Honey bee toxicity of pesticides used in United States corn and soybean production, 1998 – 2020

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# Introduction

As part of an integrated pest management program, pesticides (especially herbicides, insecticides, and fungicides) remain a crucial component of crop protection. Pesticides provide farmers with an efficient tool for controlling pests and, when used appropriately, prevent yield loss that could threaten food security (Kudsk et al. 2018) and cause devastating economic losses (Popp et al. 2013; Tudi et al. 2021). Approximately one-third of global agricultural products are produced with some dependence on pesticides (Tudi et al. 2021). In the United States, well over 95% of corn and soybean hectares are sprayed with pesticides each year (Fernandez-Cornejo et al. 2014).

However, pesticide usage in agriculture can have detrimental side effects on non-target organisms, both through misuse of pesticide products and through off-target movement of applied pesticides. Over time, as awareness of the potential for pesticide negative effects has increased, public scrutiny of pesticides has also increased. Regulatory agencies and agricultural stakeholders have continuously sought to better balance the risks and benefits of pesticide usage. Most recently, U.S. pesticide regulatory bodies have sought to increase compliance with the Endangered Species Act.

Between 1960 and 1980, the volume of pesticides applied to corn and soybean increased 9- and 50-fold in the United States, and by 1985, the percentage of planted area exceeded 95% in both crops (Fernandez-Cornejo et al. 2014; Osteen and Fernandez-Cornejo 2013). Some of this increase can be attributed to a concurrent increase in crop area, but even when adjusted for area, a steady increase in pesticide intensity has been observed (Kniss 2018).

As a reflection of increased U.S. Environmental Protection Agency (US EPA) regulation, the types of synthetic insecticides applied in agriculture has changed from mainly organophosphorus and N-methyl carbamate insecticides to mainly neonicotinoids and pyrethroids (DiBartolomeis et al. 2019). Changes in herbicide usage has been driven by the widespread adoption of herbicide-resistant crops (Benbrook 2016; Kim and Kim 2022; Kniss 2018). Similarly, fungicide usage has been predicted to rise in response to climate change, increased evolution of fungicide resistance, and spread of invasive fungal species (Boxall et al. 2009; Fisher et al. 2012).

Evaluating the risk of pesticides is a necessary and complex task that requires detailed information on active ingredients, application rates, exposure routes, toxiity and other effects on non-target organisms, and environmental fate (DiBartolomeis et al. 2019; Greitens and Day 2007). Scientists and agencies have developed numerous methods to evaluate the environmental risks associated with pesticide usage, including pesticide risk indicators incorporating varied information, such as physico-chemical properties of active ingredients, usage parameters including application rates and timings, environmental persistence and fate, and acute and chronic toxicity to different organisms (Greitens and Day 2007; Kniss 2017). Nonetheless, the assessment of pesticide risks is frequently based on incomplete knowledge, making the determination of the overall risk of pesticide use difficult and, often times, uncertain (Dushoff et al. 1994; Greitens and Day 2007; Peterson and Schleier 2014).

Generally, the first step in developing methods to evaluate the ecological risk of pesticides is to build a reliable database based on existing empirical toxicity data derived from literature review procedures. The ECOTOXicology Knowledgebase (ECOTOX Ver 5, www.epa.gov/ecotox) currently represents the world’s largest compilation of curated ecotoxicity data, providing data for assessments of safety and ecological research for over 12,000 chemicals and species with over one million test results from over 50,000 references (Olker et al. 2022). Managed by US EPA, it provides transparent and comprehensive information about toxicity measures and endpoints such as , , and other sublethal effects on both aquatic and terrestrial organisms.

Among terrestrial organisms, insect pollinators are widely used as primary surrogate species for environmental risk assessment, and regulatory agencies such as US EPA and the European Food Safety Agency (EFSA) require the submission of insect pollinator toxicity data when registering pesticides, in part, because of these species critical role in providing ecosystem services (Farruggia et al. 2022; Reilly et al. 2020). Pollinators, including honey bees (*Apis mellifera*), are at risk for several reasons including pesticide usage (Goulson et al. 2015). Honey bees also represent a useful surrogate species for ecotxicology studies because of the availability of standardized rearing and testing protocols for lab and field experiments (Farruggia et al. 2022), their ability to interact with pesticides through different exposure pathways (Johnson 2015), and their sensitivity to pesticides relative to other bee species (Arena and Sgolastra 2014). Honey bees represent the most well-studied indicator of insect health in US agricultural lands and have the most comprehensive ecotoxicology data set available. As such, honey bees are useful for assessing how non-target pesticide risks have changed over time (DiBartolomeis et al. 2019).

The objective of this study is to combine honey bee toxicological endpoints with pesticide usage data and corn and soybean yields to quantify (1) how the average overall toxicity of agricultural pesticides used in the United States has changed over time in the two largest crops by area; and (2) determine how specific pesticides and pest targets contribute to the overall non-target pesticide hazard to insects. This information will benefit the general public by informing the debate on whether domestic agricultural systems have become more or less ecologically efficient and sustainable over time, and will allow us to more holistically prioritize future pest management efforts.

# Methods

## Data sources

### Pesticide usage and crop data

Proprietary pesticide usage data were obtained in May of 2023 from the AgroTrak product maintained by [Kynetec](https://www.kynetec.com/). **[Insert proprietary data note here.]** Data included pesticide volume applied, treated acreage, timing of pesticide applications, and target pests for corn and soybean from 1998 through 2020. Application timings from the original data were condensed into either before crop emergence (PRE) or after crop emergence (POST). National estimates of crop yield and area planted to corn and soybean for each year was obtained from the USDA National Agricultural Statistics Service [(USDA-NASS)](https://quickstats.nass.usda.gov/).

### Honey bee toxicity data

Updated adult acute contact values for honey bee (*Apis mellifera*) were obtained for as many pesticide active ingredients in the AgroTrak data as possible. Our analysis is limited to the adult acute contact toxicity due to incompleteness of most other toxicity endpoints (such as oral acute or chronic endpoints). Acute contact values were obtained from the following sources: (1) the U.S. EPA [ECOTOX](https://cfpub.epa.gov/ecotox/) database; (2) Supporting Table S1 from Farruggia et al. (2022); and (3) manually searching pesticide ecological risk assessments supporting registration and re-evaluation posted to the public docket at Regulations.gov; and (4) communications with EPA personnel from the Office of Pesticide Programs’ Environmental Fate and Effects Division.

The ECOTOX database was the preferred source for all pesticide toxicity data. For each active ingredient (ai) in the AgroTrak data, adult acute contact were downloaded from ECOTOX. For many active ingredients, ECOTOX reports multiple toxicity endpoints. Some are exact estimates (e.g.  = 13 ug/bee). Some estimates are listed as inequalities, where the original study was unable to quantify an exact endpoint (e.g.  > 100 ug/bee). For active ingredients with multiple adult acute contact toxicity values reported, we used the following selection criteria to select a single toxicity value for each ai:

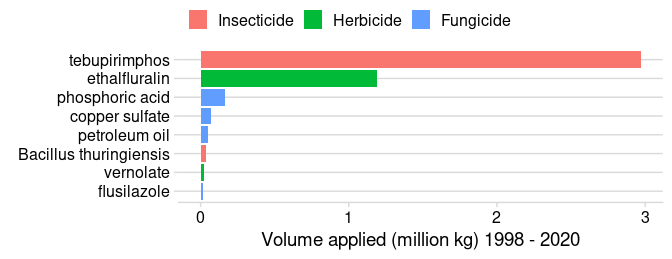
1. if there was only one *exact* estimate and one or more inequality estimates the exact estimate was selected.
2. if there were multiple exact estimates, the lowest (most toxic) value was selected.
3. if there were no exact estimates, the lowest (most toxic) inequality was selected.

For some active ingredients, the database included toxicity estimates from both technical active ingredient studies and from formulated product studies; we did not use this potentially important difference as a selection criteria to ensure our analysis included the most conservative (*e.g.* most toxic) endpoint.

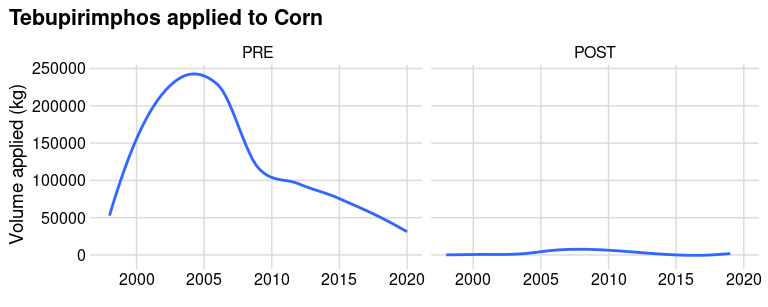
After this selection criteria was applied to the ECOTOX data, these toxicity values were compared with those published by Farruggia et al. (2022). In nearly all cases, the ECOTOX values were the same as those published by Farruggia et al. For 6 pesticides, the values reported by Farruggia et al. were lower (*i.e.* more toxic) than those selected from ECOTOX; for five of those six pesticides, the Farruggia et al. values were used to ensure we used the most conservative toxicity estimates available. One estimate from Farrugia et al (2022) was determined to be an error; dicamba adult acute contact toxicity was listed correctly in ECOTOX and so that value was used. Finally, for any active ingredient in the Kynetec data that did not have toxicity values in ECOTOX or Farruggia et al. (2022), pesticide registration and re-evaluation documents (i.e., the most recent ecological risk assessments, conducted approximately every 15 years for registered pesticides) were searched manually to obtain honey bee adult acute contact toxicity values.

In total, there were 205 pesticide active ingredients mentioned by survey respondents as being applied to either corn or soybean during the period 1998 to 2020. Of those, 57 active ingredients were mentioned by 2 or fewer survey respondents in any given year and had fewer than 10 mentions in the entire 22 year period. It is possible that these may represent mis-reporting; to determine whether these outliers may have an outsized impact on the results, the analysis was conducted with and without these pesticides with low sample sizes. Removal had no practical impact on data interpretation, so the pesticides with low sample sizes were retained in the final analysis. The AgroTrak data, like many other public and proprietary data sources, does not include seed treatments.

We were unable to find reliable honey bee adult acute contact toxicity estimates for 21 pesticides. Of the pesticides without toxicity values, 8 had a total applied volume of greater than 15,000 kg during the period 1998 to 2020 (Supplementary Figure 1). Only 2 pesticides (tebupirimphos and ethalfluralin) were applied at over 1 million kg during the study period but did not have reliable acute contact values. As an organophosphate insecticide, tebupirimphos would be expected to be highly toxic to bees; however, its only registered use is for soil-incorporated application at planting with granular products (Supplemental Figure 2). This usage pattern of tebupirimphos will reduce the potential to negatively impact honey bees compared to products applied after crop emergence.



Supplementary Figure 1: Active ingredients applied at over 15,000 kg between 1998 through 2020 without reliable honey bee adult acute contact .



Supplementary Figure 2: Tebupirimphos usage in corn, 1998 to 2020.

## Honey bee Toxicity Index

Pesticide usage data were separated into pesticides applied before crop emergence (PRE) and pesticides applied after crop emergence (POST). For each active ingredient applied to each crop in each year, an an area-adjusted toxicity index () was calculated by dividing the total pesticide volume applied in kg () by the total planted area () for each crop to account for year-to-year changes in hectares planted to corn and soybeans. That value was then divided by the adult acute contact to derive the . can be interpreted as the number of honey bee acute values (in billions) applied per hectare of crop grown.

## Target Pest Toxicity Index

For each pesticide application, AgroTrak data records which pest species were listed by survey respondents as the target for the pesticide application. A target pest toxicity index () was calculated using this information. For each active ingredient, the volume applied targeting a particular pest () was divided by the total volume of the active ingredient applied (. This proportion was then multiplied by that active ingredient’s proportion of the total toxicity index (). The can be interpreted as the relative impact that different pest species have on the overall pesticide hazard to honey bees; a pest species with a greater value is likely more responsible for pesticide applications with greater potential impact to honey bees than a pest species with a lower .

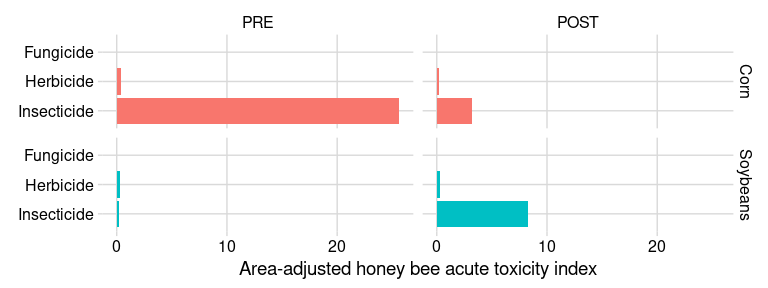
## Eco-Efficiency

Eco-efficiency () was calculated for each year and application timing by dividing crop yield (ton/ha) by . can be interpreted as the tonnes of crop yield produced per honey bee applied. Higher values of suggest greater eco-efficiency.

# Results

The summed honey bee over all years from 1998 through 2020 was 3.3-times greater in corn compared to soybean (Figure 1). Relative risk to honey bees and many other pollinator species is expected to be lower if pesticides are applied before crop emergence, as there are fewer pollinators expected to visit the field before the crop is established; just 12% of the summed applied to corn was applied after crop emergence when negative impacts are more likely, whereas 94% of the summed applied to soybean was applied after crop emergence.

For both crops, a vast majority of was driven by insecticide usage, as expected, because insecticides are inherently more toxic to insects compared to most herbicides and fungicides. In corn, insecticides were responsible for nearly 98% of . In soybean, insecticides were responsible for 93% of the summed . In terms of total volume applied, herbicides are more heavily used in both corn and soybean; however, because accounts both for applied volume and inherent acute toxicity, the relative toxicity of insecticides to honey bees outweighs herbicide usage in this metric. Because insecticides are the primary driver of overall risk to honey bees (and likely other pollinators), we will not discuss other pesticide types (herbicides and fungicides) further.



**Figure 1. Summed honey bee toxicity index applied to corn or soybean during the period 1998 through 2020 by pesticide type and application timing.**

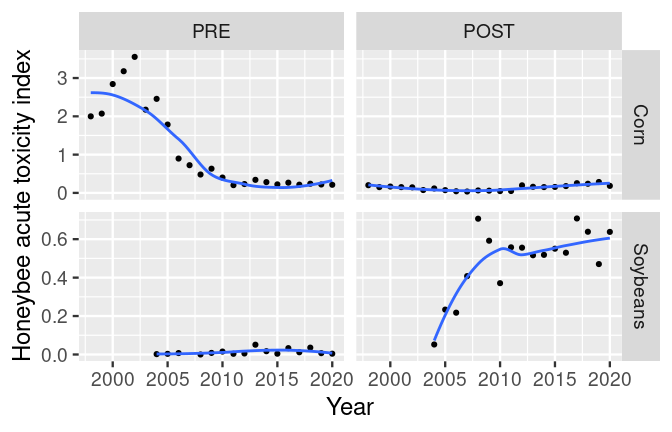
Over time, the insecticide in corn has shifted from primarily PRE applications to a mix of PRE and POST applications (Table 2). During the period 2000 to 2005, 96% of the honey bee from insecticides was applied in corn before crop emergence, whereas more recently, from 2015 to 2020, approximately 51% of honey bee was applied before crop emergence. In corn, the toxicity index applied POST has increased approximately 1.8-fold, from 0.12 to 0.22.

In soybeans, insecticides were not surveyed before 2004, suggesting very limited usage in that crop (Figure 2). During the period 2005 to 2010, 99% of the insecticide was applied after crop emergence, although the total was still relatively low (Table 2). More recently, between 2015 to 2020, 97% of soybean insecticide was applied POST, and exceeded the associated with corn insecticide usage.

**Table 2. Area-adjusted acute toxicity index values for insecticides applied before (PRE) and after (POST) crop emergence for early survey periods vs the most recent 6-year survey period.**

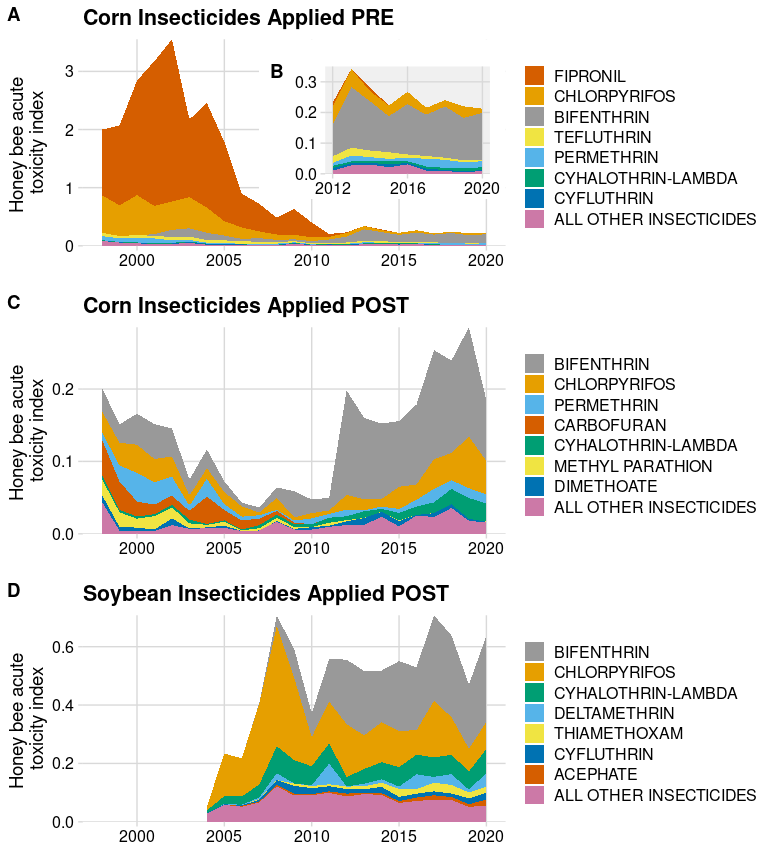
| Crop | Timing | Type | Early | Recent |
| --- | --- | --- | --- | --- |
| Corn | PRE | Insecticide | 2.7000 | 0.230 |
| Corn | POST | Insecticide | 0.1200 | 0.220 |
| Soybeans | PRE | Insecticide | 0.0058 | 0.016 |
| Soybeans | POST | Insecticide | 0.4200 | 0.590 |

† The ‘Early’ period is 2000 to 2005 for corn pesticides, and 2005 to 2010 for soybeans. The ‘Recent’ period is 2015 to 2020 for both crops.



**Figure 2. Honey bee adult acute contact toxicity index for insecticides applied to corn or soybean before (PRE) or after (POST) crop emergence. Insecticide surveys for soybean began in 2004.**

Two pesticides, fipronil and chlorpyrifos, were responsible for a majority of the applied PRE to corn until approximately 2010, when all uses of fipronil on corn were cancelled in the United States (Figure 3A). After 2010, bifenthrin became the largest contributor to in both PRE (Figure 3B) and POST (FIgure 3C) application timings in corn. Insecticide application was relatively rare in soybean before 2004. Three insecticides, bifenthrin, chlorpyrifos, and cyhalothrin-lambda, accounted for a majority of the applied POST to soybean since 2005 (Figure 3D).

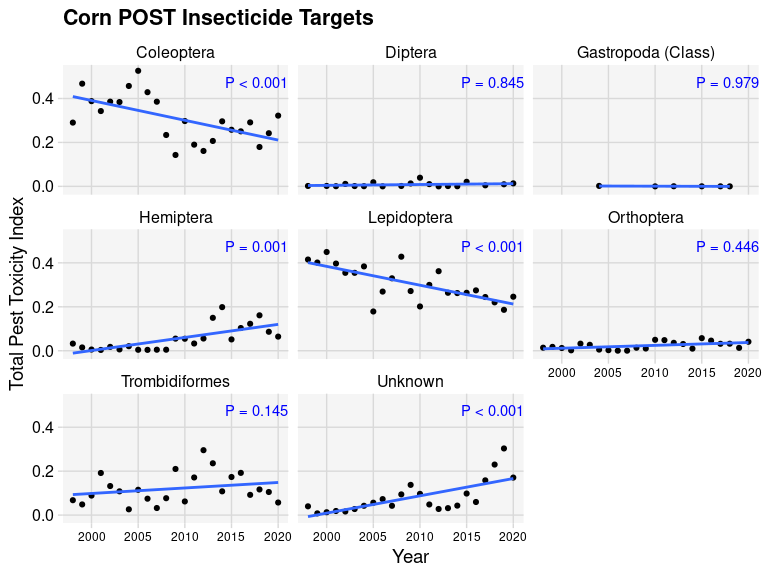


**Figure 3. Contribution of insecticide active ingredients to honey bee adult acute contact toxicity index applied PRE to corn (A, B), POST to corn (C), or POST to soybean (D). Panel B shows the period from 2012 to 2020 for corn PRE on a zoomed-in y-axis scale. The ‘All Other Insecticides’ category includes 2% of the total corn toxicity index applied PRE, 10% of the total corn toxicity index applied POST, and 13% of the total soybean toxicity index. Insecticide surveys for soybean began in 2004.**

## Pesticide Target Toxicity Index

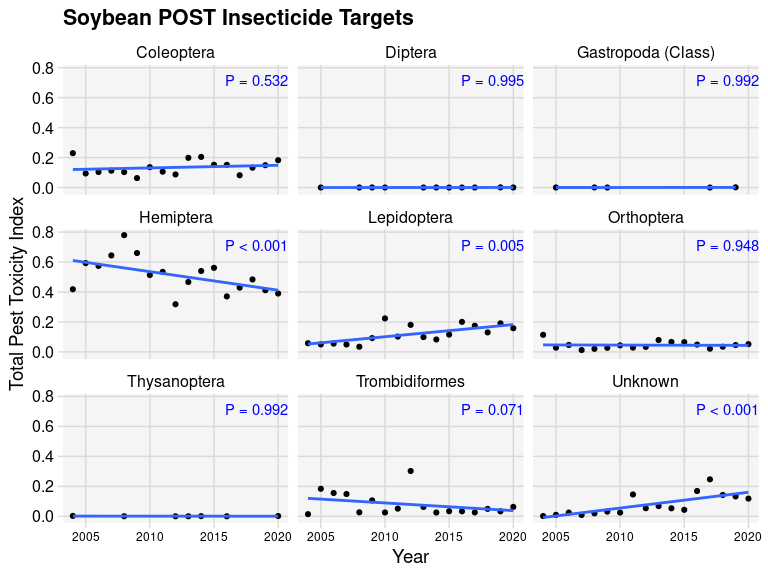
In corn, insect pests from the orders Coleoptera and Lepidoptera contributed most to the overall (Figure 4), followed by Hemipteran insects and spider mites (Trombidiformes). In corn, there was a decreasing trend for Coleoptera (P < 0.001) and Lepidoptera (P < 0.001) contributions to the over time. Hemiptera increased in importance as a pesticide target over time (P = 0.001). There was an increase in the contribution of the ‘Unknown’ pest target category (P < 0.001), which included survey responses that did not answer the question of which pest species was being targeted. Temporal trends for other taxa were not statistically significant in corn (Figure 4).

For PRE applications in corn since 2015, corn rootworm beetles, wireworms, and grubs were the most important Coleoptera pest targets, while cutworms of various species were the most important Lepidopteran pest. The from POST applications in corn was driven by corn rootworm beetles and Japanese beetles (Coleoptera) and stink bugs (Hemiptera), presumably due to potential for silk feeding. Aphids (Hemiptera) and cutworm species (Lepidoptera) were also important drivers of the corn from POST applications since 2015.



**Figure 4. Contribution of insect pests to the honey bee adult acute contact toxicity index; corn pesticides applied *after* crop emergence, 1998-2020.**

In soybean, Hemiptera pests were the greatest contributor to the overall , although there was a significant decrease in its contribution over time (P < 0.001). Stink bugs and aphid species were the greatest contributors to the among hemipteran pest species. Lepidopteran pest contribution to increased over time (P = 0.005). Since 2015, the most impactful Lepidoptera were various species referred to as ‘worms’ (including corn earworm and boll worm), ‘loopers’ (cabbage and soybean), and armyworms. Leaf beetles and Japanese beetles were the most impactful Coleoptera pest species that contributed to the from POST applications to soybean since 2015. Similar to corn, the ‘Unknown’ category also increased in importance (P < 0.001) due to survey respondents not answering the question about the targeted pest(s).

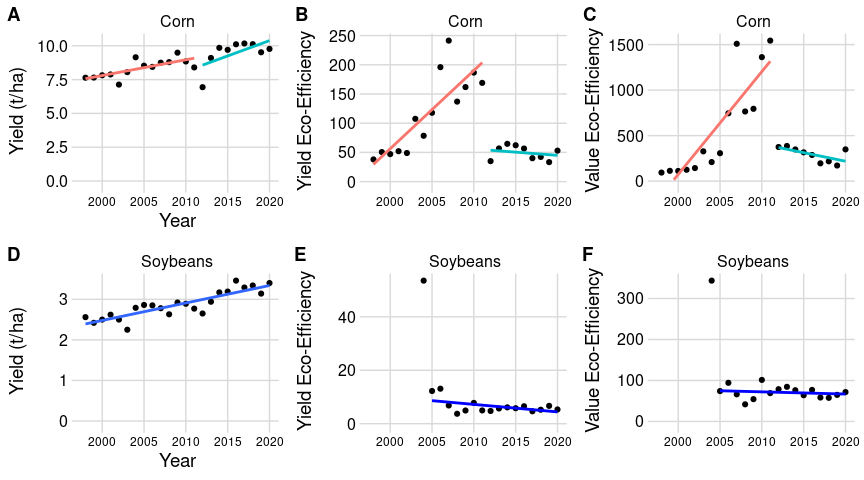


**Figure 5. Contribution of insect pests to the honey bee adult acute contact toxicity index; soybean pesticides applied *after* crop emergence, 1998-2020.**

## Eco-efficiency

Corn and soybean yields have steadily increased in the United States between 1998 and 2020 (Figure 6A, 6D). Corn production eco-efficiency for both yield (Figure 6B) and value (Figure 6C) increased substantially between 1998 through 2011, due to the observed yield increase and concurrent reduction in . However, even though corn yield continued to increase, a substantial drop in corn eco-efficiency was observed in 2012. Corn eco-efficiency decreased from 2012 through 2020, largely due to increased from bifenthrin usage. In spite of increasing soybean yields, eco-efficiency declined slowly throughout the period 2005 through 2020 (Figures 6C; 6D) due to increasing .

The units associated with eco-efficiency (crop yield per ) are difficult to interpret in a practical way, but the trend over time provides insight into whether the observed increases in yield are out-pacing changes in hazard to honey bees. Because both corn and soybean yield continued to increase throughout this period, the flat to declining trend in eco-efficiency in recent years suggests that the relative increase observed in the honey bee is out-pacing the relative increases in corn yields since 2012, at least on the national scale.



**Figure 6. Corn (A) and soybean (B) yield, and honey bee eco-efficiency index for insecticides applied to corn or soybean *after* crop emergence. Yield eco-efficiency numerator is crop yield (B, D); value eco-efficiency numerator is the farm value of crop production (E, F).**

# Discussion

The eco-effiency results here suggest that the honey bee hazard from recent insecticide usage in corn and soybean is increasing more rapidly than the yield gains observed over the same period. There has also been a shift for increased proportion of honey bee insecticide hazard to be applied after crop emergence, when there is likely to be greater exposure potential to honey bees and other pollinators. In corn, the increased insecticide hazard applied after crop emergence has been offset by a substantial decrease in insecticide hazard applied before crop emergence, and therefore, the total hazard may be negligible. But in soybean, insecticide usage went from nearly non-existent before 2004 to greater insecticide hazard to honey bees than corn in the period 2015 to 2020. Soybeans are more attractive to pollinating bees for the collection of nectar than corn (USDA 2017). While corn pollen can be consumed, overall visitation per hectare is likely to be much higher in soybeans when the crops are flowering.

This analysis, like most others published before, does not include pesticides applied as seed treatments. Public data (such as USDA surveys and census data) as well as proprietary sources like the AgroTrak data do not include seed treatments. The impact of this data limitation is an underestimate of the hazard applied PRE; however, because honey bee exposure to pesticides applied as seed treatments will be lower than those applied after crop emergence, the magnitude of this underestimate is difficult to ascertain.

Broadly, it is important to understand *why* POST insecticide usage has been increasing in recent years. Is the increase due to a perceived increase in pest pressure, or a perceived increase in the economic damage caused by insect pests? Or perhaps the cost of certain pesticides has decreased, and increased their use as a preemptive yield protection practice. The underlying cause of increased non-target hazards must be understood to develop research programs or devise policy actions that have a positive impact (Osteen and Fernandez-Cornejo 2013).

To our knowledge, this analysis is the first to estimate the relative contribution of different pest species to non-target impacts of pesticide usage. The information gleaned from this approach provides multiple avenues for future research that could benefit non-target insect species like honey bees. For example, bifenthrin appears to be the active ingredient that has contributed most to recent increases in insecticide hazard to honey bees in both corn and soybean. The pests that appear to drive bifenthrin usage include spider mites, corn rootworm, and Western bean cutworm in corn; and stink bugs and soybean aphids in soybean. Finding an efficacious pesticide with reduced non-target toxicity, or developing non-chemical approaches to manage these pests may reduce the overall hazard from insecticides.

Coleoptera and Lepidoptera (rootworm species, silk-eating insects, and cutworms) were the greatest contributors to the corn insecticide , and therefore research efforts targeting these species are likely to have the greatest impact on lowering the non-target hazard to honey bees. Conversely, Hemipteran pests (stink bugs and aphid species) are the pest targets causing the greatest insecticide hazard to honey bees in soybean. Insecticides targeting these few pests represent an out-sized proportion of the relative insecticide hazard to honey bees in the US. Efforts to reduce the need for pesticides to control these species, or education efforts on whether treatments are actually needed, would probably pay dividends in reducing non-target risks to insects like honey bees.

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