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Impacts of Neonicotinoids on Non-Target Species and Ecosystems

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Executive Summary

Neonicotinoids are broad-spectrum systemic insecticides readily absorbed by plants either by the roots or leaves and then transported throughout the plant tissues, nectar and pollen, whereby pollinators encounter them when feeding. Neonicotinoids are the fastest growing and most widely used class of insecticides worldwide and are now registered for use on hundreds of different field crops in over 120 different countries. Neonicotinoids are also widely available to the public for home and garden use, where studies show frequent over-application of the products and resulting impacts to invertebrate species.

Although pollinator species face many challenges, there is little doubt that the widespread use of neonicotinoids is a factor in drastic population declines. Documented impacts to bee species include:

- Acute toxicity from direct exposure through dust clouds following seed plantings
- Chronic exposure via foraging leading to sub-lethal effects including impairment of navigation, foraging and reproduction abilities
- Weakening of bee immune systems, reduction of lifespans and compromised larval development

While the body of research is most robust for bee species, other pollinators such as butterflies have suffered more significant population declines in areas of heavier neonicotinoid use. The chemical properties of neonicotinoids allow for easy transport through soil and to our waters. Sampling data shows the presence of neonicotinoids in more than half of streams sampled nationwide where extremely low doses prove lethal to aquatic invertebrate populations, with significant implications for the food chain. The concentration of one type of neonicotinoid in surface waters correlated to declining insectivorous farmland bird populations in the Netherlands.

In addition to bird declines caused by the decrease in insect populations, evidence also suggests direct mortality resulting from consumption of neonicotinoid-treated seeds, as well as impacts to bird reproductive success. In summary, scientific evidence clearly documents a range of impacts from neonicotinoid exposure to non-target invertebrates, aquatic and terrestrial ecosystems, as well as vertebrate species such as birds and likely mammals. Because neonicotinoids have been in use for a comparatively shorter time than other insecticides, research to date may only scratch the surface of potential impacts.

This memo, developed by New Jersey Audubon in 2016 and updated in 2018, provides an overview of recent peer-reviewed scientific studies on neonicotinoids, including documented impacts to pollinators (including native pollinators) and other non-target organisms, as well as aquatic ecosystems. The scope of this brief review, however, is not comprehensive of all available research and does not extend to all possible impacts of the entire class of neonicotinoid chemicals.

Impacts of Neonicotinoids on Non-Target Species and Ecosystems

Introduction

Bee populations have declined sharply within the past decade. This decline has brought attention to neonicotinoids, the newest class of insecticides, which are widely used because they are less toxic than other pesticides to mammals but are very toxic to insects. Aside from being economically and agriculturally indispensable, pollinator health has long been an indicator of the state of our environment. An increasing amount of evidence confirms that neonicotinoids not only affect non-target insect species, but also impact aquatic environments. The chemical properties of neonicotinoids allow for easy transport through our soils and to our waters, posing possible threats to the environment and the public that likely have yet to be fully understood. Such impacts have the potential to alter ecosystems, and it is clear the use of these chemicals requires increased scrutiny to adequately protect our environment and the critical ecosystem services provided by pollinators.

Neonicotinoids are broad-spectrum systemic insecticides that are the fastest growing class of insecticides worldwide and are now registered for use on hundreds of different field crops in over 120 different countries (Morrissey et al., 2015). When used to protect plants from pests, neonicotinoids act by becoming distributed systemically throughout the growing plant following seed or soil applications (Gibbons et al., 2015). They are readily absorbed by plants either by the roots or leaves and then transported throughout the plant tissues, including to the nectar and pollen (Goulson, 2013). The chemicals work by interfering with the normal function of the central nervous system and lead to symptoms of neurotoxicity (Gibbons et al., 2015). Neonicotinoids[1] are applied in agricultural contexts as seed coatings, foliar sprays, or soil treatments, and in urban environments as lawn and garden foliar sprays, granular, or tree injections and companion animal flea treatment (Hladik & Koplin, 2016). Notably, it is not only agricultural use of these products that affects beneficial insects, as a study on flowers treated by amateurs with a neonicotinoid (consistent with label instructions) severely impacted the survival of lacewings (Rogers in Pisa et al., 2015).

[1]There are several different types of neonicotinoids with a variety of names (clothianidin, imidacloprid, etc.). The specific chemicals mentioned herein all refer to a pesticide that is classified as a neonicotinoid.

Bees

The widespread and alarming loss of bee populations resulted in substantial research efforts focused on the potential impact of neonicotinoids. They are generally toxic to insects in minute quantities (Goulson, 2013). The mass dying of bees near cornfields among the dust cloud surrounding the sowing of neonicotinoid-treated seeds, along with the high levels of the chemicals in the dead bees' bodies, provides evidence for acute intoxication caused by direct exposure (Pisa et al., 2015). The bigger threat to pollinators, however, is the chronic exposure from encountering lower concentrations of the chemicals through foraging. There is sufficient evidence on a variety of sub-lethal effects (Goulson, 2013), including behavioral changes. Neonicotinoids impact bee behavior by impairing foraging and navigation ability, leading to disoriented and inefficient worker bees. Using a treat-and-release method in the field, one study found that crucial aspects to navigation, including learned landscape memory, motivation to forage, and ability to communicate in a social context were compromised when bees were chronically exposed to low doses of thiacloprid, a strain declared to be a less toxic neonicotinoid (Tison et al., 2016). In another study, sub-lethal doses of thiamethoxam were linked to a walking deficit in young bees (Charreton et al., 2015), which is significant because walking inside the hive is required for many tasks, such as larval feeding and social interactions. A different study determined an association between bees' exposure to neonicotinoids similar to that which they would encounter in fields and compromised non-flight thermogenesis (NFT) (Potts, Clarke, Oldfield, Wood, Ibarra, & Cresswell, 2018). This is significant as NFT allows for flight and brood incubation, among other fundamental behaviors (Potts et al., 2018).

Neonicotinoids additionally weaken bee immune systems and thus jeopardize colony survival, with thiacloprid and imidacloprid used at concentrations consistent with field exposure identified as affecting three different aspects of honeybee immunity, including a reduction in hemocyte density, wound healing response, and antimicrobial activity (Brandt et al., 2016). Further indicating reductions in immunity, evidence also suggests that clothianidin at even very low doses can promote the replication of the deformed wing virus in bees with covert infections (Di Prisco et al., 2013). In addition to immunity, reproductive capabilities are impacted as well. Neonicotinoid concentrations in crop nectar and pollen are sufficient to substantially impact colony reproduction in bumble bees (Goulson, 2013). It has been revealed that thiamethoxam and clothianidin have limiting effects on male reproduction, causing sperm count in tested drones to decrease by 39 percent (Straub et al., 2016). General longevity of male bees also proved to decrease, with 30 percent of neonicotinoid-exposed drones unable to live long enough to reach sexual maturity and mate with virgin queens. Larval health has also been affected by specific neonicotinoids. Research shows that low, field relevant concentrations of clothianidin and thiacloprid result in a reduced level of Acetylcholine (a critical component of royal jelly or brood food) by 40 percent, compromising larval development (Wessler et al., 2016).

While colony collapse disorder cannot be solely attributed to neonicotinoids considering other contributing factors such as the Varroa mite, current data clearly suggests that even low levels of neonicotinoids directly impact bee populations and cause them to be more susceptible to other threats. Recently, a study based on 18 years of bee abundance data in England found that neonicotinoid exposure is a contributing factor in reduced population persistence of wild bees over time – with bees foraging on oilseed rape, a major crop treated with neonicotinoids around the globe, as much as three times more negatively affected compared to non-crop foraging bees. Researchers from this study go on to suggest that restrictions on neonicotinoids may result in recoveries of at least some wild bee populations (Woodcock et al., 2016). A second recent study demonstrated that exposure to chronic bee paralysis virus (CBPV) and thiamethoxam together have a synergistic effect in bees causing greater mortality in bee populations than would be expected based on CBPV and thiamethoxam's individual mortality rates. The authors note that exposure to thiamethoxam and CBPV in the study emulates bees' exposure to the two threats in natural settings (Coulon et al., 2017). Authors from several studies suggest that neonicotinoids cause a weakening of bee health as a result of the greater energy bees must expend to metabolize neonicotinoids, creating energy deprivation (Bernardes, Barbosa, Martins, & Lima, 2018; Coulon et al., 2017). One study suggests energy deprivation due to extensive metabolization after neonicotinoid exposure to explain the weight loss observed in a colony exposed to imidacloprid (Bernardes et al., 2018). The impacts of neonicotinoid exposure may be even higher than previously assumed given data that suggests that honeybees and bumblebees are not only incapable of tasting three of the most common neonicotinoids at field comparable levels, but also prefer to feed on sucrose containing thiamethoxam and imidacloprid over standard sucrose (Kessler et al., 2015; Coulon et al., 2017).

Other Pollinators

Although studies on the impacts of neonicotinoids to butterflies and moths greatly lack in comparison to other non-target species (Pisa et al., 2014), there appears to be a strong correlation between butterfly trends and neonicotinoid use. UK butterfly species declined by 58 percent between 2000 and 2009, a span of time when neonicotinoid use was increasing at its most dramatic rate (Gilburn et al., 2015). The Gilburn study also cites sources that note the Netherlands, another country that employed heavy use of these chemicals, also observed large butterfly population declines. Interestingly, another study finds that Scotland, a country with lower neonicotinoid use, observes stable butterfly populations (Brereton in Gilburn et al., 2015). Specific effects include adverse impacts to the development of butterfly and moth larva within the soil following neonicotinoid soil drenches or injections (Dilling in Pisa et al., 2014), with these treatments also significantly lowering the overall abundance of insect species and species richness (Pisa et al., 2014).

A study focused on monarch butterflies found that clothianidin exposure at levels observed under field conditions may be responsible for high rates of egg and larvae mortality, possibly contributing to overall population decline (Pecenka and Lundgren, 2015). The authors found field levels of clothianidin in a milkweed plant that were sufficient to reduce larval size within thirty-six hours of evaluation, suggesting that the consequences are underestimated because monarch larvae in close proximity to maize fields are likely exposed to clothianidin throughout their larval lives. Pecenka and Lundgren include other studies that note exposure is especially heightened in the United States considering a 58% reduction in milkweed (Pleasants and Oberhauser, 2012), requiring monarchs to find viable habitats among a virtually weed-free cropland landscape, which are often agricultural field borders (Johnston, 2014; Wright and Wimberly, 2013), increasing exposure to pesticides. There are also documented neonicotinoid impacts to other pollinators and insects (some of which provide important natural pest control services), such as wasps and beetles.

Aquatic Environments & Invertebrates

Neonicotinoids are both highly water soluble and fairly persistent in soils, characteristics that enable mobility and the ability to reach adjacent water bodies (Hladik and Kolpin, 2016; Miles, Hua, Sepulveda, Krupke, and Hoverman, 2017). Soil accumulation has shown to be particularly evident in countries with long histories of using imidacloprid-treated seeds (Jones et al., 2014; Douglas and Tooker, 2015). A study conducted by the United States Geological Survey found at least one out of six neonicotinoids sampled for in 63% of 48 streams across 24 states nationwide from New Jersey to Oregon, both in agricultural and urban areas (Hladik & Kolpin, 2016). Water sampling in Indiana detected at least one neonicotinoid in 90% of water sampled (Miles et al., 2017). Globally, existing monitoring data from 11 countries, including the United States, has revealed a trend of increased neonicotinoid residue in worldwide water bodies over the past 15 years (Sánchez-

Bayo et al., 2016). It is likely that the presence of these chemicals in aquatic environments is underreported. In most countries there is a general lack of surface water monitoring, and until recently, sample analysis was often insufficient to detect the low concentrations that are known to harm aquatic invertebrates (Morrissey et al., 2015).

While wetlands and rivers that drain or receive runoff from agricultural areas appear most susceptible, neonicotinoids have also been frequently detected in similar concentrations in water draining urban environments (Morrissey et al., 2015). A review of global surface water analysis from 29 studies in 9 countries found that 74% of studies reported average neonicotinoid residues that exceeded the concentrations known to affect sensitive aquatic invertebrates (Morrissey et al., 2015). In another review, analysis of data from Maryland streams (Johnson and Pettis, 2014) in context with a model denoting various levels of sensitivity of aquatic species to imidacloprid, revealed that up to 40% of aquatic species in those streams are facing serious impacts from imidacloprid residue (Sánchez Bayo et al., 2016). While monitoring for neonicotinoids is virtually nonexistent in marine and coastal habitats, laboratory research has demonstrated that imidacloprid has an impact on oyster immunity (Roderick in Pisa, 2015).

Because of the documented presence of these insecticides in surface waters, groundwater, and wetlands, recent studies have investigated the potential impact to both invertebrate and vertebrate aquatic species. Worldwide, it is likely that neonicotinoids in surface waters are well within the range to cause both short and long-term impacts on aquatic invertebrate species over broad spatial scales (Morrissey et al., 2015). The extreme sensitivity of invertebrates, including non-target aquatic species, to neonicotinoid compounds is well documented in the scientific literature. Extremely low concentrations appear to cause measurable toxicity to a wide range of arthropods, especially insects and some crustaceans, and exert significant lethal effects on many aquatic invertebrate populations (Morrissey et al., 2015; Miles et al., 2017). While acute mortality often does not occur upon immediate exposure to lower concentrations, effects from neonicotinoids intensify for many aquatic species with exposure time – in some reported instances leading to a large number of deaths after a week, and complete die offs after a few weeks (Sánchez-Bayo and Goka 2006; Hayasaka et al., 2012).

Additionally, documented sub-lethal effects from exposure have long-term implications to organisms as well. Sub-lethal effects noted include feeding inhibition (Morrisey et al., 2015; Alexander et al., 2007; Kreutzweiser et al., 2007; Nyman et al., 2013), impaired movement (Motobayashi et al., 2012), reduced reproduction ability

(Böttger et al., 2013), reduced mayfly body size (Alexander et al., 2008), reduced body size for fish (Hayasaka et al., 2012), immune suppression in fish (Sánchez-Bayo and Goka, 2005), foraging changes in water bugs and crayfish (Miles et al., 2017), and measurable weight losses in earthworms (Morrissey et al., 2015). The range of impacts of chronic or repeated exposure to aquatic communities is not easily captured in laboratory settings with short-term pulse exposures because natural conditions and stressors can enhance toxicity (Morrissey et al., 2015), indicating many impacts may be under-detected. In a large scale, eight-year field study, neonicotinoid pollution occurring in surface water was shown to have a strong negative effect on aquatic invertebrate life (reduction in macro-invertebrate abundance), with significant implications for the food chain and ecosystem functions (Dijk et al., 2013). As opposed to other pesticides, which cause initial deaths for both target and non-target organisms, but often allow for recovery within weeks (van den Brink et al., 1996; Brock et al., 2010), neonicotinoids yield slow recovery after die-offs, or potentially eliminate aquatic populations permanently if there is competition between species (Liess et al., 2013).

Ecosystems & Vertebrates

Large-scale losses of both terrestrial and aquatic invertebrate species affect other species, as well as entire ecosystems. There appear to be vast differences in sensitivity levels to neonicotinoids among organisms, with species that are critical to supporting aquatic and terrestrial food webs—such as mayflies, caddisflies and midges—proving highly sensitive (Morrissey et al., 2015). The concentration of imidacloprid in surface waters correlates to declining farmland bird populations in the Netherlands (Hallmann et al., 2014). This study evaluated the possibility that other factors could have influenced the population declines of these bird species that are almost exclusively insectivorous in the breeding season, but ultimately determined that neonicotinoids were responsible for the noted decline and that such cascading effects deserve more examination.

In addition to bird declines caused by the decrease in insect populations, evidence also suggests the potential of neonicotinoids to cause direct mortality. The use of treated seeds constitutes an important route of exposure of wild farmland birds to pesticides, with the risk that these birds will suffer toxic effects from ingestion of treated seeds (Lopez-Antia, 2016). Consuming one single corn seed treated with imidacloprid may prove lethal to an average size bird (such as a blue jay) likely to pick up and consume such seeds during or following planting (Mineau & Palmer, 2013). Birds that survive seed ingestion may suffer sub-lethal effects. Wild songbirds consuming a small volume of neonicotinoid-coated seeds suffered impaired condition (significant declines in fat stores and failure to orient correctly on their migratory path), with implications for increased mortality or lost breeding opportunities (Eng et.al., 2017) because of these effects.

Concern that neonicotinoids may impact the reproduction of birds, including causing low reproductive rates in an endangered ibis that nests in agricultural areas in Japan, led to a study that investigated the impact of clothianidin on the reproductive success of captive quails. Embryos resulting from male quails exposed to clothianidin showed a reduction in size compared to the control group, as well as a reduced tendency to achieve full development, and it was concluded this affected reproductive function, possibly severely (Tokumoto et al., 2013). Studies also noted reproductive impairment in sensitive bird species that consume even a few treated seeds (Gibbons et al., 2015; Pandey and Mohanty, 2017).

Neonicotinoids were originally thought to have little if any impact on mammals. The authors of the quail study also note several research studies that have reported impacts of neonicotinoid breakdown products to the reproductive systems of male mice and rats, as well as the potential for harm in humans.

Conclusion

Scientific evidence clearly documents a range of impacts from neonicotinoid exposure to non-target invertebrates, aquatic and terrestrial ecosystems, as well as vertebrate species such as birds and likely mammals. Neonicotinoids have been in use for a comparatively shorter time than other insecticides (Pisa et al., 2015) and research to date may only scratch the surface of potential impacts. Several authors of the studies included herein have called for greater regulatory precaution and/or legislation to limit the use of this class of pesticide in light of their findings. The existing body of evidence is robust enough that some countries and states have taken or considered meaningful steps to limit the threats posed by this class of chemicals.

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