Measuring the Effects of Pesticide Use on Worker Bee Productivity

by

Elin Woolf

Submitted to the Distinguished Majors Program
Department of Economics
University of Virginia
April 15, 2019
Advisor: Jonathan M. Colmer

Measuring the Effects of Pesticide Use on Worker Bee Productivity[*]

Elin Woolf

University of Virginia

April 15, 2019

Abstract

Pesticides, despite being an important agricultural input, threaten the health of another essential input: pollinators. Exploiting county-level variation in the propensity to ship honey bees to California for pollination services, I use the variation in Californian toxic pesticide use over time to evaluate the impact of toxic pesticide exposure on honey bee productivity. I estimate that toxic pesticides are associated with a 1.7% decrease in bee productivity while non-toxic pesticides are associated with a 2% increase in productivity. These findings suggest that non-toxic pesticides have the potential to benefit crops and pollinators alike. However, the damages associated with toxic pesticides highlight the importance of considering the interactions between ecological and economic factors.

---

[*] Correspondence: eaw5qe@virginia.edu. Affiliations: Elin Woolf – Department of Economics, University of Virginia, USA. This work was completed as part of my Distinguished Majors Thesis at the University of Virginia. I thank my family, friends, and DMP cohort for offering helpful comments, suggestions and support. I am also grateful to Professor Miller for encouraging me through the development of my thesis topic; to Karen and Ken Hall for inspiring my love for bees and beekeeping; and to Professor Colmer for sharing my enthusiasm for this project and challenging me to learn at every opportunity - thank you for embarking on this honey bee journey with me. All errors and omissions are my own.

1 Introduction

Insects provide critical ecological services, contributing an estimated $24 billion to the United States economy each year through pollination alone (United States, Office of the Press Secretary, 2014). However, the economic costs of insect behavior are more salient, with much of the attention on pests and invasive species. One of the most common interventions to mitigate these costs is pesticide use. Pesticides can benefit society by increasing crop yields, improving food safety, and controlling the spread of disease (Cooper and Dobson, 2007; Aktar et al., 2009). However, in recent years concerns have been raised about the unintended consequences of pesticide use on non-target species, including pollinators and humans (Xavier et al., 2015; Damalas and Koutroubas, 2016; Thompson, 2003). Yet, our understanding of the economic consequences of pesticide use on non-target insect species remains limited due to data availability and identification concerns.

Exploiting administrative data on honey production and pesticide use in the United States, I explore the economic consequences of pesticides on the productivity of the western honey bee (*Apis mellifera*). I construct a plausibly exogenous measure of potential pesticide exposure, exploiting the average propensity of beekeepers in a given county to send colonies to California for pollination services, combined with time-series variation in the total quantity of bee-toxic pesticides applied in California over time. This reduced-form measure of pesticide exposure is inspired by the well-established Bartik instruments, commonly applied in labor economics and international trade (Blanchard et al., 1992; Goldsmith-Pinkham et al., 2018).

I estimate that on average, a one standard deviation increase in Californian toxic pesticide use is associated with a 1.7 percent reduction in bee productivity, measured by the amount of honey produced per colony. The value of this loss to the United States is estimated with a back-of-the-envelope calculation to be about $2,536,229. This finding is robust to controlling for local pesticide use, local weather conditions, and state-year fixed effects, which control for state-specific policy changes, economic, and environmental trends. The opposite is true for non-toxic pesticide use. On average, a one standard deviation increase in Californian non-toxic pesticide use is associated with a 2 percent increase in bee productivity. The value of this gain to the United States is an estimated $2,983,799.

These findings suggest that a shift towards pesticides that are non-toxic to bees would result in economic benefits to beekeepers, and to society more broadly through the ecological services provided by non-target species.[1] However, most of the non-toxic pesticides in this study represent fungicides and herbicides, whereas many bee-toxic pesticides are insecticides. In finding other substitutes, it is important to account for the costs of transitioning away from toxic pesticides, and the effectiveness of substitute interventions to address

---

[1] It is important to note that these estimates capture a lower bound of the broader economic and social costs associated with toxic pesticide use.

occurrences of bee mortality disrupted the nation's agricultural sector.

Incidences of Colony Collapse Disorder (CCD), a mysterious phenomenon by which large numbers of bees vanish from their colonies without a trace, were widely reported across the U.S. during the winter of 2006/07. The bee deaths associated with CCD are distinguishable from the typical winter bee die-offs that beekeepers experience. These unique cases are characterized by the absence of dead bee bodies, rapid losses of adult bees relative to brood, and an ominous delay before invasive pests and kleptoparasites enter the hive (vanEngelsdorp et al., 2009). These mysterious and widespread bee deaths caused a nationwide scare, bringing attention to the importance of bees as agricultural inputs.

With this increased attention on bees, many researchers began investigating CCD to determine its exact cause. Researchers have speculated that diseases, invasive species, and pesticides, among other factors, are potential culprits. However, a single cause of CCD has not been determined. After years of research, the current literature is in general agreement that multiple causes interact to produce this lethal effect. It is likely that pesticides contribute to CCD, but their cost to society extends beyond this epidemic to the harm they continually inflict on non-target species.

2.1 Pesticides

Pesticides are an important agricultural input that enable higher crop yields by reducing losses to pests and other injurious species. There are several classes of pesticides, including herbicides, fungicides, and insecticides. Herbicides control the growth of weeds and grasses that are not the crop of interest. Fungicides kill fungi before they cause damage to crops. Insecticides target one or more pest insect species and poison them upon entering their system. Insecticides pose the most direct threat to bees by design. While fungicides and herbicides are generally regarded as harmless to bees, recent research reveals negative effects that can appear when fungicides are applied in combinations (Fisher et al., 2017). Similarly, studies show that herbicides can have harmful effects on bee brood (Morton et al., 1972), as well as on bees' gut bacteria, increasing their susceptibility to infection (Motta et al., 2018).

Pesticides are an important agricultural input, totaling 4.2% of total farm expenditures in the U.S. in 2007, and 5% of this total expenditure in 2012 (Atwood and Paisley-Jones, 2017). However, pollinators are also an important input. Pollination services can account for up to 5% of farm costs for some crops (Ferrier et al., 2018). The potential consequences of pesticide use on pollinators and other insects need to be considered when evaluating the value of pesticides. Although pesticides are designed to deter and kill target species, many of them also pose risks to other organisms, including honey bees.

The Environmental Protection Agency (EPA) determines which pesticides can be used in the U.S.

the abundance of nectar (Frisch and Lindauer, 1956). With this information, other forager bees can leave the hive and confidently search for this source of nectar.

Much of the research on the effects of pesticides on honey bees focuses on forager bees. Honey bees rely heavily on smell to help them find nectar-rich flowers. If their sense of smell is compromised by pesticides, their ability to successfully find flowers and bring the nectar back to their hive, would decline. A common insecticide, imidacloprid, has been associated with impaired performances of olfactory learning in honey bees (Decourtye et al., 2004). This finding suggests that exposure to imidacloprid at the time of olfactory memory formation disrupts learning and makes it harder for bees to later retrieve these memories, thus hurting their ability to successfully forage. I expect that this decreasing ability would lower bee productivity.

Bees rely on their spatial mapping abilities to ensure they can frequently leave the hive and find their way back. If pesticides impair their spatial mapping abilities, forager bees will not be as effective, and thus the ability of the colony to produce honey would decrease. An experiment was designed to test the effect of fipronil, a commonly-applied insecticide, on honey bees' ability to fly through a maze (Decourtye et al., 2009). The experimental set-up was designed to imitate the visual cues processing that bees rely on for successful foraging flights. Without exposure to fipronil, 89% of bees could figure out how to fly through a maze and reach the sucrose solution at the end. When bees were exposed to 1ppb fipronil (orally), only 60% were able to successfully complete the same maze. This small amount of fipronil is less than the median dose value and no differences in bee mortality were found between the treatment and control group. Thus, a sub-lethal effect of exposure to fipronil was identified as decreasing the ability of honey bees to process the visual cues necessary for foraging. With a decreased ability to forage, I expect bee productivity to decrease.

Forager bees transport pesticides back to the hive, where some degrade quickly and others remain in food stores. A number of studies have documented traces of different pesticides found throughout beehives. Researchers have collected samples of beeswax, pollen stores, brood, and adult bees, and have found pesticide residues in each category (Calatayud-Vernich et al., 2018; Traynor et al., 2016). One study tested several components of a hive and detected 118 different pesticides and metabolites across their samples, with high concentrations of toxic pesticides found in pollen, the main food source of developing bees (Mullin et al., 2010). As aforementioned, the effects of pesticides on honey bee health have received documentation in laboratory studies. Effects of the infiltration of toxic pesticides into colonies may be more complicated to predict due to their capacity to affect every bee in the hive. Furthermore, honey bee exposure to pesticides is associated with many negative implications outside of bee mortality.

One solution to this problem would be to construct an instrument for local pesticide use; however, at the time of writing a viable instrument has not been conceived. Instead, I construct a reduced form measure of foreign pesticide exposure that is independent of local conditions. I do this by exploiting time-invariant state differences in the propensity for beekeepers to send colonies to California for pollination services, combined with aggregate time-varying information in the use of toxic pesticides within California. This measure resembles Bartik instruments often used in labor economics and international trade (Blanchard et al., 1992; Goldsmith-Pinkham et al., 2018). However, I exploit this variation as a reduced form measure given that there is no data on endogenous non-local pesticide exposure, required for a two-stage least squares estimation.

The practice of migratory beekeeping, whereby beekeepers ship their bees to other locations to provide pollination services, is especially relevant to California. Many beekeepers send bees there from across the country, starting with the early almond pollination season. This migration has occurred for years, and is still gaining in popularity (Ferrier et al., 2018). In 2017, 1.7 million colonies were shipped into California to pollinate almonds in February. This was an estimated 65% of the nation's colonies at the time. This nationwide practice sets up a plausibly exogenous exposure shock of bees to Californian pesticides.

To explore the effects of pesticide use on honey bee productivity, I estimate the effect of potential county-level bee exposure to Californian pesticides on the relevant outcome variables. The estimation equation for honey bee productivity is written as follows,

$$Y_{ct} = \beta Exposure_{ct} + \gamma X'_{ct} + \alpha_c + \delta_t + \epsilon_{ct} \tag{1}$$

Y_{ct} is the amount of honey produced per honey-producing colony in county c at time t. $Exposure_{ct}$ is the reduced form measure of pesticide exposure, discussed above and formally defined as $Exposure_c = \text{shipment share}_c \times \text{Pesticides}_{CA}$, where $\text{shipment share}_c = \frac{\text{avg. colony shipments}_c}{\text{avg. colony shipments}_{US}}$. X'_{ct} is a vector of control variables, including a standardized measure of local pesticide exposure, mean temperature during local bloom, and total precipitation during local bloom in county c at time t. α_c fixed effects absorb all unobserved, time-variant variation within individual counties. δ_t fixed effects control for time-varying differences in the outcome variable that are common across counties. The last term is the stochastic error term, ϵ_{ct}. Standard errors are clustered by county to account for within-county correlation.

each accompanied by information on the counties and state(s) in which the applications took place, the year(s) in which it was applied, and estimates of how many total kilograms of that compound were applied in each county during each year.

I constructed indicators for toxicity using a database of bee precaution pesticide ratings provided by the University of California Agriculture and Natural Resources Website for Integrated Pest Management (IPM).[4] This database provides a categorization of pesticides by their levels of reported toxicity to bees, varying from no bee precaution, to high restrictions on application times and location needed to ensure bee safety. I translated these ratings into 1. Non-toxic, 2. Moderately toxic, and 3. Highly toxic. Of the 483 compounds included in the data, 223 were found in the UC IPM database, 101 of these were non-toxic, 65 were moderately toxic, and 38 were highly toxic to bees. For the 258 compounds that were not available, I assumed there had not been many, or any, studies published on the negative effects of these pesticides on bees and therefore classified these pesticides as non-toxic. I then categorized each pesticide as simply toxic or non-toxic to bees and summed, separately, the total amount of toxic pesticides and non-toxic pesticides applied in each county, in each state, in each year. Summary statistics of these measures of local pesticide use are found in Panel C of Table 1. I also summed the amount of toxic and, separately, non-toxic pesticides applied across California, within each year, for use in constructing my treatment variables. Summary statistics of these measures can be found in Panel B of Table 1.

Constructing a Reduced-Form Bartik Measure Data on bee colony shipments into California were collected at California Border Protection Stations, beginning January 2007 and ending December 2018.[5] These data include each shipment's state of origin, month, year, and number of colonies. I calculated the share of bees from each state that make up the total amount of colonies shipped into California, and averaged these state-share values across the years of data. This provided an estimate of each state's bee exposure to Californian pesticides. The share of bee colonies shipped from each state was extended to the county level by multiplying each state's share of bee shipments by the average shares of statewide colonies held by individual counties.

$$E[\frac{Colonies_c}{Colonies_{US}}] = \frac{Colonies_s}{Colonies_{US}} \times \frac{Colonies_c}{Colonies_s}$$

These average county-specific shares were used as a measure of individual counties' bees' potential exposure to Californian pesticides. The average county share of honey colonies sent to California, multiplied by 100, is depicted in Panel B of Table 1. The treatment variable was then constructed by interacting

---

[4] Bee precaution pesticide ratings are accessible at `https://www2.ipm.ucanr.edu/beeprecaution/`

[5] Thank you to Brittney Goodrich of Auburn University for providing this data.

5 Results

I ran four specifications of each outcome variable regression on the treatment. Tables containing the results of these regressions are found at the end of this paper. In each table, Column 1 reports the estimated coefficient for the treatment variable without the inclusion of controls, using county and year fixed effects. Column 2 presents the coefficient when a control for local pesticide use is added which reflects either toxic or non-toxic local pesticide use, in line with whether the treatment variable is toxic or non-toxic. Column 3 adds in weather controls, including the mean temperature and total rainfall during local bloom periods. Column 4 is the same full regression from Column 3, but year fixed effects are replaced with state-year fixed effects. This last specification controls for the most variation and is thus the most robust estimate. The results presented in this section will focus primarily on the estimated coefficient values yielded from this final specification. The results will be evaluated in terms of the effect on an average county, and changes will be discussed in reference to the average county values depicted in Table 1. The magnitude of these effects will be estimated using a price of \$2.47 per pound of honey, which is the average retail price from the years 2002, 2007, and 2012.[7] Using the average county share value of .051, as shown in Table 1, average effects will be estimated as follows,

$$Average\ effect = (Average\ county\ share) \times (Column\ 4\ coefficient)$$

5.1 Honey Bee Productivity

Panel A of Table 2 presents the effects of one standard deviation increase in toxic pesticide application on honey bee productivity. We observe that an increase in toxic pesticide exposure is associated with a decrease in honey bee productivity and find these estimates statistically significant in Columns 1-4 at the 1% significance level. Finding this result across all four specifications demonstrates the robustness of this estimated effect. On average, one standard deviation increase in Californian toxic pesticide use is associated with a 1.7% decrease in honey production per hive. Applying this effect to the average measure of honey productivity as presented in Table 1, the average hive yield of 44.50 pounds would decrease to 43.74 pounds, exhibiting a loss of .76 pound of honey per hive, and associated loss of \$1.88 per hive. Table 1 shows that the average county has 779 honey colonies, which translates to a loss of 584.25 pounds of honey per county, on average. This reduction in bee productivity from exposure to toxic pesticides is associated with an \$1,443

---

[7] The average price from these three years was \$2.47 in 2012 dollars. Honey prices used in this calculation are available online at `https://usda.library.cornell.edu/concern/publications/hd76s004z?locale=en`

results we observed of decreased bee productivity. To explore this concern, I run another set of regressions on honey bee productivity, this time holding the number of honey colonies fixed.

5.3 Honey Bee Productivity - Fixed Number of Colonies

To explore the effects of controlling for variation in the number of honey colonies, we test holding honey colonies constant, using the average number of colonies within each county as the denominator for honey productivity. In Panel A of Table 4, we still observe a decrease in bee productivity associated with an increase in toxic pesticide application. These effects are found to be statistically significant in Columns 1-4, at the 10% significance level. Holding honey colonies constant, we find that on average, a one standard deviation increase in Californian toxic pesticide use is associated with a 1.2% decrease in honey production per hive. This translates to a decrease from 44.50 to 44 pounds of honey harvest per hive. Although this effect is slightly smaller than our previous estimate, its significance suggests that the reduction in honey productivity is not solely driven by changes in colony numbers.

The results of regressing this fixed-colony measure of bee productivity on the non-toxic treatment variable are displayed in Panel B of Table 4. We observe an increase in bee productivity associated with an increase in non-toxic pesticide use, and find these results statistically significant across all specifications at the 5% level. On average, one standard deviation increase in Californian non-toxic pesticide use is associated with a 1.6% increase in honey production per hive. This translates to an increase in average honey harvest per colony from 44.50 pounds to 45.21 pounds, a gain of .71 pound per hive. When applied to the average 779 county hives, this represents a gain of 553 pounds of honey and $1,366 in revenue.

After controlling for the variation in honey colonies, we find that the counterintuitive effects of pesticides on honey colonies do not negate our finding that toxic pesticides are associated with a reduction in productivity, and that non-toxic pesticides are associated with an increase in productivity. This suggests that changes in the bee productivity numerator, honey production, are driving our results.

5.4 Honey Production

Panel A of Table 5 presents the effect of one standard deviation increase in toxic pesticide use in California on the amount of honey produced per county. A priori, the predicted effect is that toxic pesticide exposure would reduce the amount of honey produced by reducing bees' ability to successfully forage for nectar. In line with this prediction, we observe that an increase in toxic pesticide exposure is associated with a decrease in the amount of honey produced. This result is statistically significant at the 5% level, shown in Columns 1-4. On average, one standard deviation increase in Californian toxic pesticide use is associated with a 3.2%

of pesticide use on non-target species, and evaluate whether alternative pest controls might contribute more value to the agricultural sector, and to our society, when considering increased crop yields as well as the effect our practices have on our important insect pollinators.

Frank, Eyal G., Declining Bat Populations, Increased Pesticides Use Infant Mortality," *Working Paper*, 2016.

Frisch, K. Von and M. Lindauer, The 'Language' and Orientation of the Honey Bee.," *Annual Review of Entomology*, 1956.

Goldsmith-Pinkham, Paul, Isaac Sorkin, and Henry Swift, Bartik Instruments: What, When, Why, and How," *NBER Working Papers*, 2018.

Holzman, David C., Accounting for Nature's Benefits: The Dollar Value of Ecosystem Services," *Environmental Health Perspectives*, 2012.

Kauffman, Gerald J., Economic Value of Nature and Ecosystems in the Delaware River Basin," *Journal of Contemporary Water Research and Education*, 2016.

Koh, Insu, Eric V. Lonsdorf, Neal M. Williams, Claire Brittain, Rufus Isaacs, Jason Gibbs, and Taylor H. Ricketts, Modeling the status, trends, and impacts of wild bee abundance in the United States," *Proceedings of the National Academy of Sciences*, 2016.

Krupke, Christian H., Greg J. Hunt, Brian D. Eitzer, Gladys Andino, and Krispn Given, Multiple Routes of Pesticide Exposure for Honey Bees Living Near Agricultural Fields," *Plos One*, 2012.

Morton, Howard L., Joseph O. Moffett, and Robert H. Macdonald, Toxicity of Herbicides to Newly Emerged Honey Bees," *USDA Agricultural Research Service*, 1972.

Motta, Erick V. S., Kasie Raymann, and Nancy A. Moran, Glyphosate Perturbs the Gut Microbiota of Honey Bees," *Proceedings of the National Academy of Sciences*, 2018.

Mullin, Christopher A., Maryann Frazier, James L. Frazier, Sara Ashcraft, Roger Simonds, Dennis vanEngelsdorp, and Jeffery S. Pettis, High Levels of Miticides and Agrochemicals in North American Apiaries: Implications for Honey Bee Health.," *Plos One*, 2010.

Sanchez-Bayo, Francisco and Koichi Goka, Pesticide Residues and Bees - A Risk Assessment," *Plos One*, 2014.

Stein, Katharina, Drissa Coulibaly, Kathrin Stenchly, Dethardt Goetze, Stefan Porembski, André Lindner, Souleymane Konaté, and Eduard K. Linsenmair, Bee pollination increases yield quantity and quality of cash crops in Burkina Faso, West Africa," *Scientific Reports*, 2017.

Tables

Table 1: Descriptive Statistics

	Mean	Std. Dev. (Within)	Std. Dev. (Between)	Number of Observations
Panel A: Outcome Variables				
Honey Production (lbs.)	44688.34	63682.57	161502.2	5165
Honey-Producing Colonies	779.091	933.875	2665.438	5165
Honey Productivity	44.496	33.270	38.040	5165
Panel B: Treatment Variables				
Californian Toxic Pesticide Application (tons)	8948.327	399.184	243.744	5165
Californian Non-Toxic Pesticide Application (tons)	53742.93	2927.797	1611.063	5165
County-Share of Bees Shipped to California	.051	0	.206	4812
Panel C: Other Controls				
Local Toxic Pesticide Application (tons)	56.003	20.162	82.133	5165
Local Non-Toxic Pesticide Application (tons)	85.288	58.056	345.810	5165
Total Precipitation (ml)	504.320	104.727	213.204	5165
Mean Temperature (Celsius)	21.241	.307	2.198	5165
First Bloom Day	103.602	0	27.964	5165

Table 3: The Effects of Californian Pesticide Exposure on Number of Honey Colonies

	(1) Honey Colonies	(2) Honey Colonies	(3) Honey Colonies	(4) Honey Colonies
Panel A:				
Toxic Exposure	1075.3**	1001.2**	1000.1**	836.4*
	(460.7)	(446.4)	(446.4)	(468.3)
Panel B:				
Non-Toxic Exposure	-648.1	-637.7	-644.1	-288.1
	(433.0)	(425.2)	(425.2)	(430.1)
County FE	YES	YES	YES	YES
Year FE	YES	YES	YES	–
Local Pesticide Use	NO	YES	YES	YES
Weather Controls	NO	NO	YES	YES
State-Year FE	NO	NO	NO	YES
Observations	4308	4308	4308	4308

NOTES: Significance levels are indicated as * 0.10 ** 0.05 *** 0.01. The dependent variable is defined as the number of honey bee colonies from which honey is harvested. The effects are estimated in levels. Exposure is defined as the standardized toxic/non-toxic pesticide application in CA for a given year, weighed by the average county-specific number of colony shipments to California for pesticide services. Standard errors are clustered at the county level.

Table 5: The Effects of Californian Pesticide Exposure on Honey Production

	(1) Honey Produced	(2) Honey Produced	(3) Honey Produced	(4) Honey Produced
Panel A:				
Toxic Exposure	-0.407**	-0.462**	-0.455**	-0.622**
	(0.204)	(0.212)	(0.212)	(0.280)
Panel B:				
Non-Toxic Exposure	0.660**	0.662**	0.621**	0.949***
	(0.269)	(0.269)	(0.269)	(0.367)
County FE	YES	YES	YES	YES
Year FE	YES	YES	YES	–
Local Pesticide Use	NO	YES	YES	YES
Weather Controls	NO	NO	YES	YES
State-Year FE	NO	NO	NO	YES
Observations	4308	4308	4308	4308

NOTES: Significance levels are indicated as * 0.10 ** 0.05 *** 0.01. The dependent variable is defined as the amount of honey produced in a year. An Inverse Hyperbolic Sine Transformation is applied to the dependent variable: $\log(y + (y^2 + 1)^{0.5})$. This has the same interpretation as a logarithmic transformation; however, zero is defined. Results are robust to logarithmic transformations and estimating the effects in levels. Exposure is defined as the standardized toxic/non-toxic pesticide application in CA for a given year, weighed by the average county-specific number of colony shipments to California for pesticide services. Standard errors are clustered at the county level.