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NEONICOTINOIDS : A THREAT TO BIODIVERSITY, ECOSYSTEM SERVICES, & FOOD SECURITY

Primer

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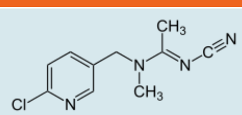
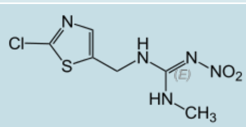
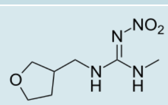
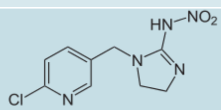
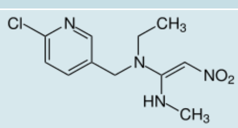
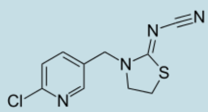
Primer : Neonicotinoids : a threat to Biodiversity, Ecosystem Services, and Food security

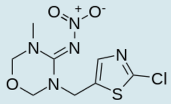
The sale and use of neoniticinoids around the world

Neonicotinoids, also known as "neonics," are synthetic nicotine analogues with insecticidal properties (Table 1). Introduced on the market between 1991 and 2002,[1] they were created specifically to thwart the resistance developed by insect pests to previous generations of insecticides (organophosphates, carbarmates and pyrethroids).[2] In just two decades, neonicotinoids have risen to the top of the global insecticide market,[3, 4] accounting for 23.7% of sales.[3]

Currently registered for veterinary and pesticidal uses in over 120 countries,[3] neonicotinoids are above all used in agriculture — and often prophylactically and indiscriminately — on such crops as corn, soya, canola, grains, cotton and sugar beets.[2, 3, 5] Neonicotinoid products are used as a soil treatment, foliar application and seed coating.[2, 3] Veterinary treatments include oral tablets and topical products[6] in liquid form and as a collar coating.

Table 1: Neonicotinoids currently available on global market[1, 3, 7]

Active ingredient	Molecular structure	Manufacturer	Market entry	Usage
Acetamiprid		Nippon Soda	1995	Phytosanitary
Clothianidin		Sumitomo Chemical Takeda Agro Co. + Bayer CropScience	2000	Phytosanitary
Dinotefuran		Mitsui Chemicals	2002	Phytosanitary
Imidacloprid		Bayer CropScience	1991	Phytosanitary Veterinary
Nitenpyram		Sumitomo Chemical Takeda Agro Co.	1995	Veterinary Phytosanitary
Thiacloprid		Bayer CropScience	2000	Phytosanitary

Thiamethoxam		Syngenta (Novartis)	1998	Phytosanitary

Certain distinguishing characteristics of these insecticides appear to drive their growing popularity. First, their high water solubility (Table 2) ensures translocation throughout plant tissues, thus extending protection to every part of the target crop.[2, 4, 17] Second, their persistence in soil and plant tissue (due to long half-lives, Table 2) means fewer applications are needed throughout the season.[2, 17] Third, the diversity of treatments available makes for great flexibility of use and application.[2, 3] Seed coatings in particular are often considered a safer form of crop protection, since they involve lesser quantities of active ingredients than spray applications.[2, 3]

Table 2: Water solubility and environmental persistence of neonicotinoids[7]

Active ingredient	Water solubility (mg/l)	Half-life, aerobic soils (d)[a]	Half-life, plant tissue (d)[a]
Acetamiprid	2,950	3	15.4
Clothianidin	340	545	16.6
Dinotefuran	39,830	82	6.8
Imidacloprid	610	191	4.9
Nitenpyram	590,000	8	ND
Thiacloprid	184	18	3.8
Thiamethoxam	4,100	121	4.4

a: The database consulted gathers numerous data for a given parameter. The data shown here are the highest obtained from the most reliable sources.

Neonicotinoids' rapid growth in sales and use can also be attributed to their mechanism of action, which targets nicotinic acetylcholine receptors (nAChRs). While these receptors are present in both vertebrates and invertebrates, they are more numerous in insects, whose nAChRs also exhibit greater neonicotinoid affinity.[2, 3] This selective targeting of arthropods is why neonicotinoids are considered safer than previous insecticide classes for non-targeted organisms, including humans.[18-22] However, despite the lower toxicity of neonicotinoids both toward vertebrates and compared to previous pesticides, a rising number of studies show that neonicotinoid exposure poses a potential risk to mammals, even humans[23]. Furthermore, given that nAChRs constitute a previously untapped biochemical target in the field of pest control, numerous pest species have yet to develop resistance, giving neonicotinoids an advantage in terms of efficacy.[2,4]

Neonicotinoid use in Canada

All types of neonicotinoids are registered in Canada, with the exception of dinotefuran.[8] Canada currently authorizes the use of 145 end-use products containing neonicotinoids (Table 3), which are dominated by products containing the neonicotinoid imidacloprid.[10] In Québec, while it is difficult to determine the total number of end-use products containing neonicotinoids, we know that 55 different end-use products are used on economically important crops.[11] Overall, many of these products are used as seed treatments; for instance, in Québec seed treatment products represent about 53% of all neonicotinoid products (calculation based on the pesticides used for economically important crops in the province).[12] Nitenpyram is used exclusively in veterinary contexts, primarily in the form of oral tablets to treat flea infestations in cats and dogs.[9]

Table 3: Number of end-use products containing different types of neonicotinoids currently registered in Canada[10]

Type of Neonicotinoid	Total number of products registered in Canada
Acetamiprid	7
Clothianidin	16
Imidacloprid	97
Thiacloprid	2
Thiamethoxam	23
TOTAL[a]	144

a: One product (Sepresto 75 WS) contains both clothianidin and imidacloprid. Though taken into account in the number of products based on each active ingredient, it was tallied only once in the "TOTAL" line.

Table 4 shows the neonicotinoid quantities sold in Canada in 2014. In this class of insecticides, clothianidin — a substance that ranked tenth among the country's top-selling active ingredients for that year[13] — accounted for the lion's share of sales. However, Health Canada's use of broad quantity intervals in reporting pesticide sales seriously undermines the accuracy of these findings. What's more, these data only partially reflect the quantities actually used, since the federal government does not monitor coated seed sales.[14, 15] The situation is the same in Québec, where the neonicotinoids used on seeds treated outside the province are not accounted for in the provincial pesticide sales report.[16] Insecticide-coated seeds are used on 500,000 hectares of cropland in Québec — close to 30% of the province's total field crop area — but only 5% of these seeds are treated in Québec.[16]

Table 4: Quantities of neonicotinoids sold in Canada in 2014[11]

Active ingredient	Quantities sold (kg of active ingredients)
Acetamiprid	< 50,000
Clothianidin	> 100,000
Imidacloprid	> 50,000
Thiacloprid	< 50,000
Thiamethoxam	> 50,000

The Task Force on Systemic Pesticides sounds the alarm

Alarmed by a sharp decline of arthropod populations across Europe, scientists from around the world came together in 2009 to investigate the causes of this worrying phenomenon, with roots that could be traced as far back as the 1950s. The scientists quickly determined that the decline had accelerated significantly between 1990 and 2000, and was accompanied by a marked reduction in the populations of certain bird species that were considered 'common.' The group hypothesized that neonicotinoids and fipronil (a pesticide with similar properties), introduced into the market in the early 1990s, were among the key causes of the catastrophic decline.[24]

These observations led to the official establishment of the Task Force on Systemic Pesticides, which brings together scientists from a range of disciplines (agronomy, biology, chemistry, ecotoxology, entomology, risk evaluation, toxicology and zoology) from 15 nations across four continents.[24] In 2011, the group launched the Worldwide Integrated Assessment on Systemic Pesticides, an imposing synthesis of 1,121 peer-reviewed studies that was published in 2015 as a report[25] and as a series of eight papers in a special issue of the Springer journal, Environmental Science and Pollution Research.[2, 5, 17, 24, 26-29]

In brief, the group's conclusions in regards to neonicotinoids were clear:

The wide-scale use of these persistent, water-soluble chemicals is having widespread, chronic impacts upon global biodiversity and is likely to be having major negative effects on ecosystem services such as pollination that are vital to food security and sustainable development.[24]

The Task Force recently updated its assessment to take into account data from over 500 new peer-reviewed studies.[30] The update, published in 2018 in Environmental Science and Pollution Research, continues to reinforce the group's 2015 conclusions, and builds new arguments about the declining efficacy of neonics and the availability of affordable, effective alternatives.[30]

The Task Force's findings in terms of the impacts of environmental contamination and the value of neonicotinoids as pest control are summarized below.

Neonicotinoids in pollen, nectar and air: Pollinators under threat

Because neonicotinoids spread throughout all tissues of treated plants, they are found in the nectar and pollen of several treated plant species (Table 5). Pollen and nectar become a source of exposure for pollinating insects (bees, bumblebees, leafcutter bees, butterflies, etc.).

Table 5: Presence of neonicotinoids in the nectar and pollen of treated plants

Compartment	Plant	Active ingredient	Av. conc. (ppb)[a]	Max. conc. (ppb)[a]	No. of Ref.
Nectar	Canola	Imidacloprid	ND	0.8	28
		Clothianidin	0.58	2.4	29
	Squash	Imidacloprid	10	14	30
		Thiamethoxam	11	20	30
Pollen	Canola	Imidacloprid	ND	7.6	28
	Squash	Imidacloprid	14	28	30
		Thiamethoxam	12	35	30
	Corn	Imidacloprid	2.1	ND	31
		Clothianidin	3.9	ND	32
		Thiamethoxam	1.7	ND	32
		Clothianidin	1.8	5.7	29
	Sunflower	Imidacloprid	3.0	11	31

a: ND = non determined

The fact that the neonicotinoid concentrations detected (Table 5) are low is no gauge of their impact on pollinating insects. Indeed, though some authors consider it unlikely that these concentrations can cause pollinator death, even following chronic exposure,[31-32] such concentrations can nonetheless alter the development, behaviour, orientation, memory and learning abilities of pollinating insects. For example, studies have revealed negative effects on the development of bee and bumblebee larvae when their food contained doses of imidacloprid (5 to 16 ppb) at the same low level as those found in the nectar and pollen of plants treated with neonicotinoids.[34, 35] Another study reported decreased levels of activity and olfactory capacity in bees that were fed a sugar solution containing 24 ppb of imidacloprid,[36] a concentration that can be found in the environment (Table 5). For a list of studies on the sublethal effects of neonicotinoids in pollinators, consult the literature reviews carried out by Blacquière et al, 2012[33] and Van der Sluijs et al, 2013.[22]

Pollinator health is also impacted by the irreversible affinity between imidacloprid and insect nicotinic acetylcholine receptors.[37] Like other neonicotinoids, imidacloprid mimics the action of acetylcholine when it binds to nAChRs, but unlike the neurotransmitter, imidacloprid is not degraded by acetylcholine, resulting in the irreversible blockage of postsynaptic nAChRs.[37] As a result, the dose of the exposure is less important than the exposure duration, since the toxic effects are cumulative.[38, 39]

Untreated plants, particularly those growing along the edges of fields, are also a source of exposure for pollinators, since they can be contaminated at levels similar to treated plants.[40] For example, it has been well established that planting seeds coated with neonicotinoids using pneumatic seeders contaminates the air by generating dust that disperses with the wind; this dust, which contains neonicotinoids from the seed coatings, falls on and contaminates adjacent vegetation.[40, 41]

As a result of their toxic impacts on pollinators, neonicotinoids are recognized as one of the leading causes for noted declines in bee and other pollinator populations in various regions worldwide.[5, 22, 30, 42-45] In Canada between 2006 and 2014, for instance, annual honey bee colony losses were consistently above the norm of 10% to 15%, reaching a high of 35% in winter 2007/2008[43]. This trend continued between 2015 and 2017.

Ecosystem impacts: Food security for people under threat

Massive declines in pollinating insects is extremely worrying given their vital role in plant reproduction. Given that just over a third of the world's food production by volume[46] and more than two-thirds of food production by diversity depend on pollination, significant declines in pollination services ultimately threaten our food security[24, 27, 47, 48]. When public health researchers conducted a study to determine how humans around the world might be affected by the total loss of animal pollinators, such as bees, they estimated that global fruit supplies would decrease by 23%, vegetables by 16%, and nuts and seeds by 22%. They predicted that these changes in food supplies could increase global deaths from chronic and nutrition-related diseases by 1.42 million people per year[49].

Neonicotinoids in soils: Earthworms and microorganisms under threat

Neonicotinoids have also been detected in soils, where they can persist for years.[17, 50] A study conducted in France on different soils subject to varied climatic conditions and agricultural practices revealed imidacloprid concentrations in 91% of the samples analyzed.[51] While this insecticide had been detected in 100% of treated soils in the year the study was conducted (average concentration of 12 ppb), it had also been detected in 97% of treated soils one year (average concentration of 6 ppb) or two years (average concentration of 8 ppb) prior to the study. Concentrations were higher in the soils treated for two consecutive years, showing the insecticide's potential to accumulate in the ground.[51] Still, neonicotinoid concentrations generally tend to stabilize to roughly 6 to 7 ppb within three to five years of consecutive application. This was demonstrated in an American study (corn treated with clothianidin)[52] and another in Canada (corn treated with clothianidin or thiamethoxam).[53]

The presence of neonicotinoids in soils is not without impact for soil organisms, which in turn can affect soil ecosystem processes and services. Earthworms, in particular, which play a key role in soil maintenance, aeration and biogeochemical dynamics,[54-55] are just as susceptible to neonicotinoids as the insects these products target.[56] Earthworms can come directly into contact with neonicotinoids through applied granules (soil treatment) or coated seeds,[5] be exposed to residues found in the litter of treated plants,[57] or ingest contaminated soil particles during feeding activities.[58] Neonicotinoids are among the pesticides most toxic to certain earthworm species,[49-60] the lowest median lethal concentrations (LC_{50}) reported in the order of tenth or ppm unit.[5] While residual concentrations found in the soil are 100 to 1,000 times lower than such doses[52, 54, 61] and as a result, very unlikely to be lethal, they can still induce sublethal toxic effects in earthworms[5,24], affecting behaviour and reproduction.

Beyond impacts to soil invertebrates, neonicotinoids can also alter the metabolism of microorganisms[27] vital to the health and equilibrium of soil ecosystems, particularly in terms of nutrient (biogeochemical) cycles.[62] One study suggests that acetamiprid can inhibit respiration of soil bacteria at concentrations that are likely to be encountered in the environment.[63] Another study shows that imidacloprid induces changes in the structure, genetic diversity and catabolic activity of soil bacterial communities.[64]

Neonicotinoids in the water: Invertebrates and marine food webs at risk

Contamination of marine ecosystems occurs by leaching and runoff because neonicotinoids are highly water soluble, regardless of the mode of use, as well as by atmospheric drift from foliar applications and the planting of treated seeds.[5] Numerous marine invertebrates — crustaceans, amphipods and insects in particular — are therefore directly exposed to neonicotinoids, potentially for extended periods of time, which affects their abundance, reproduction, development, behaviour and ability to fulfil their trophic or biogeochemical functions.[5, 27] While these effects are based on extensive long-term environmental monitoring of imidacloprid contamination,[65] other studies have shown clothianidin and thiamethoxam are toxic for a wide range of aquatic invertebrates as well.[66, 67]

At the level of the ecosystem, the negative impact of neonicotinoids on invertebrates can alter the base of the aquatic food chain because invertebrates play a critical role in the transfer of energy and nutrients between primary producers and higher trophic levels .[27] Not only does the equilibrium and resilience dynamics of aquatic ecosystems risk being disturbed, but terrestrial ecosystems are also vulnerable, given the fact that numerous aquatic insects live on land during their adult life stage[27] and that many terrestrial organisms (e.g. birds, mammals) feed on aquatic invertebrates. Certain ecosystem services linked to the decomposition of organic matter and nutrient cycling may also be compromised.[27]

As a result of the risks posed by neonicotinoids, some provinces and nations have enacted control measures. This is the case in Ontario, that enacted new regulations in 2015 that target an 80% reduction in the number of acres planted with neonicotinoid-treated corn and soybean seeds by 2017. France, in turn, has banned the use of neonicotinoids as of September 2018.

The value of neonicotinoids seriously in question

The Pest Management Regulatory Agency (PMRA) determines the value of a given pesticide in light of three considerations: its effectiveness, its economic and competitive advantages, and its contribution to sustainable development.[68] Since these insecticides were first introduced in the 1990s, research has seriously undermined the value of neonicotinoids to the point that their utility and necessariness have been brought into question.

Certain insects have developed resistance to neonicotinoids, rendering less effective and even not useful.[30] This is the case for imidacloprid for which the silverleaf whitefly (Besimia tabaci), green peach aphid (Myzus persicae), melon aphid (Aphis gossypii) and brown planthopper (Nilaparvata lugens) are now resistant.[71, 72] According to the Arthropod Pesticide Resistance Database,[73] the first case of resistance worldwide was observed in 1994 in a single species, B. tabaci, and concerned only imidacloprid. However, by 2016 a total of 28 insect species had developed resistance to seven different neonicotinoids on the market. The more insect pests develop resistance to neonicotinoids, the less efficaceous they become and accordingly, the less value they have as insecticides.

Various other studies and literature reviews also cast doubts on the economic benefits of neonicotinoids[30, 74]. In a recent U.S. study on soybean seeds coated with clothianidin, imidacloprid and thiamethoxam, the Environmental Protection Agency (EPA) concluded that the overall benefits of these neonicotinoids to soybean yields were negligible in most situations.[75] A three-year study in Indiana on the use of clothianidin-coated maize seeds came to the same conclusion.[76] In Québec, the *Centre de recherche sur les grains* (CEROM) declared that the systematic use of neonicotinoid-treated seeds was unjustified in the province,[77] since few fields required treatment. For example, in abbreviated wireworm larvae (Hypolithus abbreviatus), research determined that only in 11,6% of fields under study reached the intervention threshold (the point at which pesticides are deemed necessary) [83] Also, the economic gains associated with using neonicotinoid-treated maize seeds were found to be insignificant.[78]

Neonicotinoids' contribution to sustainable development -- the final condition in the value assessment-- is questionable as a result of their negative environmental impact. While the main criticisms to date have centred on the role of neonicotinoids in the decline of insect populations vital to plant pollination, particularly in commercial crops,[5, 22, 30, 44-47] these insecticides also harm the natural predators of insect pests, a consequence with the potential to override the anticipated pest control benefits.[27]

Illegally registered in Canada?

About a decade ago, the PMRA granted conditional registration to two neonicotinoids, clothianidin and thiamethoxam, which served to authorize their sale and use in Canada without having enough scientific data to conclude that their impacts on human health and the environment were not unacceptable. Today, the agency is still waiting to receive the manufacturers' data that would justify full registration of these products in Canada — products that continue to be used in the meantime.

Given these facts, in 2016 Écojustice filed a against the PMRA[84] on behalf of a number of environmental groups for granting conditional registration to these pesticides. The lawsuit aims to prove that these pesticides should never have been registered in Canada without sufficient data on risks, and that the PMRA's decision therefore violates federal legislation.

This "approve now, study later" approach has since been discontinued in Canada, following the Health Minister's announcement[85] that conditional registrations would no longer be permitted. While the PMRA committed to resolve all current conditional registrations by 2017, they have not yet followed through with that commitment.

Ongoing Canadian Regulatory Process: Slow and Fragmented

Canada's Pest Control Products Act (PCPA) mandates that the Minister of Health must ensure that pesticides registered for use in Canada do not pose unacceptable risks to the environment and human health. Table 6 identifies the number of risk assessments that the PMRA has been conducting recently and will be conducting on neonics over the next few years. It is hard to understand how the PMRA can assess the collective impact of neonicotinoids on biodiversity and ecosystem services when each pesticide is assessed individually and all potential risks are parsed out separately across different reviews spanning multiple years. This piecemeal approach also extends the timeline required for risk assessments, while neonicotinoids continue to contaminate the environment.

Table 6 : Neonicotinoids Re-evaluations and Special Reviews Planned in Canada, Over Next 3 Years.

Neonicotinoids Re-evaluations in Canada	Date expected
Clothianidin (proposed decision - pollinators)	December 2017
Imidacloprid (proposed decision – pollinators)	December 2017
Thiamethoxam (proposed decision – pollinators)	December 2017
Clothianidin (proposed decision)	To be determined
Thiamethoxam (proposed decision)	To be determined
Clothianidin (final decision)	To be determined
Thiamethoxam (final decision)	To be determined
Imidacloprid (final decision)	December 2018
Imidacloprid (final decision – pollinators)	December 2018
Clothianidin (final decision – pollinators)	December 2018
Thiamethoxam (final decision – pollinators)	December 2018
Neonicotinoids Special Reviews in Canada	**Date expected**
Clothianidin (aquatic invertebrates - proposed decision)	Spring 2018
Thiamethoxam (aquatic invertebrates – proposed decision)	Spring 2018
Clothianidin (squash bees – proposed decision)	December 2018
Thiamethoxam (squash bees - proposed decision)	December 2018
Imidaclopride (squash bees - proposed decision)	December 2018
Clothianidin (aquatic invertebrates – final decision)	June 2019
Thiamethoxam (aquatic invertebrates – final decision)	June 2019
Clothianidin (squash bees – decision finale)	March 2020
Thiamethoxam (squash bees – decision finale)	March 2020
Imidacloprid (squash bees – decision finale)	March 2020

In 2012, Canada launched a re-evaluation of neonicotinoids[86] and their risks to pollinators as a result of a high number of reports of bee deaths associated with the time of planting of neonicotinoid-treated corn and soy seed. The PMRA increased monitoring in corn- and soybean-growing areas where the incidents were reported, and ultimately found that bees were being exposed to neonicotinoids through dust during the planting of treated seed. The PMRA's assessement decision released in December 2017, however, failed to adequately protect pollinators by offering only very limited risk management strategies. While the PMRA restricted or removed certain uses and applications of neonicotinoids, it failed to ban them outright and failed to ban the use of neonic treated seeds.

In November 2016, as part of its cyclical re-evaluation of health and environmental risks, the PMRA proposed a gradual phasing out of all agricultural, and most other outdoor uses, of imidacloprid over a three- to five-year period. The evaluation identified concentrations of imidacloprid in Canadian aquatic environments at levels harmful to aquatic insects; it also indicated that the continued use of high volumes of imidacloprid in agricultural areas is unsustainable. However, the re-evaluation did not identify human health concerns from any exposure route when used according to current label standards.

The Health Minister will finalize her decision on imidacloprid in December 2018. The proposed schedule would therefore lead to elimination between 2021 and 2023 for a pesticide posing unacceptable risks to the environment.

Équiterre, the David Suzuki Foundation and the Canadian Association of Physicians for the Environment (CAPE) have expressed their concerns regarding the proposed re-evaluation decision on imidacloprid. These concerns target in particular the three- to five-year phase-out period, which will unnecessarily prolong the environmental risks, and the PMRA's dismissal of any risks to human health, since the evaluation fails to take into account studies on human populations and experimental research on human cells. Research on the impact of neonocotinoids on the human health is still advancing but concerns have been raised in recent years as the literature expands. For instance, studies in Japan have concluded that neonicotinoids may harm the developing brains of unborn babies[87], disrupt the endocrine system and impact reproductive systems[88].

The PMRA has also announced that it will conduct special reviews of two other neonicotinoids, clothianidin and thiamethoxam[89], on the one hand regarding their risk to aquatic invertebrates (draft decision in spring 2018 and final decision in June 2019) and on the other, their risks to the squash bee (draft decision in December 2018 and final decision in March 2020). At the same time, the PMRA is currently re-evaluating these two neonicotinoids.

Conclusion

Neonicotinoids were initially hailed as the new, necessary heroes in pest management, and farmers have taken to using these insecticides prophylactically, particularly in the form of coated seeds. Environmental contamination with neonicotinoids continues to increase as a result, and what we know now is that this is causing devastating impacts to invertebrates that play an important role in ecosystems and food webs. Furthermore, the extensive and systematic use of neonicotinoids has led to the decline of pollinating insect populations, which ultimately threatens the foundations of our food security.

Beyond the environmental risks posed by neonicotinoids, more and more research shows that their value is limited. Their effectiveness as a pest control agent is weakening, since a growing number of insect pests are developing resistance, and their contribution to economic benefits is illusory, since they offer only marginal gains in terms of crop yields. Neonicotinoids have been deemed not necessary in most agricultural scenarios under observation, and not worth the consequences of negatively impacting a number of vital ecosystem services, including pollination services and natural predation of pests. According to the Task Force on Systemic Pesticides, neonicotinoids amount to a pest management fail[30], which is a far cry from their early status as "heroes."

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