the time, Tennekes did not find much support for his views and went on to publish his warnings as a book — *The Systemic Insecticides: A Disaster in the Making*. Recent papers from other researchers are now supporting his concerns, as they show that the damage arising from systemic pesticides isn't limited to pollinators and that many other species, from earthworms to birds, are also affected.

Birds in decline

A recent study has combined the highly detailed records of bird populations on the one hand and surface water contamination with pesticides on the other to demonstrate that the rate of decline of several insectivorous birds in plots all across the Netherlands correlates significantly with the contamination of surface water with the neonicotinoid imidacloprid in the same area (Nature (2014) *511*, 341–343). The species showing statistically significant correlation include: Eurasian skylark (*Alauda arvensis*), barn swallow (*Hirundo rustica*), yellow wagtail (*Motacilla flava*), common starling (*Sturnus vulgaris*), common whitethroat (*Sylvia communis*), and mistle thrush (*Turdus viscivorus*).

While correlation does not prove causation, the authors have carefully controlled for several possible causes, leaving the pesticide contamination as a likely factor contributing to the

Sowing seeds: A century after Van Gogh, agriculture in his native country started to become highly reliant on seeds coated with systemic pesticides. Ecologists are now warning that their accumulation in the environment affects a wide range of species, including birds.(Photo: Wikimedia Commons.)



Contaminated grounds: The geographic distribution of imidacloprid contamination in the Netherlands, shown here, correlates significantly with the local decline rates of 6 out of 15 bird species studied by Caspar Hallman and colleagues. (Used with permission from: Declines in insectivorous birds are associated with high neonicotinoid concentrations. Caspar A. Hallmann, Ruud P. B. Foppen, Chris A. M. van Turnhout, Hans de Kroon and Eelke Jongejans. Nature *511*, 341–343 (17 July 2014) http://dx.doi.org/10.1038/nature13531.)

bird decline. The mechanism of the effect could go via the availability of insects for the birds to feed their brood with — it doesn't have to involve acute toxicity to the birds themselves. The cascading effect though the food chain is supported by an earlier Dutch study led by Jeroen van der Sluijs (Utrecht University), which found a strong reduction of macro-invertebrate abundance in surface water polluted with imidacloprid (PLoS ONE (2013) *8*, e62374).

The two-year ban imposed by the European Commission on three neonicotinoids came into effect in December 2013, but, as it is designed to protect bees, it only applies to flowering plants. The pesticide can still be used on cereals, for instance, and thus can continue to build up in the environment. In a separate decision, the EU has banned the use of fipronil in applications that may expose pollinators, such as seed treatment for sunflowers and maize (corn), but German authorities have cleared its application as a granulate in potato fields in February 2014.

Accumulating problems

The accumulation of neonicotinoids in the environment in the densely crowded and intensively farmed Netherlands, as highlighted in Tennekes' warnings from 2010, is an issue that Van der Sluijs together with a network of colleagues around the country has been studying over the last few years. There is no doubt that the pesticides have been accumulating in the environment to worrying levels, but picking apart the subtle and manifold effects that they may exert on the workings of natural ecosystems remains a challenge.

Now Van der Sluijs and an international group of colleagues organised in the Task Force on Systemic Pesticides (TFSP) have conducted a large-scale meta-study surveying all information that might be relevant to the effect of neonicotinoids and fipronil on the soil and water ecosystems. Their conclusions rely on the analysis of scientific data reported in more than 800 peer-reviewed publications from the last five years, including industry-sponsored ones.

This so-called Worldwide Integrated Assessment of the Impact of Systemic Pesticides on Biodiversity and Ecosystems (WIA) includes separate investigations into the effects of systemic pesticides on non-target invertebrates, on vertebrates, and on ecosystem functions and services. The study appears as a set of papers in a themed issue of the journal *Environmental Science and Pollution Research*, currently in press. Links to the individual papers of the study will be included on the TSFP website, http://www.tfsp.info/, as they appear and the papers will be open access.

In the review of effects on invertebrates, L. Pisa *et al.* (Environ. Sci. Pollut. Res. (2014) in press) find that many soil organisms, including bacteria, can cope well with the exposure to pesticides, but a few crucial ones, most notably the earthworm and other annelids, are affected by the toxins, meaning their ecological role may be harmed by pesticide accumulation.

Research on vertebrate species, reviewed by David Gibbons from the RSPB Centre for Conservation Science, UK, indicates that current levels of pollution with the neonicotinoids imidacloprid and clothianidin are unlikely to produce direct mortality effects in vertebrates (Environ. Sci. Pollut. Res. (2014) http://dx.doi.org/10.1007/s11356-014-3180-5). In some locations, however, the systemic pesticide fipronil is sufficiently concentrated to harm fish, and some bird species are at risk of being poisoned if they ingest seeds treated with neonicotinoids.

Gibbons and colleagues conclude that the more significant risks for vertebrates are indirect ones, including, for instance, the loss of invertebrate prey species. Rather than relying on traditional toxicity tests, the authors conclude, the environmental safety of systemic pesticides should take into account such indirect effects which are more difficult to assess.

In another part of the WIA, Madeleine Chagnon, who is associated with the University of Quebec at Montreal, Canada, and colleagues tackle the effects on this higher level, to see how systemic pesticides may harm ecosystems and affect the services they provide (Environ. Sci. Pollut. Res. (2014) http://dx.doi.org/10.107/s11356-014-3277-x). For this purpose, Chagnon and colleagues took into consideration the detailed analyses made in other parts of the study for specific groups of organisms, including microbes, invertebrates, and vertebrates, and re-examined them from the perspective of threats to ecosystem services.

Pollination not only by domesticated bees but also by a large number of wild insect species is one ecosystem service that is affected by systemic pesticides. It is also a key example where the value of ecosystem services to human society can be easily recognised, quantified and communicated. According to a recent estimate cited by Chagnon and colleagues, annual insect pollination benefits amount to $215 billion. “The global loss of bee species, as bioindicators of environmental health, is an early warning that global biodiversity and ultimately, human welfare, may be threatened,” the authors conclude.

Neonicotinoids can persist in the soil for several years, posing an as-yet poorly understood threat to ecosystem services, such as decomposition of organic matter, nutrient recycling, and water filtration. The existing literature suggests that microbial communities in the soil may have sufficient amounts of functional redundancy to absorb the impact of systemic pesticides without reduction in their ecosystem function and services, but at costs of ecosystem resilience. However, ecological functions that depend on key species, such as earthworms, which are known to be sensitive to environmental concentrations of neonicotinoids, are likely to suffer from the accumulation of these pesticides in the soil.

With the run-off from the soil, neonicotinoids also get into the freshwater system, where they may disrupt useful ecological roles of crustaceans such as *Gammarus pulex*, which makes an important contribution to the breakdown of fallen leaves (Environ Toxicol. Chem. (2014) *33*, 648–653). Ultimately, the disruption of such functions may lead to the loss of the provision of clean freshwater, another important ecosystem service for people and animals alike. Moreover, pesticides in the water system may decimate invertebrate prey species and thereby reduce fish stocks, another ecosystem service that large human populations rely on.

Given these dangers, which are still poorly understood in detail, it appears ironic that neonicotinoids are applied both in aquaculture and in the combined rice-fish farming system, as the authors report. In oyster production in Willapa Bay (Washington State, USA), workers apply imidacloprid to exposed sediments at low tide in order to control a native shrimp species. What the pesticide washed away with the tide then does to non-target species and the wider ecosystem remains unknown.

Meanwhile, rice-fish farming systems, which represent a popular tool for rural development in parts of Asia, often rely on pesticides like imidacloprid to protect the rice from insect pests. There is evidence, however, that the neonicotinoid accumulates in the rice paddy waters and may from there also seep into the freshwater system. The authors conclude that, even though the direct toxicity of neonicotinoids to cultured fish species appears to have a relatively high threshold, the risk of indirect and synergistic effects would be reason enough to keep these pesticides away from aquaculture.

Too much of the same?

In a paper summarising the overall conclusions from the WIA's analyses, Jeroen van der Sluijs and colleagues identify the key reasons why systemic pesticides, although initially hailed as a greener solution, have become such a large cause for concern. The problems arise, essentially, from the combination of their widespread, often prophylactic use, their very high toxicity to invertebrates, their persistence in the environment, their mobility, and their chronic toxic effects, which are not always adequately reflected in routine tests of acute toxicity.

Feeding time: Many bird species depend on insect prey, particularly for feeding their offspring, which means that a broad decimation of insect species by pesticides can have knock-on effects on the bird populations. The image shows the barn swallow (*Hirundo rustica*), one of the six species whose decline across the Netherlands was found to follow a statistical correlation with the accumulation of the neonicotinoid imidacloprid in the environment. (Photo: Wikimedia Commons.)

The key parameter that can be changed by policy decisions is the extent of use. The systemic pesticides may just have become victims of their own runaway success. No matter how specific a pesticide is, blanketing the biosphere with it will never be a good idea, even though it may look like a commercially attractive prospect for the manufacturers. In a commentary accompanying the above-mentioned study of bird declines in the Netherlands, Dave Goulson from Sussex University at Falmer, UK, compares the present over-reliance on systemic pesticides to the excessive use of organochlorides such as DDT in the 1950s, which Rachel Carson criticised in her book *Silent Spring* (1962), and which eventually led to a global ban on DDT. Goulson concludes that Carson "would undoubtedly think that we seem to have learnt little from our past mistakes." To prove him wrong, authorities would have to introduce some serious policies for the monitoring and limitation of systemic pesticides in order to stop their unbridled application in the future.

The WIA authors even question whether the widespread prophylactic application of these products actually produces a net gain for agriculture, as analysed in detail by Furlan and Kreutzweiser as part of the assessment (Environ. Sci. Pollut. Res. (2014) in press). The analyses found that the blanket use of neonicotinoid-coated seeds often brings no economic gain and may even be a loss-maker.

Thus, a more evidence-based application of pesticides, along with alternative strategies should be applied. In the concept of Integrated Pest Management (IPM), for instance, chemicals are considered only as a last resort. It is a key weakness of the systemic approach that the decision whether or not a chemical insecticide is to be used must be made right at the start, when the seeds are

Service disruption: The systemic pesticides can severely affect off-target invertebrate species, including bumblebees and other wild pollinators, thereby also disrupting important ecosystem services. (Photo: Michael Gross.)

purchased. Too often, this leads to the decision to use the chemicals 'just in case' even when their application may cause more harm than good.

Alternatives that could be used as part of an IPM strategy include crop rotation and diversity, inter-row planting, management of planting schedules, tillage and irrigation according to the minimisation of pest dangers, and biological strategies, such as trap crops and biological control agents, leaving the selective use of certain insecticides as a last resort. In theory, the EU has made the IPM approach compulsory for all crops as of the beginning of this year, but member states have been slow in implementing the directive.

What is less easy to control or even understand is what systemic pesticides do once they have entered the soil. Generally, it has emerged that their effects on the natural environment are much more subtle and complex than what the simplistic toxicity tests could account for. The WIA highlights a number of 'knowledge gaps' surrounding these products.

Intriguingly, the first big gap is the lack of knowledge regarding the quantities of systemic pesticides that have been used. This kind of information is crucial for a more detailed assessment of the ecological impact, and it should be a straightforward political measure to make detailed information publicly accessible.

Further weaknesses in our knowledge include the accumulation of pesticides in soil, water and sediments, which is well-screened in the Netherlands, and is starting to be better understood in a few other countries, e.g. Canada, but not everywhere else. Even less is known about the long-term fate of these substances and their metabolites, along with their chronic toxicity, sublethal effects, and any synergistic effects between those substances. As an international collaboration led by Nicolas Desneux from the INRA's Institut Sophia Agrobiotech at Sophia-Antipolis, France, has shown in a recent paper, the complex relationship between exposure time and toxic effects in ants, bees and termites further complicates the issues (Sci. Rep. (2014) *4*, 5566, http://dx.doi.org/10.1038/srep05566).

Thus, there are many questions to be answered while the partial EU moratorium on neonicotinoids continues. Only one thing appears to be clear already: applying systemic pesticides to all seeds regardless probably never was a good idea to begin with.

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Q & A

Stephen F. Goodwin

"As long as I'm learning something, I figure I'm OK — it's a decent day"
Hunter S. Thompson

Born in Banbridge, Northern Ireland, Stephen Goodwin spent his childhood growing up in Belfast and attending Methodist College Belfast grammar school. He studied genetics as an undergraduate at the University of Glasgow, and researched Drosophila *learning and memory for his Ph.D. in Kim Kaiser's lab. During a postdoctoral stint in Jeff Hall's lab at Brandeis University, he used molecular-genetic and behavioral approaches in the fruit fly to understand how the sexual identity of a nervous system and its behaviors are specified. He worked on a fly gene, nicknamed* fruitless, *mutations of which specifically disrupt male reproductive behaviors. Research on* fruitless *— in Hall's lab and others — was the first to pinpoint a single gene that works in the brain to govern nearly all aspects of a complex behavior in adult animals. He returned to the UK and spent 10 years leading a research group at the University of Glasgow, before moving to Oxford in 2009, where he is an Associate Professor in Biomedical Sciences and a Tutorial Fellow in Medicine and Physiology Sciences at Magdalen College. His laboratory continues to use* Drosophila melanogaster *to study the genetic, developmental, and neural mechanisms that underlie sex-specific behaviors.*

How did you get into biology, and how did you come to be working in this area? My father was a mechanical engineer by training but an enthusiastic biologist, and in the late 70s he studied for an Open University degree in biology. He was a believer in broadening your mind in a way that isn't connected to your working life and getting a sense of achieving something new and amazing. He adored the way different disciplines could cross-pollinate new and exciting ideas, and preached this doctrine throughout his life. I think I got my initial curiosity for working things out from my father — he spent much of his career involved in design engineering. He was always amazed by evolutionary design in the natural world—this