OPINION

Neonicotinoids pose undocumented threats to food webs

S. D. Frank[a,1,2] and J. F. Tooker[b,2]

One of the main lessons that emerged from *Silent Spring* (1) is that we overuse pesticides at our own peril because human and natural environments are unquestionably linked. It is time to revisit these lessons given current use patterns of neonicotinoid insecticides.

Since their introduction in the early 1990s, neonicotinoids have become the most widely used insecticides in the world. Their toxicity allows less active ingredients to be used and, compared with older classes of insecticides, they appear to have relatively low toxicity to vertebrates, particularly mammals (2). Neonicotinoids have been repeatedly called "perfect" for use in crop protection (2).

Yet recent research calls this perfection into doubt as neonicotinoids have become widespread environmental contaminants causing unexpected nontarget effects. In particular, researchers have found that neonicotinoids can move from treated plants to pollinators and from plants to pests to natural enemies. Worse, transmission through simple food chains portends widespread, undocumented transmission into entire food webs. We believe that neonicotinoids

Neonicotinoids pose broader risks to biodiversity and food webs than previously recognized. Serious efforts must be made to decrease the scale of their use. Image credit: Shutterstock/lantapix.

[a]Department of Entomology, North Carolina State University, Raleigh, NC 27695-7613; and [b]Department of Entomology, The Pennsylvania State University, University Park, PA 16802

The authors declare no competing interest.

Any opinions, findings, conclusions, or recommendations expressed in this work are those of the authors and have not been endorsed by the National Academy of Sciences.

[1]To whom correspondence may be addressed. Email: sdfrank@ncsu.edu.

[2]S.D.F. and J.F.T. contributed equally to this work.

First published September 2, 2020.

pose broader risks to biodiversity and food webs than previously recognized. Although further research is needed to document the ecosystem-wide transmission and consequences of neonicotinoids to establish their true costs and benefits, serious efforts must be made to decrease the scale of their use.

Toxic Choice

In 2014, the neonicotinoid market exceeded $3 billion and accounted for about 25% of the global pesticide market (3). Neonicotinoids are popular in part because they are very good at what they do. In fact, they are among the most toxic insecticides ever developed. The active ingredient imidacloprid, for example, is 10,000 times more potent to insects than nicotine, the biological inspiration for neonicotinoids and a very toxic compound in its own right (4). There are at least seven neonicotinoid active ingredients that are available to manage insects from at least nine taxonomic orders in many different pest systems, including large-scale agriculture, livestock production, fruit and vegetable crops, forestry, home landscapes, and even pets (4). Now, about 20 years after their introduction, ubiquitous use of three main neonicotinoid active ingredients (imidicloprid, clothianidin, thiamethoxam) is increasing the toxic load of agricultural landscapes, forests, and other ecosystems throughout the world, posing threats to beneficial insects and other sensitive taxa (5). Here we focus on neonicotinoid use for plant protection and potential disruption of above-ground terrestrial food webs, but our argument could be extrapolated to aquatic and detrital food webs where neonicotinoids also pose concerning nontarget risks (6, 7).

We contend that the efficient and well-documented transmission of neonicotinoids through tripartite food chains—plant to pest to natural enemy—combined with the diversity of nontarget herbivores on treated plants threatens entire food webs by disrupting arthropod communities and interactions.

Agrochemical companies, pest managers, and farmers use neonicotinoids to manage a broad range of herbivorous insect species that attack above- and belowground plant tissues. Neonicotinoids can be applied to plant foliage to kill insects on contact, but a primary advantage of neonicotinoids is that they can be absorbed through roots, leaves, or bark and transported to the rest of the plant through xylem or phloem. Because of this systemic movement, neonicotinoids applied in root zones or injected into plants (e.g., tree trunks) will move through the vascular system and make plant tissues toxic for insects to consume for long periods (8).

Seeds coatings (i.e., seeds coated with imidicloprid, clothianidin, or thiamethoxam, nitroguanidine neonicotinoids which are absorbed after germination) are the most common use of neonicotinoids and are used annually in the United States over more than 150 million acres of corn, soybeans, canola, cotton, wheat, and other crops (9). Plants from neonicotinoid-coated seeds have toxic neonicotinoid concentrations that last two to three weeks (10).

Neonicotinoids applied to the root zone of trees or injected into tree trunks can remain at toxic concentrations for three or more years (11). The long-lasting systemic nature of neonicotinoids, particularly in woody plants, can reduce the number of insecticide applications, potentially reducing risks of direct contact to applicators and other nontarget organisms.

Systemic transport and persistence of neonicotinoids also pose risks to beneficial insects, including pollinators and predators, through direct or indirect exposure. Susceptible insects, including pest and non-pest herbivores, pollinators, and omnivorous natural enemies, die after directly consuming plant tissues or fluids containing lethal neonicotinoid concentrations. Nonsusceptible invertebrate herbivores, including resistant individuals, those that receive sublethal doses, and taxa that are insensitive to neonicotinoids, encounter neonicotinoids as they feed. These individuals persist in food webs, alive but contaminated, exposing other consumers to the insecticides. For example, spider mites (Acari: Tetranychidae) and slugs (Mollusca: Gastropoda) do not die from consuming neonicotinoid treated plants, but their hemipteran and colepteran predators, respectively, die or sustain sublethal effects on survival or fitness after feeding on contaminated prey (12, 13). Thus, transmission of neonicotinoids through food chains can result in fewer predators and more herbivores and herbivory than without neonicotinoids.

Recent research has revealed that neonicotinoids can also be transmitted in a sugary liquid called honeydew that is excreted by phloem-feeding insects (Hemiptera), such as aphids, mealybugs, scale insects, and whiteflies. This research found that mealybugs, which are susceptible to neonicotinoids at certain concentrations, excreted honeydew that contained imidacloprid and was toxic to beneficial hoverflies and parasitoid wasps that consumed it (14). Neonicotinoids are used to manage many honeydew-excreting pests, which are primary pests in most agricultural systems, including field crops, vegetables, fruit and nut production, tree plantations, and urban forests, suggesting that neonicotinoids used in these systems have strong potential to pass to nontarget species via honeydew. Moreover, this route of exposure is likely to increase with growing introductions and populations of exotic, invasive, honeydew-producing species, like hemlock woolly adelgid (HWA; *Adelges tsugae*) and spotted lanternfly (*Lycorma delicatula*).

Widespread Contamination

We contend that the efficient and well-documented transmission of neonicotinoids through tripartite food chains—plant to pest to natural enemy—combined with the diversity of nontarget herbivores on treated plants threatens entire food webs by disrupting arthropod communities and interactions. Ecosystems harbor thousands of innocuous invertebrate species, most of which are either susceptible to neonicotinoids, could transmit them to higher trophic levels, or both. These species, often just acting as prey, provide critical linkages that effect food web stability and resilience. Inadvertently removing or changing the abundance of species makes food webs vulnerable to perturbation or collapse.

To illustrate how easily and completely food webs could be contaminated and disrupted, consider two systems—trees and field crops—in which neonicotinoids are extensively used. Trees host hundreds or thousands of arthropod species including detritivores, herbivores, omnivores, and predators feeding at third or fourth trophic levels. Eastern hemlock (*Tsuga canadensis*) trees are frequently treated with neonicotinoids to combat hemlock woolly adelgid (HWA; *Adelges tsugae*) but host more than 400 native arthropod species including herbivores, predators, and scavengers. Imidacloprid and its toxic metabolite olefin occur at toxic concentrations (to HWA) for at least three years and perhaps at detectable concentrations for at least seven years (11, 15). For this duration, susceptible and nonsusceptible herbivores are feeding on lethal and sublethal imidacloprid concentrations and transmitting it to higher trophic levels. Just within Great Smoky Mountains National Park, nearly 200,000 hemlock trees have been treated (16). All arthropod guilds on hemlock are negatively affected by imidacloprid applications (15). Although there are clear benefits to protecting hemlocks or other threatened tree species that form the basis of key ecosystems, we have little understanding of the influence of this widespread treatment and subsequent transmission on food webs. Thus, we have neither a basis for a cost/benefit analysis to evaluate the practice of protecting trees with neonicotinoids nor an understanding of what is being lost in these ecosystems.

The same phenomenon is happening on quite a different scale, over hundreds of millions of hectares of crop fields in the U.S. and Canada, among other countries, where nitroguanidine neonicotinoids are coated on crop seeds, like maize, soybeans, oilseed rape, cotton, and wheat. Soil and foliage arthropod communities in these fields are exposed annually to neonicotinoids with negative consequences (7, 9). Crop plants absorb neonicotinoids, protecting against a handful of typically secondary pest species, but crop fields host hundreds of other arthropod species. In addition, co-occurring weeds and fieldside vegetation, which host their own arthropod communities, also take up neonicotinoids from field soil and water, which are often heavily contaminated. Significant repercussions have been documented for arthropod communities within and adjacent to fields (17). Undoubtedly, many species are being exposed to lethal or sublethal neonicotinoid doses that may be simplifying communities in these and other ecosystems where neonicotinoids are applied.

Beyond arthropod species, vertebrates are also being exposed to neonicotinoids through multiple routes with largely unknown effects. The full range of effects of direct consumption of neonicotinoid-treated seeds and plants by vertebrates is unknown, but it is clear that neonicotinoids at field-relevant doses can be physiologically disruptive or even lethal to birds and mammals and that their site of action may not be in the nervous system, as is the case for insects (18). The risk of indirect exposure through food webs is also unknown, but birds are among top consumers of arthropods from all trophic levels. Ingestion and accumulation of neonicotinoids by birds appears to be widespread, with one study finding 100% of sparrows with neonicotinoids in their feathers (19). Just as concerning, birds and other vertebrates with higher trophic positions in food webs may be suffering from arthropod depletion and/or contamination by neonicotinoids, as suggested by some declining bird populations (20). In a recent alarming example from Japan, use of neonicotinoids to control insect pests in rice production inadvertently resulted in collapse of a local fishery because zooplankton that were a key portion of the fishes' diets declined dramatically with the introduction of neonicotinoids (21).

As students we learn that the risk of a toxin is the product of toxicity and exposure. We know that neonicotinoid exposure is far higher than necessary to achieve plant protection and yield objectives.

Not Worth the Risks

Owing to their systemic activity, low vertebrate toxicity, and long persistence, neonicotinoids initially showed promise to increase the efficacy and safety of pest management. A growing body of evidence, however, suggests that current use patterns, which are poorly documented (9, 22), may actually be creating more risks than benefits. Risks to many terrestrial, aquatic, and detrital organisms and ecosystems have been documented. Considering these risks, advocacy groups have frequently promoted outright bans on all neonicotinoids in all circumstances, and this stance seems easy to justify.

However, plant systems frequently sprayed with neonicotinoids are also awash in other insecticides that are as toxic or worse for a wide range of organisms (23). Assuming that the bulk of world agriculture will not become organic anytime soon, big agriculture and farmers will continue to use and sometimes abuse pesticides. To balance plant protection with human and ecosystem health, we should use neonicotinoids only when they will improve economic returns for farmers, rather than corporations, and risks can be minimized.

As students we learn that the risk of a toxin is the product of toxicity and exposure. We know that neonicotinoid exposure is far higher than necessary to achieve plant protection and yield objectives. Neonicotinoid seed coatings rarely improve crop yield (24), and neonicotinoids are applied preventively to vast areas of turf, which cover more land in the United States than any other irrigated crop, even when pests are absent or below thresholds (25). Applying neonicotinoids only when scouting and monitoring reveal pest populations exceeding an economic threshold, a basic tenet of Integrated Pest Management, would drastically reduce neonicotinoid application and environmental exposure. Despite the convenience of seed coatings, recent evidence indicates that only about 5% of crop fields actually benefit from their use (26). Thus, most of the volume of neonicotinoids used to protect large-acreage crops—its dominant use—could be eliminated, which according to the most recent use estimates (22) would reduce environmental loading by more than 2.8 million kg. That's an enormous amount when considering that individual seeds receive milligram amounts of active ingredient.

The cost–benefit calculation of some neonicotinoid uses, such as protecting trees from invasive species, is a matter of some debate [similarly, many argue that dichlorodiphenyltrichloroethane (DDT) use is justified to protect humans from malaria (27)]. But the benefit of needless preventive deployment in 95% of crop fields is indefensible. Eliminating preventive applications in other systems would similarly eliminate vast quantities of neonicotinoids from entering food webs.

Unfortunately, the agrochemical industry is not known for restraint in promoting and selling plant protection products, including neonicotinoids and genetically modified crops—even when problems, such as resistance or environmental contamination, arise. Growers often have limited choices in the seed they purchase and understandably favor the convenience and insurance of seed coatings when they do have a choice. In other industries, like turf and landscape maintenance, the long-lasting properties and convenience of preventive neonicotinoid applications encourage excessive use (25). Voluntary change from neonicotinoid producers or end users is unlikely.

DDT offers a close analogy to the current debate over neonicotinoids. By the time governments and companies had curtailed DDT use, the ecological and human health effects were indisputable and in some cases irreversible. Birds, such as California condors and peregrine falcons, are just recently emerging from near extinction, DDT or its metabolites still contaminate food and food chains around the world (28), and the majority of the U.S. population and people around the world have detectable DDT levels in their bodies (29). The extent to which these problems would have been curtailed by an earlier ban on DDT is unknown.

The full extent of environmental risk from neonicotinoids may not be known for years. If use is not voluntarily restrained, then regulation is the only hope. Otherwise, we risk a return to the toxic, simplified environment that prompted *Silent Spring*—a work that documents a history we should actively work to avoid repeating.

1 R. Carson, *Silent Spring* (Houghton Mifflin, 1962).

2 A. Elbert, M. Haas, B. Springer, W. Thielert, R. Nauen, Applied aspects of neonicotinoid uses in crop protection. *Pest Manag. Sci.* **64**, 1099–1105 (2008).

3 C. Bass, I. Denholm, M. S. Williamson, R. Nauen, The global status of insect resistance to neonicotinoid insecticides. *Pestic. Biochem. Physiol.* **121**, 78–87 (2015).

4 P. Jeschke, R. Nauen, Neonicotinoids-from zero to hero in insecticide chemistry. *Pest Manag. Sci.* **64**, 1084–1098 (2008).

5 M. DiBartolomeis, S. Kegley, P. Mineau, R. Radford, K. Klein, An assessment of acute insecticide toxicity loading (AITL) of chemical pesticides used on agricultural land in the United States. *PLoS One* **14**, e0220029 (2019).

6 J. C. Miles, J. Hua, M. S. Sepulveda, C. H. Krupke, J. T. Hoverman, Effects of clothianidin on aquatic communities: Evaluating the impacts of lethal and sublethal exposure to neonicotinoids. *PLoS One* **12**, e0174171 (2017).

7 A. Dubey, M. T. Lewis, G. P. Dively, K. A. Hamby, Ecological impacts of pesticide seed treatments on arthropod communities in a grain crop rotation. *J. Appl. Ecol.* **57**, 936–951 (2020).

8 L. Weichel, R. Nauen, Uptake, translocation and bioavailability of imidacloprid in several hop varieties. *Pest Manag. Sci.* **60**, 440–446 (2004).

9 M. R. Douglas, J. F. Tooker, Large-scale deployment of seed treatments has driven rapid increase in use of neonicotinoid insecticides and preemptive pest management in US field crops. *Environ. Sci. Technol.* **49**, 5088–5097 (2015).

10 A. Alford, C. H. Krupke, Translocation of the neonicotinoid seed treatment clothianidin in maize. *PLoS One* **12**, e0173836 (2017).

11 R. S. Cowles, M. E. Montgomery, C. A. Cheah, Activity and residues of imidacloprid applied to soil and tree trunks to control hemlock woolly adelgid (Hemiptera: Adelgidae) in forests. *J. Econ. Entomol.* **99**, 1258–1267 (2006).

12 A. Szczepaniec, S. F. Creary, K. L. Laskowski, J. P. Nyrop, M. J. Raupp, Neonicotinoid insecticide imidacloprid causes outbreaks of spider mites on elm trees in urban landscapes. *PLoS One* **6**, e20018 (2011).

13 M. R. Douglas, R. J. Rohr, J. F. Tooker, Neonicotinoid insecticide travels through a soil food chain, disrupting biological control of non-target pests and decreasing soybean yield. *J. Appl. Ecol.* **52**, 250–260 (2015).

14 M. Calvo-Agudo *et al.*, Neonicotinoids in excretion product of phloem-feeding insects kill beneficial insects. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 16817–16822 (2019).

15 C. Dilling, P. Lambdin, J. Grant, R. Rhea, Community response of insects associated with eastern hemlock to imidacloprid and horticultural oil treatments. *Environ. Entomol.* **38**, 53–66 (2009).

16 National Park Service (NPS), Hemlock woolly adelgid (2015). https://www.nps.gov/grsm/learn/nature/hemlock-woolly-adelgid.htm. Accessed 26 March 2020.

17 C. Botías *et al.*, Neonicotinoid residues in wildflowers, a potential route of chronic exposure for bees. *Environ. Sci. Technol.* **49**, 12731–12740 (2015).

18 A. Lopez-Antia, M. E. Ortiz-Santaliestra, F. Mougeot, R. Mateo, Experimental exposure of red-legged partridges (*Alectoris rufa*) to seeds coated with imidacloprid, thiram and difenoconazole. *Ecotoxicology* **22**, 125–138 (2013).

19 S. Humann-Guilleminot *et al.*, A large-scale survey of house sparrows feathers reveals ubiquitous presence of neonicotinoids in farmlands. *Sci. Total Environ.* **660**, 1091–1097 (2019).

20 C. A. Hallmann, R. P. Foppen, C. A. van Turnhout, H. de Kroon, E. Jongejans, Declines in insectivorous birds are associated with high neonicotinoid concentrations. *Nature* **511**, 341–343 (2014).

21 M. Yamamuro *et al*., Neonicotinoids disrupt aquatic food webs and decrease fishery yields. *Science* **366**, 620–623 (2019).
22 J. F. Tooker, M. R. Douglas, C. H. Krupke, Neonicotinoid seed treatments: Limitations and compatibility with Integrated Pest Management. *Agric. Environ. Lett.* **2**, 1–5 (2017).
23 United States Geological Survey (USGS), Pesticide National Synthesis Project, (2020). https://water.usgs.gov/nawqa/pnsp/usage/maps/. Accessed 5 June 2020.
24 S. Mourtzinis *et al*., A. Herbert A, Y. R. Kandel, Neonicotinoid seed treatments of soybean provide negligible benefits to US farmers. *Sci. Rep.* **9**, 1–7 (2019).
25 J. L. Larson *et al*., Optimizing pest management practices to conserve pollinators in turf landscapes: Current practices and future research needs. *J. Integr. Pest Manag.* **8**, 10 (2017).
26 G. Labrie, A. È. Gagnon, A. Vanasse, A. Latraverse, G. Tremblay, Impacts of neonicotinoid seed treatments on soil-dwelling pest populations and agronomic parameters in corn and soybean in Quebec (Canada). *PLoS One* **15**, e0229136 (2020).
27 World Health Organization (WHO), *World Malaria Report* (World Health Organization, Geneva, 2008). https://www.who.int/malaria/publications/atoz/9789241563697/en/. Accessed 5 June 2020.
28 Agency for Toxic Substances and Disease Registry (ATSDR), *Toxicological profile for DDT, DDE, DDD* (Draft for Public Comment). Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service (2019). https://www.atsdr.cdc.gov/ToxProfiles/tp.asp?id=81&tid=20. Accessed 5 June 2020.
29 Centers for Disease Control and Prevention (CDCP), *Fourth National Report on Human Exposure to Environmental Chemicals*. Atlanta, GA: Centers for Disease Control and Prevention. National Center for Environmental Health (2009). https://www.cdc.gov/exposurereport/index.html. Accessed 5 June 2020.