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Pesticides and Soil Invertebrates: A Hazard Assessment

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Citations
For full citations found in the text below, please see the study.

Questions and Answers

Q Can you briefly summarize your key findings?

A In an analysis of 394 studies in the published literature, we found that pesticides negatively impacted soil invertebrates such as springtails, beetles, earthworms, ants and ground nesting bees in 70.5% of cases. We found that in 1.4% and 28.1% of cases, pesticide exposure resulted in a positive or no significant effect, respectively.

Q What is new about this study? Have there been previous studies like this one?

A This paper is the largest, most comprehensive review of the impacts of agricultural pesticides on soil invertebrates ever conducted. While previous review papers have typically analyzed a particular pesticide class or type of organism, this is the first review to incorporate all pesticide types, all soil invertebrates that live or develop in the soil and all measured health outcomes available in the literature. A related review conducted in 2012 focused solely on microorganisms (like bacteria and fungi) and identified similar hazards (Puglisi, 2012).

Q Why does this matter?

A From these data it is apparent that, as a set of chemical poisons, pesticides pose a clear hazard to soil invertebrates. Negative effects are evident in both lab and field studies, across all studied pesticide classes, and in a wide variety of soil organisms and health outcomes. This indicates that all pesticides can counteract the benefits of healthy soil and that pesticide use is not compatible with a healthy soil ecosystem. The prevalence of negative effects in our results underscores the need for soil organisms to be represented in any risk analysis of a pesticide that has the potential to contaminate soil, and for any significant risk to be mitigated in a way that will specifically reduce harm to soil organisms and to the many important ecosystem services they provide, like cycling nutrients that plants need to grow, decomposing dead plants and animals so that they can nourish new life, regulating pests and diseases, and sequestering carbon in the soil.

Q What types of harm did you find soil invertebrates experience in relation to pesticide exposure?

A Impacts included mortality; decrease in abundance, richness and diversity of soil organisms; changes in behavior; molecular and cellular changes; impairment of reproduction and growth; and structural changes to the organism. While mortality is largely studied, it is generally the least sensitive indicator of harm. Studies looking at sublethal effects like impaired growth and reproduction often find harm at much lower doses.

Q What do you mean by "positive" effect?

A We found that in 1.4% of cases, pesticide exposure resulted in a "positive" effect. A positive effect indicates a benefit to one soil organism that may come at a detriment to other soil taxa or soil ecosystem functioning. For example, abundance of certain soil taxa could increase if a pesticide reduces competitors or predators, either through mortality or emigration from the area. Therefore, while certain effects were designated as "positive" to one species or taxa in this analysis, it does not indicate, nor is it likely, that pesticides had a positive effect on the ecosystem as a whole.

Q What trends did you identify in relation to different pesticide classes?

A Organophosphates and neonicotinoids were the most studied classes of insecticides; of herbicides, phosphonoglycines (glyphosate) and triazines; and of fungicides, inorganic compounds such as copper and zinc, as well as conazoles. Among these, organophosphate, neonicotinoid, pyrethroid and carbamate insecticides, amide/anilide herbicides, and benzimidazole and inorganic fungicides negatively affected soil taxa more than 70% of the time.

Q Do your findings contribute insight to the growing body of science on the "insect apocalypse"?

A Our findings provide further evidence that pesticides are contributing to widespread declines of insects via increased mortality and decreased fitness. In North America, terrestrial insects and mites and insects that depend on soil for portions of their life cycle, like ground beetles and ground nesting bees, have declined greatly in recent decades (Sullivan and Ozman-Sullivan; Forister et al., 2019; Sánchez-Bayo and Wyckhuys, 2019; van Klink et al., 2020). Habitat loss due to agricultural intensification and pollution, primarily from synthetic agricultural pesticides and fertilizers, are thought to be the major driving factors in recent insect declines (Hallmann et al., 2017; Forister et al., 2019; Seibold et al., 2019; Sánchez-Bayo and Wyckhuys, 2019; Miličić et al., 2020). Further, in a 2019 survey of member countries of the Food and Agriculture Organization of the United Nations (FAO), overuse of chemical control mechanisms (e.g. pesticides, antibiotics, etc.) was identified as the most impactful practice that has been driving the loss of soil biodiversity in the last 10 years (FAO, 2020). Our results corroborate these findings.

This has important implications for human well-being. The loss of soil biodiversity from increases in land conversion and agricultural intensification contribute to approximately a 60% reduction of soil ecosystem services that we depend on, like soil creation, pollination, pest control and carbon transformation (Díaz et al., 2006; Veresoglou et al., 2015; Singh et al., 2019).

Q Do your findings contribute insight into the potential for soils to serve as a carbon sink?

A Our findings support the conclusion that reducing the use of agricultural pesticides is a critical intervention for maximizing the capacity of soils to serve as a carbon sink. Soil invertebrates are key contributors to soil carbon sequestration. They form up to half of all soil aggregates by breaking down litter and releasing organically rich casts and feces (Stork and Eggleton, 1992). The formation of these large soil aggregates allows for greater soil carbon sequestration, thus these ecosystem engineers play a role in offsetting fossil fuel emissions and combating climate change.

Q **Can the soil community recover from pesticide exposure?**

A It has been suggested that recovery of the soil invertebrate community is slow and can take more than 15 years (Menta, 2012). Therefore, while recovery from some sublethal negative effects is possible, it necessarily depends on quick elimination of the soil pesticide followed by a sufficient period for recovery to take place before another application is made. Yet, soil organisms are exposed to a cocktail of toxic chemicals. Research shows that mixtures of pesticide residues in the soil are the rule rather than the exception because farmers typically use multiple pesticides at a time and over the course of a season. As an example, the United States Department of Agriculture estimates that Washington apples are treated with an average of 51 different pesticides in a total of 6 to 17 applications per year (USDA, 2016), while East coast apples are treated 15 to 25 times with pesticides throughout a given year (USDA, 2016). With some pesticides persisting in soil for months or years, and the real prospect of recurrent applications during the growing season in many fields, soil organisms often do not have the opportunity to recover.

Q **Is pesticide use getting safer or more harmful for soil organisms?**

A Agricultural soils are increasingly being exposed to pesticides at higher levels due to trends in pesticide application methods. Use of pesticides as seed treatments has increased considerably (Hitaj et al., 2020). Neonicotinoid seed treatments are estimated to be used in over half of soybean acres and nearly all non-organic corn grown in the U.S. (Douglas and Tooker, 2015; Mourtzinis et al., 2019). Because 80% or more of the active ingredients from neonicotinoid seed treatments remain in the soil (Sur and Stork, 2003; Alford and Krupke, 2017) soil organisms may be exposed to high doses of these insecticides. Large-scale use of seed-applied fungicides presents another risk, as almost all U.S. corn is also treated with seed-applied fungicides (Lamichhane et al., 2019). In addition to the pesticides that are currently on the market, several new seed- and soil-applied pesticide active ingredients are currently going through the registration process in the USA, such as the pyrazolecarboxamide fungicide inpyrfluxam (U.S. EPA, 2020a), the diamide insecticide tetraniliprole (U.S. EPA, 2020d), and the novel insecticide broflanilide (U.S. EPA, 2020c).

Recent work has shown that while overall pesticide application amounts have decreased, the toxicity to invertebrates has doubled since 2005, largely due to increased use of neonicotinoids and other highly insect-toxic pesticides. We found that neonicotinoids greatly negatively affect soil organisms like springtails, beetles, earthworms, ants and solitary ground-nesting bees.

Q **What are the implications for regulation?**

A The prevalence of negative effects in our results underscores the need for soil organisms to be represented in any risk analysis of a pesticide that has the potential to contaminate soil, and for any significant risk to be mitigated in a way that will specifically reduce harm to soil organisms and to the many important ecosystem services they provide. The United States Environmental Protection Agency (EPA) does not have sufficient testing requirements in place to quantify risk to soil dwelling organisms. The European honey bee (*Apis mellifera*) is the only terrestrial invertebrate for which the U.S. EPA requires testing for pesticide toxicity, and only on an acute-contact exposure basis (40 C.F.R. §158.630; 2020). The practice of using the honey bee as a surrogate underestimates harm to many taxa and results in mitigation strategies that do not address impacts on soil organisms. For example, spray restrictions during flower bloom, increasing droplet size to reduce drift, or label language identifying a pollinator hazard, will likely have little impact on soil organism exposure to a pesticide.

The European honey bee is a highly specialized species whose sensitivity to chemical stressors is not typically representative of other terrestrial invertebrates. Nor is the life cycle of the honey bee representative of organisms that develop or spend most or all of their life in the soil. *A. mellifera* is not even a good surrogate for other bees. Over 80% of bees, the vast majority of which are solitary, are ground nesting (Anderson and Harmon-Threatt, 2019) and are at greater risk of pesticide exposure, as adult females spend the majority of their life cycle constructing nests in the soil (Willis Chan et al., 2019b).

The European Food Safety Authority (EFSA) currently requires chronic toxicity tests on one earthworm species (*Eisenia fetida or Eisenia andrei*), one springtail species (*Folsomia candida*) and one mite species (*Hypoaspis aculeifer*) (Ockleford et al., 2017). The EFSA also requires a study on nitrogen transformation as a readout of soil microbial activity (Ockleford et al., 2017). If the ratio of exposure to toxicity exceeds a predetermined threshold, higher tier tests, such as field testing, may be required. Additional protection goals have recently been identified, and the EFSA is currently considering strengthening its requirements to include additional exposure pathways and to require tests on Isopods and mycorrhizal fungi (Ockleford et al., 2017).

We strongly support the inclusion of soil invertebrates in the U.S. pesticide regulation process along the model of the European Food Safety Authority.

Q Did you identify gaps in the research?

A We identified several broad trends and directions for future research. For example, insecticides were the most studied type of pesticide and generally had greater negative impacts on soil invertebrates than herbicides, fungicides and other pesticide types. Fewer studies evaluated the impacts of pesticide mixtures — given that pesticide mixtures are more commonly found in agricultural soils than individual active ingredients, this is a gap in the literature that needs to be addressed. Another gap is a lack of research on the inert ingredients of pesticides products. One recent study showed that surfactants added to the herbicide Roundup were the cause of bumble bee mortality. There is a need to look at the impacts of product formulations available for sale, not just active ingredients.

Studies evaluating pesticide impacts often use a narrow range of surrogate species that are easy to rear, identify, or study, while smaller and more cryptic organisms are rarely analyzed. In some cases, the organisms that are the most extensively studied are known to be less sensitive to pesticides than other organisms, suggesting that we have limited insight into the extent of harm caused by these pesticides. Thus, we need a wider range of species tested.

Q How did you conduct the analysis?

A This is a review paper that looked at 394 studies that fit our criteria on the effects of pesticides on non-target invertebrates that have egg, larval, or immature development in the soil. This review encompasses 275 unique species, taxa or combined taxa of soil organisms and 284 different pesticide active ingredients or unique mixtures of active ingredients. We identified and extracted relevant data in relation to the following health outcomes: mortality, abundance, biomass, behavior, reproduction, biochemical biomarkers, growth, richness and diversity, and structural changes. This resulted in an analysis of over 2,800 separate "cases," measured as a change in a specific health outcome following exposure of a specific organism to a specific pesticide. All cases measured a specific health outcome following exposure of a specific organism to a specific pesticide. For instance, if a study tested how three different pesticides (chlorpyrifos, imidacloprid and permethrin) affected two health outcomes (mortality and DNA damage) on one species (*Caenorhabditis elegans*), then we would be able to extract six unique cases, any of which could result in a negative effect, positive effect or no significant effect to the tested species. We found that 70.5% of cases showed negative effects, whereas 1.4% and 28.1% of cases showed positive or no significant effects from pesticide exposure, respectively.

Q Are there limitations to your study?

A There are many invertebrates that come into contact with the soil during their life cycle, such as mud dauber (potter) wasps that use wet soil to make nests and butterflies that take minerals from the soil in a behavior known as "puddling," we did not include those organisms in the study because they did not fit the criteria of development *in* the soil, but they are most certainly being exposed to pesticides in the soil. Thus, it is likely that the impact of pesticides in the soil on invertebrates is more widespread than we were able to capture or than is even known in the literature at this time.

Q How was the study funded?

A The project is possible thanks to the generous members of the Center for Biological Diversity and Friends of the Earth U.S. (FOE). FOE's organizational policy on funding can be found here.