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Cicadian Rhythm: Insecticides, Infant Health and Long-term Outcomes

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Cicadian Rhythm: Insecticides, Infant Health and Long-term Outcomes[*]

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Abstract

This paper utilizes a peculiar ecological phenomenon, the mass emergence of cicadas in 13 and 17-year cycles, to identify the impact of pesticides on human health and long-term development. I rely on the fact that cicadas only damage woody plants (e.g., apple trees), through egg laying in branches and subsequent nymph-feeding on roots—and not agricultural row crops. Using the natural temporal and geographic variation of cicada emergence, I show that a sharp increase in insecticides coincides with cicada emergence in places with high tree crop production. This is followed by higher subsequent-year infant mortality and adverse health impacts. Looking at long-term effects, I find evidence of lower elementary test scores and then higher dropout rates among exposed cohorts. This paper supports the conclusion that moderate levels of environmental pollution, not just extreme exposure, can affect human health and development. *JEL Codes: I10, Q10, Q53, Q57.*

1 Introduction

Farmers in the US spend $7.9 billion annually on pesticides (US EPA 2017). Modern pesticides, along with other technological advances in agriculture, have brought about significant increases in productivity. But concerns have long been raised about the potential negative environmental and health impacts of pesticides given their toxicity by design.

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Since the high-profile federal ban of DDT in 1972, dozens of pesticides have been banned by the EPA on account of their potential risk to humans and the environment (Buffington and Mcdonald 2006).

I utilize an ecological phenomenon, the emergence of periodical cicadas (*Magicicada septendecula*), as a source of quasi-exogenous temporal and spatial variation in the application of insecticides to identify a potential causal channel for the impact of insecticides on health. My identification strategy hinges on the fact that cicadas emerge as mass broods in the same locations every 13 or 17 years such that each brood is linked to a specific year and unique geographic footprint. For example, Thomas Jefferson described the 'great locust years' of Brood II cicadas that arrived every 17 years at his home in Monticello, Virginia (Jefferson 1944). This same brood still emerges on schedule at Monticello 250 years later, most recently in summer 2013.

I find a significant increase in insecticide use in years and in counties experiencing a cicada emergence. This impact, however, is limited to places with a large proportion of woody crops like fruit trees—and not herbaceous row crops like corn and soy. This is because cicadas only damage woody plants. Adult cicadas lay their eggs in small branches and nymphs feed on tree roots.

Using apple production as a proxy for woody crop intensity, I exploit this variation and compare treated counties (i.e., counties with high apple production in years of a cicada emergence) to untreated counties. In the treated counties, I find a corresponding increase in county-wide insecticide use and subsequent increase in next-year infant mortality of 0.3 deaths per thousand births (the current mean in the US is six deaths) following a cicada emergence. An investigation of the quarterly impacts aligns with the timing and patterns of insecticide usage by farmers. Treated counties also see an increased probability of premature births and other adverse infant health outcomes. There is evidence of long-term impacts in the form of lower elementary school test scores and higher high school dropout rates among exposed cohorts.

The findings are likely generalizable outside of just agriculturally-intensive regions. Tree crops cover a relatively small portion of US counties (always less than 5% of county land area, generally far less than 1%), especially compared to row crops like soy and corn which account for a majority of total acreage in many counties. Baseline pesticide use is moderate to low in many tree-intensive counties. These facts support the conclusion that moderate levels of pesticides, not just extreme exposure, affect human health and development. And since this analysis looks only at average county-level impacts, it likely understates the health impacts among those living in close proximity to insecticide application.

Overall this paper contributes to the environmental and health economics literature on the health impacts of agricultural inputs. This is a timely topic considering the many current pesticide lawsuits and regulatory proposals.[1] While acknowledging the importance of pesticides to agricultural productivity, the findings warrant caution in the over-application of insecticides. This paper also provides an example of how ecological phenomena like cicadas may be used to generate quasi-random variation that can be employed to answer important economic and public health questions.

2 Background

2.1 Pesticides and health

Pesticides, and insecticides in particular, are toxic by design. Many were initially developed for warfare purposes. One prominent insecticide type, organochlorides (e.g., DDT), opens sodium channels in the nerve cells; another, organophosphates, targets the nervous system like the nerve agents in chemical weapons.

While laboratory and controlled studies have documented the negative impacts of pesticides on organisms and ecosystem services such as water quality, few have demonstrated a direct causal link between pesticides and human health. Almond and Currie 2011 show that fetal shocks, particularly ones occurring early in a pregnancy, can have long-lasting impacts. Environmental shocks including heavy metal exposure, high temperatures, and air pollution have been causally linked to adverse birth outcomes (Chay and Greenstone 2003; Zheng et al. 2016).

But there is little evidence causally linking pesticides to health outcomes like infant mortality, low birth weight, and premature birth. And no study, to my knowledge, has directly linked pesticide exposure to long-term outcomes like educational achievement and attainment.

Most estimates of the health impacts of pesticides come from non-randomized studies with small sample sizes (Jurewicz et al. 2006; Andersson et al. 2014). Many focus on occupationally-exposed groups who are unlikely to be representative of the broader population. Among farm workers, there is evidence of higher levels of still births and infant

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[1] See link for debate on regulating the insecticide chlorpyrifos and link for the recent $10 billion glyphosate herbicide settlement.

deaths within 24 hours of birth (Regidor et al. 2004) and birth defects (Garry et al. 2002), especially for conceptions occurring during the spring pesticide application season. Others highlight the impact of pesticide exposure during the first trimester (Bell et al. 2001) and a link between agricultural chemicals in water and birth defects (Winchester et al. 2009). Schreinemachers 2003 find that birth defects increase with a county's wheat acreage, which is used as a proxy for herbicide exposure.

Larsen et al. 2017 use detailed spatial and micro-level panel data in California to show that pesticide exposure increases adverse birth outcomes among populations exposed to high quantities of pesticides (i.e., 95th percentile exposure). Brainerd and Menon 2014 exploit variation in planting times to link agrichemical exposure to adverse birth outcomes in India. Dias et al. 2019 link herbicide use driven by genetically modified crop adoption to negative birth outcomes in Brazil. Rauh et al. 2012 find evidence of long-term impacts in the form of lower IQ scores among a small sample of children exposed to insecticides in utero. Frank 2018 exploits a bat-killing fungus and finds that farmers compensate for the mortality of insect-eating bats with insecticides resulting in higher (primarily female) infant mortality.

2.2 Cicadas and Insecticides

Periodical cicadas (*Magicicada septendecula*) occur throughout the eastern half of the US.[2] Bob Dylan described the distinctively loud mating song of the cicada (often colloquially called a locust) as follows:

> *And the locusts sang, yeah, it give me a chill*
> *Oh, the locusts sang such a sweet melody*
> *Oh, the locusts sang their high whining trill*
> *Yeah, the locusts sang and they were singing for me*

There are fifteen extant broods, three of which are on 13-year cycles and twelve of which are on 17-year cycles. Rarely flying more than 50 meters from where they emerge from the ground, each brood returns to the same place at the cycle's end. Figure 1 maps each brood's range, cycle, and next year of emergence. Note that some counties receive multiple broods.

There is ample agronomic and ecological research on cicadas and tree health, with a considerable focus on fruit trees in particular. Cicadas spend most of their lives underground

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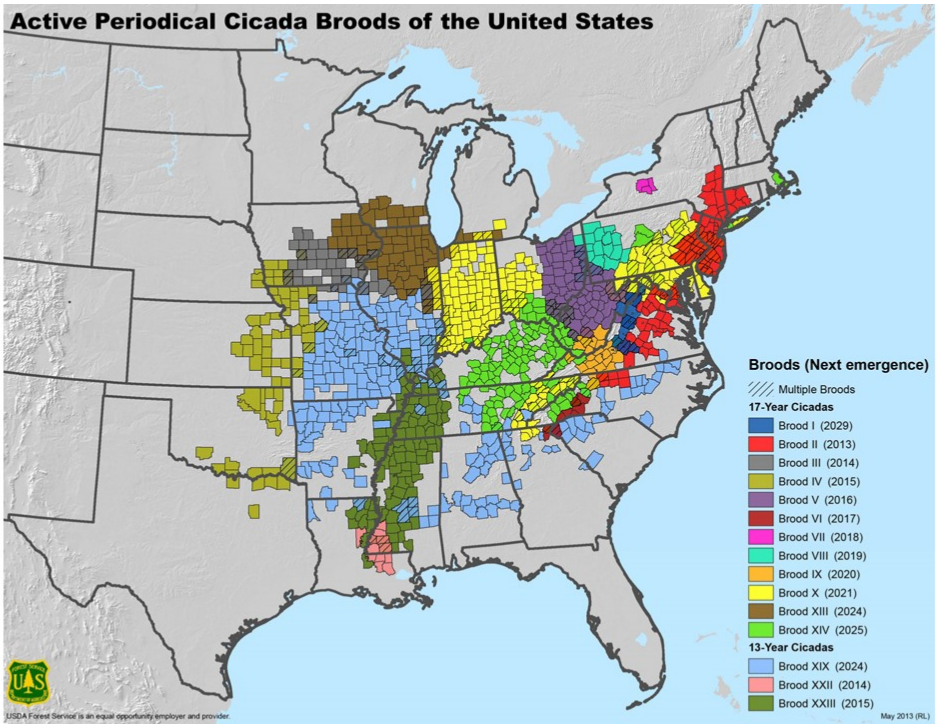
[2] There are several species of annual (i.e., non-periodical) cicadas that exist globally, including in ranges that overlap with periodical cicadas in the US. But the populations of such species do not tend to vary greatly year to year.

Figure 1



Source: Liebhold, A. M., Bohne, M. J., and R. L. Lilja. 2013. USDA Forest Service Northern Research Station.

feeding on the xylem fluids of tree roots before synchronously emerging in the late spring at any given location. Emergence densities of 1.5 million cicadas per acre have been reported (Dybas and Davis 1962), representing some of the highest biomass values of any naturally occurring terrestrial creature. Cicadas remain active for four to six weeks to mate and lay their eggs in small tree branches (i.e., oviposition), causing harm especially to young trees. When the eggs hatch, the nymphs fall to the ground to begin their development. Tree growth is further damaged by cicada nymphs feeding on tree roots, which can reduce growth by up to 30% (Karban 1980).

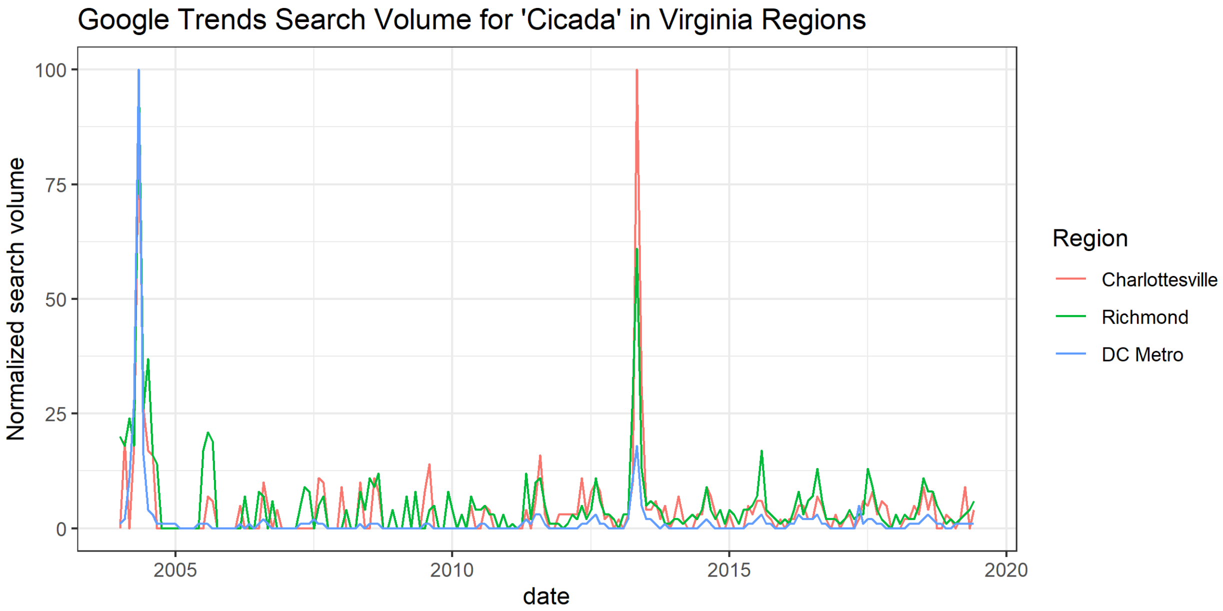
Both the egg-laying and nymph-feeding processes have a negative impact on orchard trees. In an early study, Hamilton 1961 reported a complete loss among unprotected young apple and pear trees in the Hudson Valley following a cicada event in 1945. Karban 1982 conducted an experiment on apple trees and found that removing cicada nymphs significantly increased wood accumulation relative to when nymphs were present.

Most commercial tree growers and serious gardeners are well aware of the damage that cicadas can cause, and utilizing insecticides to mitigate cicada damage is well documented. Hamilton 1961 describes the process and efficacy of spraying trees with insecticides to kill adult cicadas as well as soaking the soil with insecticides to control nymphs. Lloyd and White 1987 recommended killing off understory grasses to starve young nymphs. There are many publicly-available resources on cicada management for fruit growers, including information on pesticide use and application methods (Krawczyk 2017; Johnson and Townsend 2004).[3]

3 Empirical Strategy

Cicada emergence is anticipated by both tree growers and, to a certain extent, the general population. There is ample news coverage leading up to what some call 'cicada mania'. Figure 2 shows the Google Trends of average monthly search volume for the word 'cicada' in metropolitan regions of Virginia, including Charlottesville, the area where Thomas Jefferson noted the creatures in his writings over two centuries ago. This event study demonstrates the distinct temporal pattern of periodical cicadas. The two spikes in 2004 and 2013 coincide with the emergence years of the two endemic broods to the region.

Figure 2



Source: Google Trends

Despite the public awareness, I argue that cicada emergence is effectively exogenous in relation to anything that could affect public health outcomes at a county level. I have found no research or media reports documenting any aggregate increase in pesticide usage in

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[3] See link for example guidance from Purdue University on protecting fruit trees from cicada damage.

cicada years, and nothing about the health risks related to cicadas and pesticide use. In fact, most media coverage highlights the fact that cicadas are harmless to humans.

Further, note that the Charlottesville region accounts for much of Virginia's fruit production, whereas Richmond and DC have few orchards. Yet Figure 2 shows that public interest in cicadas follows similarly predictable patterns across regions—regardless of land use. Cicada emergence therefore would act as a quasi-experiment where tree-intensive counties receive more insecticides during emergence years relative to the same counties during non-emergence years, and where tree-intensive counties receive more insecticides relative to non tree-intensive counties in emergence years. I include several robustness checks and alternative specifications to ensure the exclusion restriction holds.

Insecticide exposure and its potential impact on health should be related on the life cycle of the cicada, the risk to tree crops, and the timing of human exposure. The Timing Framework provides a conceptual diagram. If accurate, one would expect: first, an increase in insecticide use in the year of cicada emergence; second, birth impacts in the year following emergence, starting in the spring; and third, yield impacts on tree crops beginning in the year before emergence as nymphs increase their root feeding and continuing for several years. Each of these propositions is tested and confirmed in the analyses that follow.

Timing Framework

Timing	Spring and year(s) prior	Summer	Fall (and late summer)	Winter	Next spring (and throughout the following year)
Insecticide use	Some documented insecticide pre-spraying to kill nymphs before emergence	Primary spraying to prevent cicadas from mating and laying eggs on tree branches	Primary spraying to kill eggs and nymphs	Ground spraying/soil soaking to kill nymphs before establishment	Follow on ground treatments to kill nymphs
Cicada behavior	Nymphs increasing feeding, size, moving toward surface	Cicada emergence and mating	Eggs hatch and tiny nymphs fall to ground	Nymphs bury themselves into ground, feeding on tree roots	Nymph establishment and passive feeding for next 13/17 years

Health impacts

Maternal exposure to insecticides
(primary timing = solid line;
other potential timing = dashed line)

First birth impacts from 1st trimester exposure previous summer; continuing through year

4 Data

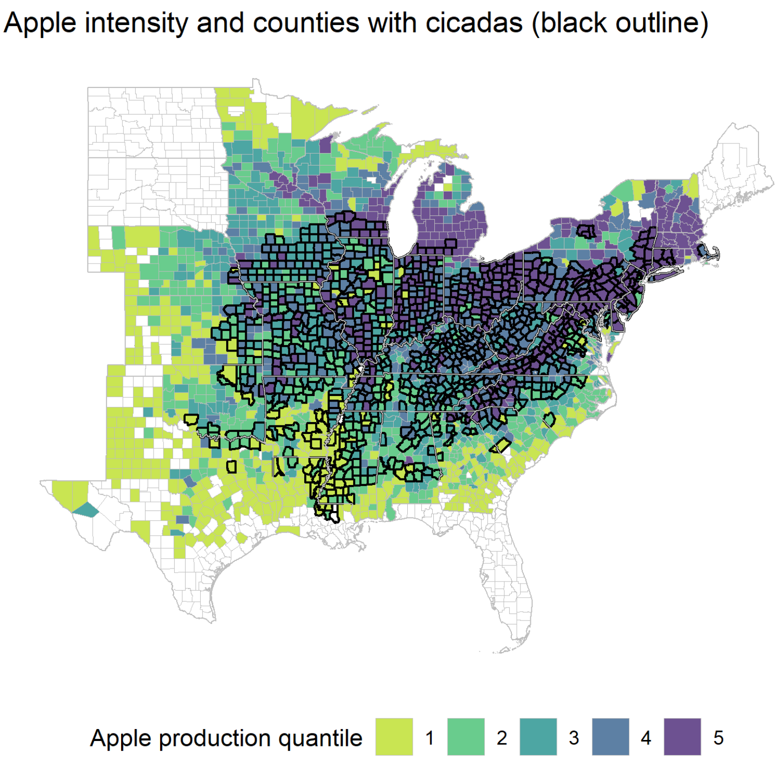
Cicada data

The US Forest Service provides shapefiles with county-level presence-absence data on periodical cicadas by brood with emergences projected through 2031 (Koenig et al. 2011). Given the temporal and spatial consistency of cicada emergence, I extend the time series further into the past using each brood's 13 or 17-year cycle assuming that cicada emergence occurred in the same counties. While there are some examples of accelerations in cycles and changes in the range of broods (Williams and Simon 1995), cicada behavior and brood distribution has been remarkably consistent for the most part (Marshall 2001).

Agricultural data

The land use dataset comes from the USDA's National Agricultural Statistics Service (NASS) online tool and from the historical U.S. Census of Agriculture, available online through the Inter-university Consortium for Political and Social Research (ICPSR) compiled by Haines et al. 2014. I collected various measures of apple and woody crop intensity at the county-year level (i.e., number of acreage and production in bushels).[4] I choose apples as my preferred explanatory variable because apples are the historically dominant tree crop in the US. There is also ample agronomic and ecological literature on the effect of cicadas on apple trees, as described earlier. Apple production is well-distributed geographically among the cicada-endemic eastern US states, with top producers in the Northeast (NY, MA, CT), Central-Midwest (PA, MI, OH), and the South (VA, NC). Figure 3 shows the states included in my analysis along with cicada presence and quantile of apple production intensity.

Figure 3



Source: USDA Census average values in 1964 and 1997.

Unfortunately, an annual time series cannot be constructed for tree crop variables for several reasons: the agricultural census takes place every five years, variables were not measured consistently over time, and surveys in the 1970s and 1980s only included 50% of counties. Therefore, I used a time invariant measure of county-level tree crop intensity,

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[4] County-year data values of ‘(D)’, which NASS uses to denote confidentiality, were coded as not available, and values of ‘(Z)’, which denote being too small to estimate, were coded as zero. Given that only positive values are included in NASS output, excluded county-years are assumed to have a value of zero. All measures of agricultural intensity are standardized by county land area.

varying the base year for robustness checks. But since tree crops are long-term investments with an asset value over multiple decades, there is very little annual change in planted area, unlike row crops. Even over the longer period between 1964 and 1997 there is a 0.84 correlation in county-level apple production in bushels—a time of significant agricultural change in the US.

Note that of the 2,464 eastern US counties across 34 states in our sample, 1,038 have endemic periodical cicadas (42%). Apple production is distributed among both cicada and non-cicada counties. Among the former, 136 counties are in the top decile of sample-wide apple production. Among the 1,426 non-cicada counties, 111 counties are top apple producers.

Pesticide data

The United States Geological Survey (USGS)'s National Water-Quality Assessment Project provides county-level pesticide use data from 1992 to 2016 (USGS 2019). Information was compiled from surveys of farm operations in USDA Crop Reporting Districts and annual crop acreage reports. My preferred measure is the sum of all insecticide-categorized constituents using the 'EPest-high' measure in kilograms per county. [5] Insecticide intensity is also standardized by county land area.

Infant health data

Infant mortality and birth outcome data come from the National Center for Health Statistics (NCHS 2019). NCHS Natality Data Files contain full records for data publicly available from 1968 to 1988, while records from 1989 to 2016 were obtained under confidentiality agreement. NCHS Linked Birth-Infant Death Data Files contain confidential microdata from 1995 to 2016. For longer-term analysis of infant mortality, I use the Inter-university Consortium for Political and Social Research (ICPSR)'s County-Level Natality and Mortality Data, 1915-2007 (Bailey et al. 2016). The ICPSR data are averaged annually and do not allow for within-year or demographic disaggregation aside from race. I use ICPSR's preferred 'fixed' variables whenever available.

ICPSR's resident infant death data become available starting in 1941 and are based on the residence county of the mother (rather than the county of birth occurrence). After 1988, ICPSR masks counties with populations less than 100,000, which presents challenges given that many of the counties of interest are agricultural and have populations lower than 100,000. Since the NCHS Linked Birth-Infant Death data begin in 1995, there is a data gap from 1989 to 1994 for low population counties. Starting in 1995 I use infant mortal-

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[5] The USGS pesticide dataset was classified by function (i.e., insecticide, herbicide, fungicide) like in Frank 2018. 160 of the constituents had insecticidal properties.

ity rates derived from these linked files. I address concerns about sample composition by running alternate analyses on a subset of observations ending in 1988, as well as a sample using IPUMS data which is available from 1990 to 2007 (Manson et al. 2020).[6]

I use the NCHS Linked Birth-Infant Death data from 1995 to 2016 to compute infant mortality rates at the sub-year level (i.e., quarter averages that can be linked to timing of insecticide application). I use NCHS Natality data from 1968 to 2016 to construct detailed birth outcome measures like Apgar scores, gestation time, and birth weight, as well as for constructing controls for maternal characteristics.

Education data

For educational achievement, I use standardized annual county-level test scores from the Stanford Education Data Archive 2.1 (Reardon et al. 2018). SEDA harmonized state and federal NAEP test results to create a spatially and temporally consistent dataset available for the seven years from 2009 to 2015. Despite the challenges in comparing state level test results, Kuhfeld et al. 2019 find high correlations between the SEDA data and NWEA's MAP Growth which is another nationally administered test given to a subset of the population. I average SEDA county data across the third, fourth, and fifth grades to produce an elementary school average score for each cicada exposure cohort (e.g., 3rd graders nine years after a cicada event, fourth graders ten years afterwards, and fifth graders eleven years afterwards).

For a measure of educational attainment, I construct a dataset on high school dropout rates using the National Center for Education Statistics (NCES) Local Education Agency Universe Survey Dropout and Completion Data. I average across school districts to get county-level values from 1991 to 2008. My preferred measure is twelfth grade dropout rate, which is the total number of twelfth graders dropping out of high school in a given year divided by the total number enrolled.

Economic and demographic data

County-level economic data come from US Department of Commerce, Bureau of Economic Analysis. Decadal county-level migration rates are from Winkler et al. 2013.

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[6] Results hold whether using the infant mortality dataset constructed by combining the Linked Infant Birth/Death Files with historical ICPSR calculations, incorporating IPUMS data, or just using the ICPSR dataset which underwent additional data cleaning as described in Bailey et al. 2016.

5 Model

My empirical approach consists of two main parts: I use a triple difference estimator to first test whether there is an increase in insecticide use in treated counties in cicada emergence years, and second, whether there is a follow-on impact on infant health and longer-term outcomes. I restrict the sample to all the counties in the 34 states in the eastern half of the US that span the range of periodical cicadas. Note there are some counties in these states in which cicadas never emerge.

In all models, the independent variable is a cicada presence-absence dummy, $cicada_{it}$, taking the value of 1 if there is a cicada emergence in county i in year t, and 0 otherwise. Cicada emergence for each brood is based on its endemic location and cycle time, as visualized in Figure 1.

For the first step, I specify a model with insecticide use intensity, $insecticide_{it}$, as the dependent variable, measured in kilograms of insecticide per km^2 in county i in state s in year t. The cicada dummy is interacted with a measure of tree crop intensity (e.g., apple production), $apple_i$, in county i, which is unvarying over time:

$$insecticide_{it} = \beta_1 cicada_{it} + \beta_2 cicada_{it} * apple_i + \alpha_i + \gamma_t + \rho_s + \epsilon_{it} \tag{1}$$

where α_i includes county fixed effects and γ_t includes year fixed effects. The former accounts for any time-invariant properties of the county that could affect outcomes. Year fixed effects account for national-level time trends and annual anomalies like changes in commodity prices and recessions. State time trends ρ_s account for trends that could be driven by state-level policy.[7] The coefficient of interest, therefore, is β_2, which estimates the change in insecticide use in tree crop-intensive counties driven by cicada emergence.

For health outcomes, I specify a model similar to Equation 1 but replace insecticide intensity with infant mortality rate (infant deaths per thousand live births), $imr_{i,t+1}$, in county i in the following year, $t+1$:

$$imr_{i,t+1} = \beta_1 cicada_{it} + \beta_2 cicada_{it} * apple_i + \alpha_i + \gamma_t + \rho_s + \epsilon_{it} \tag{2}$$

The coefficient of interest is again β_2, which estimates the change in infant mortality rate stemming from a cicada emergence in tree crop-intensive counties. In addition to imr, I

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[7] State-year fixed effects are not used because some cicada brood-years encompass much of certain states (i.e., Brood X and Indiana).

test for other impacts of infant health and educational outcomes.

6 Results

6.1 Insecticides and Cicadas

The first analysis examines the relationship between insecticide use and cicada emergence using the model specified in Equation 1. The sample is limited to the 25 years from 1992 to 2016 in which county-level USGS pesticide data exist. Table 1 regresses insecticide use on a cicada dummy and the cicada dummy interacted with fixed top-decile indicators (top 10th percentile) of tree crop intensity.

Table 1: Cicadas and Insecticides

	Insecticide use (kg km^{-2})							
	———Levels———				———Logs———			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cicada	1.08	−0.18	0.13	0.29	−0.03	−0.05	−0.05	−0.04
	(1.35)	(0.63)	(0.90)	(0.94)	(0.04)	(0.04)	(0.04)	(0.04)
Cicada:Fruit Acres		10.73*				0.19**		
		(6.10)				(0.07)		
Cicada:Apple Acres			6.72*				0.14*	
			(3.63)				(0.07)	
Cicada:Apple Bushels				5.67*				0.09
				(3.25)				(0.05)
County FE	X	X	X	X	X	X	X	X
Year FE	X	X	X	X	X	X	X	X
State-Yr Trend	X	X	X	X	X	X	X	X
Observations	61,133	61,133	61,133	61,133	60,784	60,784	60,784	60,784
R^2	0.42	0.42	0.42	0.42	0.87	0.87	0.87	0.87

Notes: Linear regression. Dependent variable is county-level insecticide use, which is the combined sum of the USGS EPest-high values with insecticidal properties divided by county land area. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Interacted covariates include the top decile counties in fruit acreage, apple acreage, and apple production in bushels per land area in 1997. Time series limited to USGS pesticide data, 1992 to 2016. State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level. *p<0.1; **p<0.05; ***p<0.01

Model (1) shows the impact of cicada emergence on insecticide use alone. Models (2)-(4)

interact cicada emergence with the top decile of fruit and apple acreage and apple production in bushels, respectively. Models (5)-(7) replicate the analysis using log insecticide values instead of levels. Cicada emergence, in itself, is not associated with increased insecticide usage except in tree crop-intensive counties. Apple counties see an increase in pesticide use in the range of 5 to 7 kg km^{-2}, a moderately large effect given that mean county pesticide use is 10 kg km^{-2}.

Bushels of apple production is used as the primary measure of tree crop intensity going forward. The broader category of fruit acreage is less consistently measured and includes a wide array of woody plants (e.g., berries) and management practices. As described earlier, apple production is well distributed across the country: among the 247 counties in the top decile of apple producers in the eastern half of the US, 27 states have at least one county in this group. Orchards are a long-term investment with an asset value over multiple decades, so it is not surprising that 70% of counties in the top apple production decile in 1964 remained there in 1997.

Figure 4 plots the coefficients from Model (4) as an event study with the inclusion of leads and lags of cicada emergence.[8] Insecticide use increases in the year of cicada emergence. This outcome aligns with the first prediction of the Timing Framework in which farmers apply insecticides primarily to control the adult egg-laying population in the year of emergence. And given that cicada emergence is anticipated, any small uptick in insecticide use in the year prior could reflect pre-spaying to kill nymphs before the emergence. (Cahoon and Danoho 1982).

Appendix Table A1 shows that *only* insecticide use responds to cicada emergence in apple-intensive counties, while herbicide and fungicide use do not appear to change. This provides assurance that any resulting health impacts are attributable to insecticides and not a more general change in agricultural practices. Table A2 shows that cicada emergence is *not* associated with increased insecticide use in agriculturally-intensive places containing a high proportion of soy and corn, which aligns with the fact that farmers understand that cicadas damage woody plants and not herbaceous row crops.

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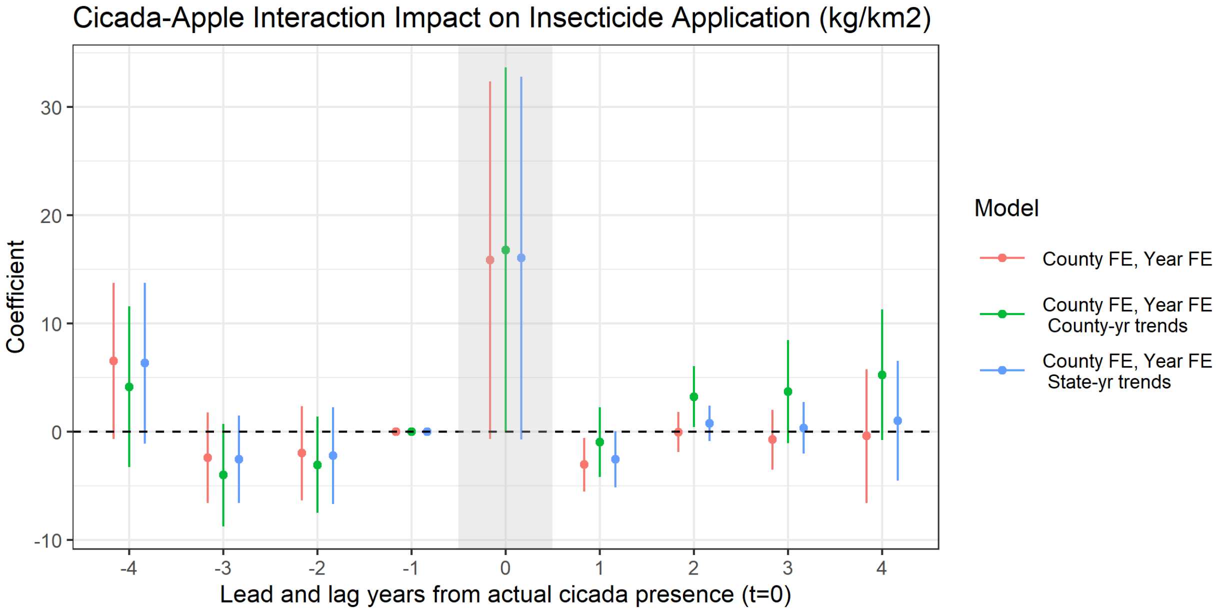
[8] Leads and lags are limited to four years to reduce distortion of the event study from the fact that many counties receive more than one cicada brood, as seen in the national distribution map in Figure 1 and in Virginia specifically in Figure 2. The sample is limited cicada-endemic counties (42% of full sample) in order to assign treatment event time.

Figure 4



Notes: Event study based on Model (4) from Table 1 with the inclusion of cicada leads and lags. Sample limited to counties with cicada events and to observations with no leading or lagging cicada events during the sample time period are excluded to balance the panel. Models allow for different fixed effects and geographic trends. Standard errors clustered at the state level. Solid lines show 95% confidence intervals. Normalized to the year before cicada emergence.

6.2 Cicadas and Infant Mortality

To assess potential causal channels, I run the model specified in Equation 2. Given the link established between cicada emergence and insecticide use, one would expect a relationship between cicada emergence and infant mortality in tree crop-intensive areas if insecticides indeed have an impact on health. In contrast to the regressions using insecticide data, this analysis allows for the use of a much longer time series. ICPSR starts tracking resident infant mortality at the county level in 1941, while USGS pesticide data is only available from 1992 to 2016. I restrict the sample to after 1950, which encompasses the post-WWII era when farmers started using synthetic pesticides at a large scale.

Table 2 regresses next-year infant mortality on cicada emergence.[9] Model (1) of shows no significant impact of cicada emergence, in itself, on birth outcomes. Model (2) interacts cicada emergence with county apple acreage. Model (3) interacts cicada emergence with a dummy for high apple production (i.e., top decile counties). Models (4) and (5) use county

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[9] In the main specification, counties with less than five births in a given year are dropped to minimize the inclusion of unreasonably high infant mortality rates due to small sample size (i.e., if there are two births in a county, and one death, IMR is 500 compared to the current US average of six). Results are robust to varying the birth cutoff threshold. Table A3 shows similar results weighting the regression by the number of county births in order to include observations with less than five births.

area normalized apple production in bushels in 1964 and 1997, respectively, the years in which apple data in the agricultural census is the most extensive. All standard errors are clustered at the state-level, which is the administrative level at which birth records are collected and aggregated. General results hold if standard errors are clustered at other levels.

Table 2: Cicada Impact on Infant Mortality, 1950-2016

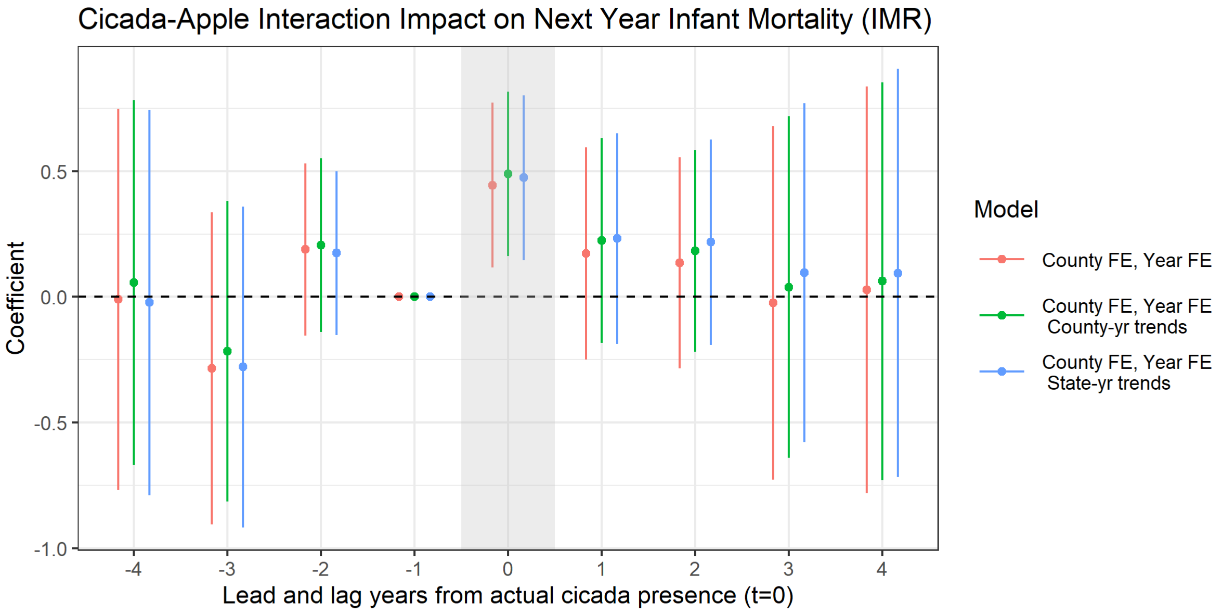
	Dependent variable:				
	Next-Year Infant Mortality Rate (IMR)				
	(1)	(2)	(3)	(4)	(5)
Cicada	0.07	0.05	0.03	0.05	0.06
	(0.12)	(0.13)	(0.13)	(0.13)	(0.13)
Cicada:Acres		0.31^{***}			
		(0.10)			
Cicada:Bushels(decile)			0.28^{*}		
			(0.16)		
Cicada:Bushels 1964				0.54^{***}	
				(0.15)	
Cicada:Bushels 1997					0.42^{**}
					(0.17)
County FE	X	X	X	X	X
Year FE	X	X	X	X	X
State-Yr Trend	X	X	X	X	X
Observations	144,083	144,083	144,083	144,083	144,083
R^2	0.52	0.52	0.52	0.52	0.52

Notes: Linear regression. Dependent variable is next-year infant mortality rate (deaths per 1000 live births). Excludes county-year observations with less than 5 births. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Covariates include apple acreage, a dummy for the top decile apple production, and apple production in bushels in 1997 and 1964. Time series from 1950 to 2016. State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level. *p<0.1; **p<0.05; ***p<0.01

For interpretation, top decile apple counties see an increase in next-year infant mortality of 0.3 deaths per thousand. In terms of apple production levels, a one standard deviation in production is equal to 167 bushels km^{-2} in 1964 and 225 bushels/km^{-2} in 1997 on a cross-county basis. Units are in 1,000s of bushels. Therefore, a one standard deviation increase in county apple production, when accompanied by cicada emergence, is associated with an increase in infant mortality of about 0.1 deaths per thousand.

For robustness, Appendix Table A4 restricts the sample to the period from 1950 to 1988, allowing for a more balanced panel. As discussed in the Data section, the ICPSR infant mortality data are limited after 1988 to counties with populations over 100,000, while the infant mortality rates derived from restricted NCHS Infant Linked Birth/Death files are not available until 1995. Additionally, Appendix Table A5 shows results using other compilations of county-level infant mortality rates, including ones derived from restricted NCHS data, ICPSR, and IPUMS. The resulting coefficients are all of similar magnitude.

Figure 5



Notes: Event study with level of apple production based on Model (5) of Table 2, but including cicada leads and lags. Sample limited to counties with cicada events and to observations with no leading or lagging cicada events during the sample time period are excluded to balance the panel. Models allow for different fixed effects and geographic trends. Standard errors clustered at the state level. Solid lines show 95% confidence intervals. Normalized to the year before cicada emergence.

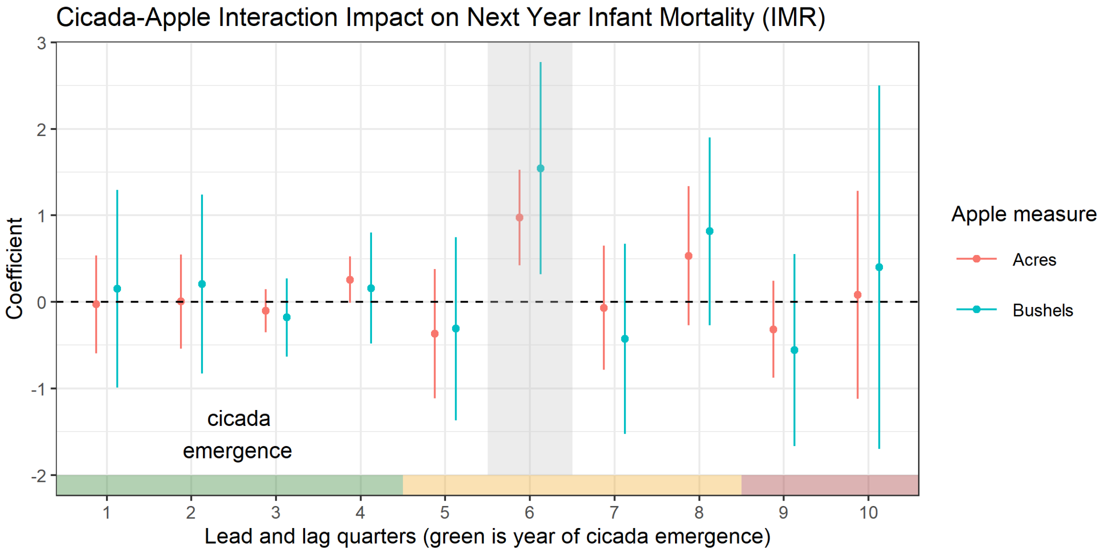
Figure 5 plots the cicada-apple interaction coefficients from Model (5) of Table 2 as an event study with the inclusion of cicada emergence leads and lags. Infant mortality increases in the year following cicada emergence. Showing a similar pattern, Appendix Figure A1 plots the event study coefficients using county-level apple acreage as an alternate measure of apple intensity.

These results align with the second prediction of the Timing Framework and the coefficient plot in Figure 4, which shows an increase in pesticide use by tree growers in the year of cicada emergence. The increase in next-year infant mortality would follow from insecticide exposure among first trimester pregnancies during cicada emergence. Effect timing is discussed in the next section.

6.3 Timing and Sub-annual Impacts

Figure 6 shows the impact on infant mortality by quarter. This analysis is limited to the period from 1995 to 2016 when Linked Infant Birth/Death Files are available that allow for sub-annual aggregation. Model (4) of Table A5 shows an overall positive but less precise effect for this sub-period, but one in line with the estimates from the longer-duration analyses in Models (1)-(3), and as shown in Table 2 and Figure 5. Looking sub-annually, Figure 6 shows that the effect is concentrated in the second quarter (April to June) of the year following cicada emergence.

Figure 6



Notes: Output similar to Model (5) of Table 2 but with quarterly IMR as outcome variable estimated using separate regressions. Time series limited to 1995 to 2016. Apple intensity interaction measure is apple crop acreage or production in bushels in 1997. Green area is the year of cicada emergence, yellow is the next year, and red is the third year. Gray area is the second quarter in the year following cicada emergence. State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level. Solid lines show 95% confidence intervals.

Cicadas arrive in the late spring and insecticide spraying starts in June to control the adult population from laying their eggs in tree branches as well as throughout the summer to prevent cicada nymphs from establishing in the soil in order to mitigate detrimental growth effects (Hamilton 1961; Lloyd and White 1987). Summer conceptions occurring in June, July, or August, for example, would entail a first trimester coinciding with a period of high potential for insecticide exposure. Assuming full-term gestation, such births would occur the following March, April, or May. Our finding of elevated infant mortality in the second quarter (April to June) would align with this cohort considering that two-thirds of infant deaths occur within the neonatal phase (i.e., first 28 days), and much of the remaining occur within the first three months of life (Ely and Hoyert 2018).

These sub-annual results support the predictions of the Timing Framework and are in line with known cicada behavior and orchard management practices. Going forward, we will focus on annual impacts given the longer time series and the lack of sub-annual data for most other historical variables.

6.4 Brood analysis

The next section assesses impacts by individual cicada brood. This specification involves a difference-in-difference where the same counties are treated every 17 years. Neighboring counties that do not receive that cicada brood are used as a control. Table 3 shows the results for the largest of the five 17 year broods. Excluded are the two primary 13-year southern broods which are located in hotter areas with very little apple production, as visualized in Figure 3.[10]

Table 3: Cicada Impact on Infant Mortality, 1950-2016

	Dependent variable:					
	Next-Year Infant Mortality Rate (IMR)					
	All	Brood 2	Brood 5	Brood 10	Brood 13	Brood 14
	(1)	(2)	(3)	(4)	(5)	(6)
Cicada	0.06	0.19	0.10	0.19	−0.12	0.13
	(0.13)	(0.26)	(0.20)	(0.17)	(0.16)	(0.16)
Cicada:Bushels	0.42^{**}	0.57^{***}	0.69^{***}	0.42^{**}	0.54^{**}	0.45^{**}
	(0.17)	(0.14)	(0.17)	(0.16)	(0.19)	(0.18)
County controls	All	<100km	<100km	<100km	<100km	<100km
County FE	X	X	X	X	X	X
Year FE	X	X	X	X	X	X
State-Yr Trend	X	X	X	X	X	X
Observations	144,083	16,816	11,256	38,094	13,375	36,811
R^2	0.52	0.66	0.60	0.61	0.58	0.60

Notes: Linear regression. Dependent variable is next-year infant mortality rate (deaths per 1000 live births). Excludes county-year observations with less than 5 births. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Bushels is apple production in 1997 per county land area. State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level.

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[10] 13-year broods may also have different physiological mechanisms governing their development (White and Lloyd 1975).

For comparison, Model (1) pools all the broods as done in our primary specification in Model (5) of Table 2. The remaining columns show a consistently positive effect for each brood in which apple-intensive counties experience higher infant mortality in the year following a cicada emergence. Figure 7 plots the leading and lagging coefficients as done in Figure 5 but includes neighboring counties as controls. Each brood involves a different treatment year and different geographic footprint as seen in the maps. For example, Brood X, the Great Eastern Brood, emerges in three distinct pockets of the US in the summer of 2021.

For most of the broods, there is a clear increase in infant mortality the year following a cicada event, which sometimes seems to extend into subsequent years.[11] The noisier coefficients may be attributable to the smaller sample size, different regional pest management practices, and the fact that some counties are treated twice by different broods. Overall, however, brood-level results provide increased confidence that the paper's main finding is not driven by a particular brood, location, or set of treatment years.

6.5 Interpretation of Infant Mortality Impact

Infant mortality decreased by 80% over the course of this study, from a national average of 30 deaths per thousand in 1950 to the current average of 6, so the interpretation of coefficient magnitudes depends on the time period. For the longer timeframe from 1950 to 2016 the average infant mortality rate is 16, for the balanced panel from 1950 to 1988 the average is 21, and for the period when pesticide data is available from 1992 to 2016, the average is 7. This warrants some caution when interpreting and comparing coefficient magnitudes.

Table 1 shows that among top decile apple counties, insecticide use increases during a cicada emergence by about 6 kg km^{-2}. These same treated counties see an increase in next-year infant mortality by 0.28 to 0.47 deaths per thousand, based on Table 2 and the balanced panel in Table A4, respectively. This equates to about a 2% increase over the sample average infant mortality rates. Therefore, one additional kilogram of insecticide use per km^2 can be equated to an increase in the infant mortality rate by one-third of one percent. For context, mean insecticide use across counties and over time is 10 kg/km^2, so one more kilogram represents an approximate 10% increase over the sample mean.

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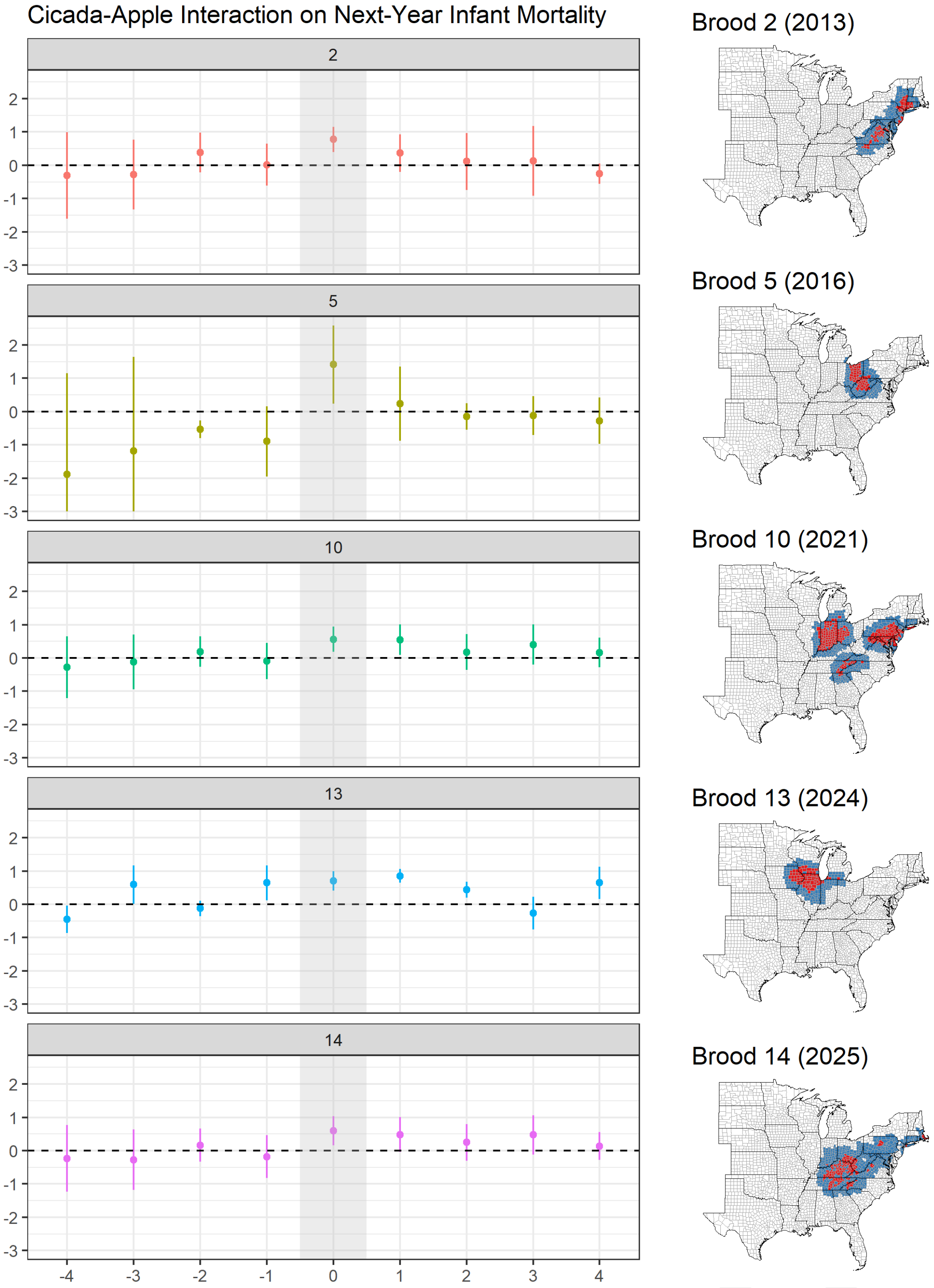
[11] An extended effect could potentially reflect the fact that insecticide treatments are known to occur in the year after to control nymph establishment, or a delayed pesticide exposure from differential leaching rates into water, or the fact that infant mortality includes deaths that occur up to 12 months following birth.

Figure 7



Notes: Event study by cicada brood based on Table 3, but including cicada leads and lags. Sample includes counties receiving the given brood (red), as well as those within 100km of treatment area (blue). State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level. Solid lines show 95% confidence intervals. Coefficients relative to omitted years outside of four years plus/minus a cicada event.

Linking these results to a specific type of insecticide is challenging because this analysis uses an aggregate measure of insecticides that sums up 160 insecticide constituents by weight. Further, there is little evidence that orchard growers and farm managers consistently choose one type of insecticide over others for cicada control, especially given that pest management practices vary greatly across the US and over time. Finally, different combinations of insecticide types are used depending on the cicada's stage of development (e.g., pyrethroid 'knock down' insecticides for live adults, carbamates for soaking soil to control nymphs).

6.6 Other Infant Health Outcomes

Next I assess infant health impacts beyond infant mortality. Using NCHS Natality Data files from 1968 to 2016, I compute three binary measures of infant health. The first is Apgar score (indicator for a score below 7 out of 10), a quick assessment of infant newborn health based on appearance, pulse, grimace, activity, and respiration (hence acronym, Apgar). The second is premature birth (indicator if gestation period is under 37 weeks, the clinical threshold for premature birth). The last is birthweight (indicator if under 2500 grams, the clinical threshold for low birthweight).

Table 4 shows regression results using the model specified in Equation 2. The cicada-apple interactions have a small but positive impact on the probability of adverse birth outcomes. The relationship is the clearest for premature birth, followed by low Apgar score. The birthweight coefficient is positive but not significant. These results are consistent with the public health literature on fetal exposure and pesticide impacts (Ling et al. 2018), as well as our infant mortality findings given that low birthweight and premature birth is highly correlated with neonatal infant mortality (Ely and Hoyert 2018).

6.7 Education and Long-Term Impacts

I now look at the potential impact on educational achievement via elementary school cohorts exposed to a cicada emergence during conception or during the first year of life. Table A6 shows the impact on county-level scores in math and English language arts using Stanford Education Data Archives NAEP-equivalent test scores (Reardon et al. 2018). County scores are pooled by cicada exposure cohorts, i.e., averaging the scores of third graders 9 years after a cicada event, fourth graders 10 years after, and fifth graders 11 years after.

Table 4: Cicada-Apple Interaction Impact on Other Birth Outcomes

	Next-year birth outcome					
	Prob. Low Apgar		Prob. Premature		Prob. Low Birthweight	
	(1)	(2)	(3)	(4)	(5)	(6)
Cicada	−0.045	−0.041	−0.068	−0.065	−0.080	−0.074
	(0.053)	(0.053)	(0.082)	(0.082)	(0.059)	(0.058)
Cicada:Acres	0.135**		0.143***		0.161	
	(0.056)		(0.036)		(0.109)	
Cicada:Bushels		0.157*		0.184***		0.133
		(0.087)		(0.054)		(0.150)
County FE	X	X	X	X	X	X
Year FE	X	X	X	X	X	X
State-Yr Trend	X	X	X	X	X	X
Observations	83,426	83,426	109,387	109,387	112,165	112,165
R^2	0.102	0.102	0.205	0.205	0.261	0.261

Notes: Linear regression. Dependent variables are various next-year birth outcomes averaged at the county level: Apgar low is a dummy for a score below 7 out of 10 (time series from 1978 to 2016); Premature is a dummy if gestation is under 37 weeks (time series from 1968 to 2016); Birthweight low is a dummy if under 2500 grams (time series from 1968 to 2016). Each dummy is multiplied by 100. Excludes county-year observations with less than 5 births. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Covariates include apple acreage and apple production in bushels in 1997. State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level. *p<0.1; **p<0.05; ***p<0.01

Figure 8

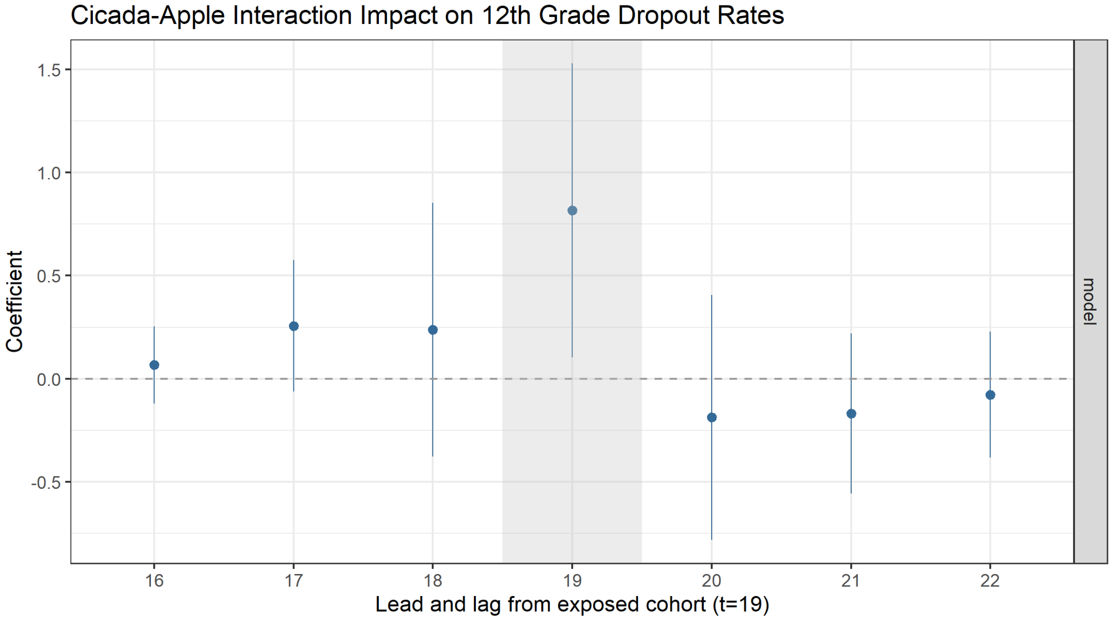
Notes: Event study based on Models (2) and (5) in Table A6 using NAEP-equivalent Stanford Education Data Archive data. Scores averages by cicada exposure cohort: 3rd graders 9 years after cicada exposure, 4th graders 10 years after, and 5th graders 11 years after. Apple intensity measure is top decile of apple production. Solid lines show 95% confidence intervals.

Figure 8 plots the impact with the inclusion of year leads and lags. There is a decline in average test scores of 1 to 1.3 NAEP-equivalent points among exposed cohorts. Each successive grade level NAEP score is, on average, 10 points higher, so this coefficient can be crudely interpreted as a reduction of 10-13% of one grade-level's worth of learning.

Next I analyze even longer-term impacts: whether cohorts conceived during a cicada emergence in tree crop-intensive counties experience a change in educational attainment. Using NCES data, I calculate the average dropout rate across school districts at a county-year level from 1991 to 2009. Table A7 shows the results of regressing the twelfth grade dropout rate on an indicator of whether there was a cicada event 19 years prior, which is interacted with the various apple intensity measures. Figure 9 plots the interaction coefficients using long-term cicada lags ranging from 16 years after emergence to 22 years. The dropout rate increases most at the 19-year point among exposed cohorts conceived during a cicada exposure, which is the time when these students would most likely be in the twelfth grade. The coefficients for the 16 to 18 year lags are also positive but of a smaller magnitude, implying that there may be impacts on exposed infants and toddlers.

The median twelfth grade dropout rate during this period is four per hundred students,

Figure 9



Notes: Event study based on models in Table A7. 12th grade dropout rates averaged across school districts at a county-year level from 1991-2009. Bushels production by county. Solid lines show 95% confidence intervals.

and the standard deviation in apple bushel production in 1997 is 0.225 thousand bushels km^{-2} (225 bushels). Therefore, in the event of a cicada emergence, counties with one standard deviation higher apple intensity see an increase in the future dropout rate by 0.18 per hundred students (0.225 x 0.80, which is the coefficient from Model (3) of Figure 9), or about a 5% increase. The same results, however, are not found when using a dummy for top apple production decile instead of production intensity.

It is important to note that the composition of counties over time is unknown. Since many people move in and out of counties over the course of two decades, it is not possible to know if those conceived during a cicada emergence were the same individuals in the county taking the elementary school tests and attending high school. However, I later test the relationship between cicadas and migration in Table A9 and find no evidence that people are migrating as an avoidance response. While caution is warranted in interpreting these results, these findings generally align with Rauh et al. 2012 who find that insecticides have long-term cognitive impacts that affect life outcomes beyond just infant health.

7 Robustness Checks

There are certain factors that could undermine the cicada-infant mortality story. Plausible candidates need to affect tree crop-intensive counties in the year following cicada emergence in ways that are different than those same counties in non-cicada years, as well as other tree crop-intensive counties in that same year that did not experience a cicada emergence.

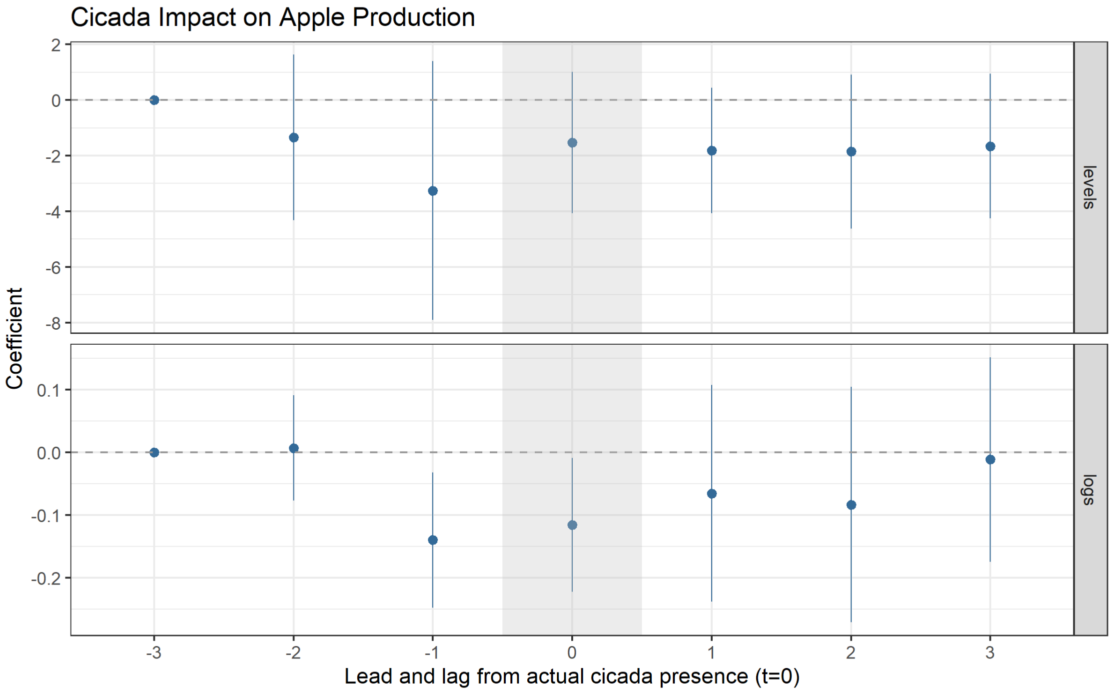
7.1 Yields and income

One candidate is agricultural yields. If cicadas decimate apple production, for example, there could be a health impact via an economic channel. Our main dataset comes from the agricultural census which is collected approximately every five years and thus does not allow for testing annual shocks. USDA does, however, track annual apple production for a subset of 170 counties in the states of Virginia, South Carolina, Kansas, Pennsylvania, and New Jersey from 1972 to 2012. Using this limited data, I regress county-level apple production on leads and lags of cicada emergence. Figure 10 plots the coefficients, with level of production on the top panel and log production on the bottom panel.

While there is no significant relationship with level of production, the log values show a decrease in apple production in the year before and the year of cicada emergence. A weaker but non-significant effect seems to persist afterward. Nymphs feed strongly on roots leading up to emergence as well as in the years that follow during their establishment. The timing of this yield impact aligns with the third prediction of the Timing Framework and partly justifies why orchard owners apply insecticides. It also aligns with the agronomic and ecological literature showing that cicadas reduce tree growth, with feeding nymphs being a major main culprit (Karban 1982). This negative yield impact, however, is less than the 30%-plus reduction in tree growth observed in natural settings in the absence of insecticides.

There are two main reasons that this economic channel is unlikely to undermine the infant mortality relationship. First, yield declines occur in the year prior and the year of a cicada emergence, but the infant mortality impact occurs in the year afterward. If the negative yield shock was driving the health effect, then we would expect an increase in infant mortality in the year of cicada emergen—which is not observed. Second, tree crops comprise a very small portion of the economic value of most counties. For example, Wayne County, NY, the largest apple producer in the eastern half of the US, has a county GDP in 2012

Figure 10



Notes: Event study of cicada impact on apple production. Dependent variable is county-level apple production in millions of bushels. Upper panel is levels, lower panel is log values. Annual time series is from 1972 to 2011 for select states with annual production data. Observations with no leading or lagging cicada events during the sample time period are excluded to balance the panel. State-level annual time trends and county and year fixed effect dummies included. Solid lines show 95% confidence intervals. Normalized to three years before cicada emergence.

of $3 billion according to the Bureau of Labor Statistics. The combined value of all fruit production is $79 million according to USDA NASS, or just 2.5% of GDP. Taken together, it seems unlikely that a yield-based economic channel is the main driver of observed health impacts, especially ones that are averaged over an entire county.

To more formally test the income channel in agricultural settings, I regress in Table A8 measures of county-level farm income from the US Bureau of Economic Analysis spanning 1969 to 2016 on cicada emergence and the apple intensity interaction term. While there appears to be a weak negative relationship between farm income and cicadas in general, it does not appear that cicada emergence negatively affects economic outcomes in apple intensive counties.

7.2 Migration

One may be concerned that people migrate over the long term to avoid the negative health impacts in apple intensive areas. This is unlikely given that there has been no past research documenting the cicada-pesticide-health link. Nevertheless, I test this in Table A9 by running a cross-sectional regression of county-level migration rates from 1960 to 1990 on a dummy of whether cicadas are endemic to a county, interacted with a dummy for top decile apple producing county in 1964. Note that positive values represent net migration into a county. The average decadal rate from 1960 to 1990 was 2.3% and there is no evidence of out-migration or lower in-migration from apple intensive cicada counties. This holds both across states and within states, and using either net migration rates or absolute net migration.

7.3 Composition and Births

There may be concerns that the composition of mothers somehow changes. In other words, maybe the mothers in tree crop-intensive counties who give birth in the year following cicada emergence are somehow different in ways that could explain some of the variation in health outcomes. Table A10 is a balance table of maternal characteristics using NCHS natality data comparing those giving birth in the year following a cicada emergence versus other years. There is no meaningful difference in the mothers' average education level, racial makeup, weight gain, age, or cigarette consumption. Further, no evidence of migration was found, which could also change maternal composition.

Another factor that could complicate the cicada-infant mortality story is if cicadas alters behavior in ways that affect birth outcomes outside of the insecticide channel (e.g., if people engage in more or less risky behavior). A cicada's life is short, generally lasting only four to five weeks, so it seems unlikely that their emergence would *in themselves* alter average outcomes at the county level over the course of the entire following year. Further, one would have to believe that people in counties with a high proportion of tree crops behave differently in response to cicadas than people in places with fewer tree crops.

Table A11 shows the results of a regression of next-year birth rate on cicada emergence and apple intensity. Birth rate is computed with ICPSR natality data as total annual births per thousand people (crude) and thousand women of child-bearing age (ages 15-44). The apple-cicada interaction coefficients are close to zero and insignificant for the most part. Behavior, as it relates to number of births, is not different in apple-intensive 'treated' counties relative to untreated counties.

However, overall births seem to increase in the year following a cicada emergence. This interesting finding holds after controlling for various combinations of fixed effects and time trends.[12] I calculate a back-of-the-envelope estimate using the crude birth rate impact of 0.11 per thousand and the fact that the population averaged 87 million between 1950 to 2016 in the counties with a cicada presence. Since cicadas emerge every 16 years on average (3 broods have 13-year cycles, 12 broods have 17-year cycles), this means that an additional 600 people could be born in the US each year, on average, because of cicadas.

This modest but strange result could reflect a dynamic similar to that found in Evans et al. 2010 and Burlando 2014 where birth rates increase after hurricanes (when people are forced to stay inside) or power outages. Or perhaps there is a physiological effect that science has yet to uncover, one that occurs when humans witness millions of frenzied creatures emerging from over a decade underground only to live for a few weeks, just long enough to sing a shrill song, mate, and die.

8 Conclusions

Insecticides are essential to agricultural productivity, but they also pose risks to the population that are difficult to measure. In this paper, I use the mass emergence of periodical cicadas in 13 and 17-year cycles to identify the impact of insecticides on human health. I find an increase in insecticide use in counties experiencing a cicada emergence that is limited to areas with a large amount of woody crops (i.e., apple trees), as opposed to herbaceous row crops like corn and soy. This is because cicadas only damage woody plants: nymphs feed on tree roots and adult cicadas lay their eggs in small branches.

I exploit this variation to compare treated counties (i.e., counties with high levels of apple production that experience a cicada emergence) to untreated counties. In the treated counties, there is a jump in next-year infant mortality by 0.3 deaths per thousand births. Sub-annual impacts align with the timing and patterns of insecticide usage by farmers. Treated counties also see adverse infant health outcomes including an increase in premature births and low Apgar score. There is also evidence of long-term cohort effects in the form of lower elementary school test scores and higher high school dropout rates.

It may be surprising that tree crop acreage, given its small footprint, can produce effects that are measurable at the county level. The largest apple producer in our sample, which

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[12] In the main specification, I include state-year fixed effects to account for anomalous state-level sampling processes related to birth counts at the year level.

spans the cicada endemic states of the Eastern US, is Wayne County, NY. It has about 20,000 acres of apples trees, which is less than 5% of its land area. This is a small fraction compared to counties that intensively grow soy and corn, where row crops comprise a majority of the land. Further, apples account for only 1.4% of pesticide use in the US, while crops like corn, soy, cotton, potatoes, sorghum, and wheat account for 86% (Fernandez-Cornejo et al. 2014). Together, this supports the idea that externalities from agriculture may extend beyond farm-intensive areas, and that moderate levels of pesticides, not just extreme exposure, can have negative long-term impacts.

Overall this paper contributes to the environmental and health economics literature on the impacts of agricultural inputs. While acknowledging the large benefits of pesticides to agricultural productivity, the findings warrant caution in the application of insecticides. This paper also provides a model of how ecological phenomena like periodical cicadas may be used to generate quasi-random variation to help answer important economic and public health questions—showing that humans remain beholden to the ancient cicadian rhythm.

9 Appendix

9.1 Pesticide response to cicadas

Table A1: Falsification by Pesticide Type (kg/km2)

	Dependent variable:		
	Insecticide (1)	Herbicide (2)	Fungicide (3)
Cicada	0.29	0.65	-0.19
	(0.94)	(1.07)	(0.36)
Cicada:Bushels	5.67^{*}	-2.03	0.97
	(3.25)	(1.93)	(1.61)
County FE	X	X	X
Year FE	X	X	X
State-Yr Trend	X	X	X
Observations	61,133	61,133	61,133
R^2	0.42	0.84	0.54

Notes: Linear regression. Dependent variable is county-level pesticide use divided by county land area. Pesticide use is the combined sum of the USGS EPest-high values for constituents with insecticidal, herbicidal, and/or fungicidal properties. Many pesticides had multiple properties. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Bushels is a dummy for the top decile counties in apple production in 1997. Time series limited to USGS pesticide data, 1992 to 2016. State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level. *p<0.1; **p<0.05; ***p<0.01

Table A2: Falsification by Crop (kg/km2)

	Dependent variable:		
	Insecticide use (kg/km2)		
	(1)	(2)	(3)
Cicada	0.29	1.34	0.52
	(0.94)	(1.50)	(1.08)
Cicada:Bushels	5.67*		5.54*
	(3.25)		(3.20)
Cicada:Corn Soy		−2.18	−1.72
		(1.44)	(1.18)
County FE	X	X	X
Year FE	X	X	X
State-Yr Trend	X	X	X
Observations	61,133	61,133	61,133
R^2	0.42	0.42	0.42

Notes: Linear regression. Dependent variable is county-level insecticide use, which is the combined sum of the USGS EPest-high values with insecticidal properties divided by county land area. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Bushels is a dummy for the top decile counties in apple production in 1997. Corn Soy is a dummy for the top decile counties in the combined corn and soy production by county area, averaged during the sample period. Time series limited to USGS pesticide data, 1992 to 2016. State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level. *p<0.1; **p<0.05; ***p<0.01

9.2 Impacts on infant mortality

Table A3: Cicada Impact on Infant Mortality, 1950-2016, Weighted by Births

	Dependent variable:				
	Next-Year Infant Mortality Rate (IMR)				
	(1)	(2)	(3)	(4)	(5)
Cicada	0.09	0.07	0.05	0.06	0.07
	(0.12)	(0.12)	(0.13)	(0.12)	(0.12)
Cicada:Acres		0.34^{***}			
		(0.11)			
Cicada:Bushels(decile)			0.25		
			(0.16)		
Cicada:Bushels 1964				0.61^{***}	
				(0.17)	
Cicada:Bushels 1997					0.45^{**}
					(0.18)
County FE	X	X	X	X	X
Year FE	X	X	X	X	X
State-Yr Trend	X	X	X	X	X
Observations	152,107	152,107	152,107	152,107	152,107
R^2	0.49	0.49	0.49	0.49	0.49

Notes: Linear regression. Dependent variable is next-year infant mortality rate (deaths per 1000 live births). Regression weighted by the number of county births. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Covariates include apple acreage, a dummy for the top decile apple production, and apple production in bushels in 1997 and 1964. Time series from 1950 to 2016. State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level.

Table A4: Cicada Impact on Infant Mortality, 1950-1988

	Dependent variable:				
	Next-Year Infant Mortality Rate (IMR)				
	(1)	(2)	(3)	(4)	(5)
Cicada	0.12	0.10	0.05	0.09	0.10
	(0.16)	(0.17)	(0.17)	(0.17)	(0.17)
Cicada:Acres		0.38^{**}			
		(0.17)			
Cicada:Bushels(decile)			0.47^{**}		
			(0.20)		
Cicada:Bushels 1964				0.69^{**}	
				(0.32)	
Cicada:Bushels 1997					0.51^{**}
					(0.23)
County FE	X	X	X	X	X
Year FE	X	X	X	X	X
State-Yr Trend	X	X	X	X	X
Observations	95,832	95,832	95,832	95,832	95,832
R^2	0.43	0.43	0.43	0.43	0.43

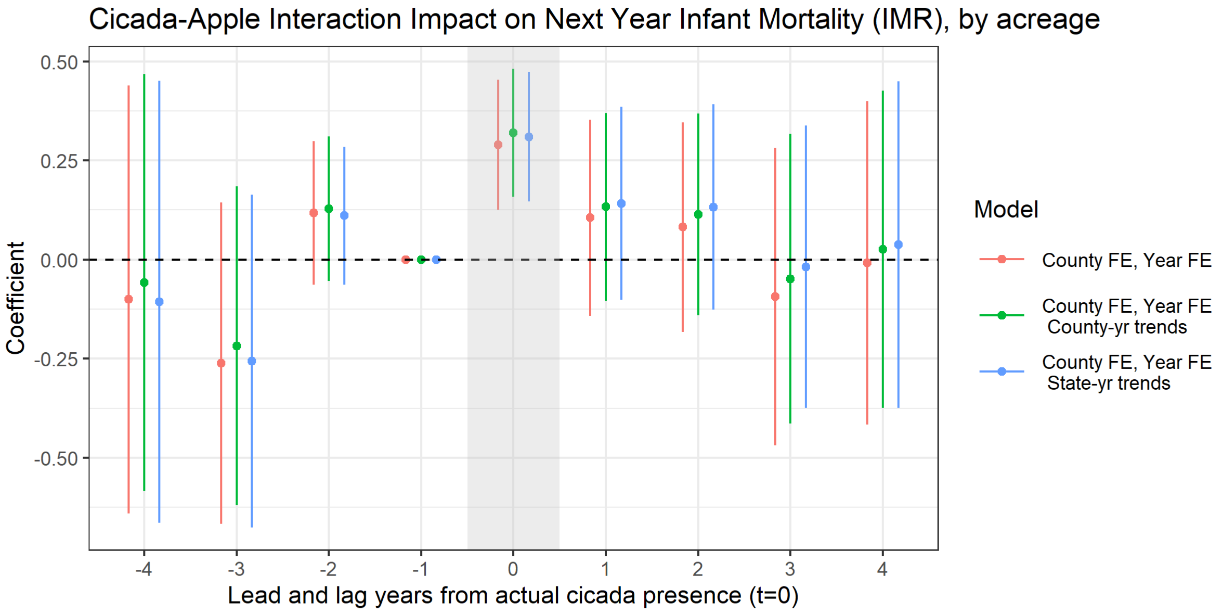
Notes: Linear regression. Dependent variable is next-year infant mortality rate (deaths per 1000 live births). Excludes county-year observations with less than 5 births. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Covariates include apple acreage, a dummy for the top decile apple production, and apple production in bushels in 1997 and 1964. Time series limited to 1950-1988, when infant mortality data is available for all counties. State-level annual time trends and county and state fixed effect dummies included. Standard errors clustered at the state level. *p<0.1; **p<0.05; ***p<0.01

Table A5: Cicada Impact on Infant Mortality, 1950-2016

	Dependent variable:			
	Next-Year Infant Mortality Rate (IMR)			
	(1)	(2)	(3)	(4)
Cicada	0.06	0.03	0.11	−0.16
	(0.13)	(0.13)	(0.15)	(0.16)
Cicada:Bushels	0.42**	0.41**	0.45**	0.39
	(0.17)	(0.16)	(0.22)	(0.23)
IMR measure	Baseline	Baseline + IPUMS	ICPSR	NCHS Linked
County FE	X	X	X	X
Year FE	X	X	X	X
State-Yr Trend	X	X	X	X
Observations	144,083	154,726	105,719	46,239
R^2	0.52	0.52	0.48	0.14

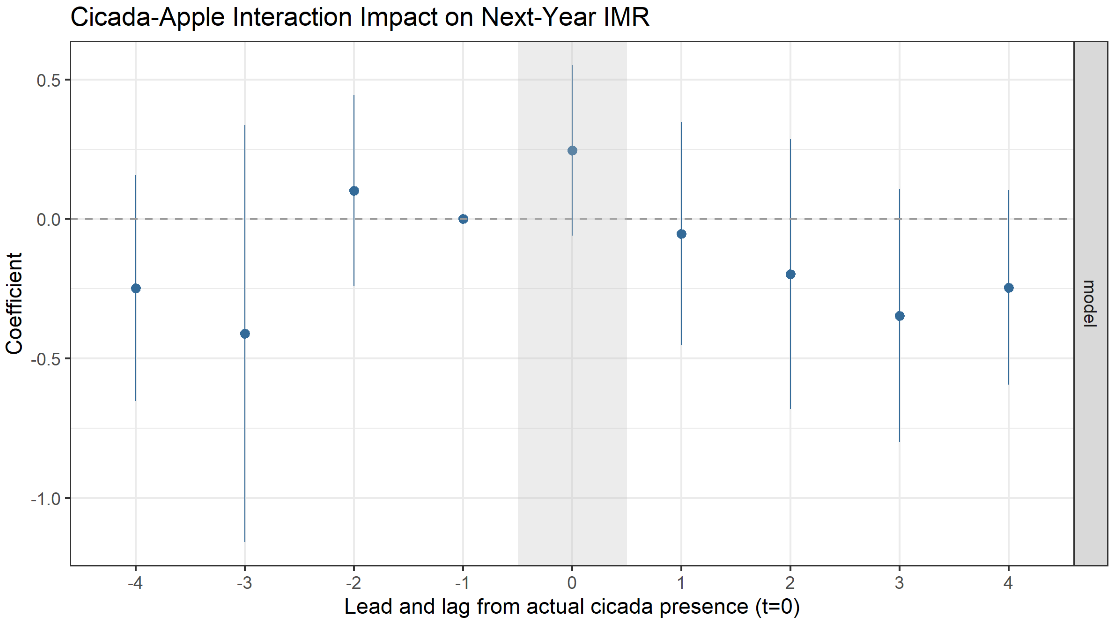
Notes: Linear regression. Dependent variable is next-year infant mortality rate (deaths per 1000 live births). Excludes county-year observations with less than 5 births. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Bushels is apple production in 1997 per county land area. State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level.

Figure A1



Notes: Event study with level of apple acreage based on Model (2) of Table 2, but including cicada leads and lags. Sample only includes counties with cicada events and observations with no leading or lagging cicada events during the sample time period are excluded to balance the panel. Models allow for different fixed effects and geographic trends. Standard errors clustered at the state level. Solid lines show 95% confidence intervals. Normalized to the year before cicada emergence.

Figure A2



Notes: Event study with top decile apple producing counties, but including cicada leads and lags. Observations with no leading or lagging cicada events during the sample time period are excluded to balance the panel. Solid lines show 95% confidence intervals. Normalized to the year before cicada emergence.

9.3 Educational impacts

Table A6: Cicada-Apple Interaction Impact on Elementary School Test Scores

	NAEP-equivalent average test scores					
		Math			English	
	(1)	(2)	(3)	(4)	(5)	(6)
Cicada	0.20	0.33	0.21	0.02	0.18	0.02
	(0.23)	(0.26)	(0.22)	(0.24)	(0.27)	(0.24)
Cicada:Acres	-0.51^{***}			-0.31		
	(0.10)			(0.20)		
Cicada:Bushels(decile)		-1.15^{**}			-1.27^{**}	
		(0.54)			(0.56)	
Cicada:Bushels			-1.15^{***}			-0.72^{*}
			(0.38)			(0.40)
County FE	X	X	X	X	X	X
Year FE	X	X	X	X	X	X
State-Yr Trend	X	X	X	X	X	X
Observations	10,866	10,866	10,866	11,557	11,557	11,557
R^2	0.91	0.91	0.91	0.90	0.90	0.90

Notes: Linear regression. Dependent variable is county-level averages of Stanford Education Data Archive's NAEP-equivalent test scores averaged for all elementary school students (grades 3-5) in the same 'cicada exposure cohort'. For example, scores include the average of 3rd graders 9 years after cicada exposure, 4th graders 10 years after cicada exposure, and 5th graders 11 years after cicada exposure. Annual scores available from 2009 to 2015. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Covariates include apple acreage, a dummy for the top decile apple production, and apple production in bushels in 1997. State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level.

Table A7: Cicada-Apple Interaction Impact on Dropout Rates

	Dependent variable:		
	Dropout rate per 100 students		
	(1)	(2)	(3)
Cicada	-0.10	-0.09	-0.10
	(0.13)	(0.15)	(0.13)
Cicada:Acres	0.36^{*}		
	(0.19)		
Cicada:Bushels(decile)		0.04	
		(0.25)	
Cicada:Bushels			0.80^{**}
			(0.33)
County FE	X	X	X
Year FE	X	X	X
State-Yr Trend	X	X	X
Observations	23,051	23,051	23,051
R^2	0.22	0.22	0.22

Notes: Linear regression. Dependent variable is 12th grade dropout rates. Dropout rates are averaged across school districts at a county-year level and available from NCES from 1991 to 2009. Cicada lags are a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year (i.e., cicada_plus19 denotes a cicada occurrence 19 years before the year of the dropout observation). Covariates include apple acreage, a dummy for the top decile apple production, and apple production in bushels in 1997. State-level annual time trends and county and year fixed effect dummies included. Standard errors clustered at the state level.

9.4 Robustness

Table A8: Cicada Impact on Farm Income per Capita

	Dependent variable:					
	Farm Income ($1,000s)			Farm Income (Log)		
	(1)	(2)	(3)	(4)	(5)	(6)
Cicada	-1.032^{*}	-0.899	-0.903	-0.057^{*}	-0.055^{*}	-0.055^{*}
	(0.608)	(0.597)	(0.598)	(0.032)	(0.030)	(0.030)
Cicada:Acres	1.058			0.028		
	(1.090)			(0.030)		
Cicada:Bushels(Decile)		0.428			0.057	
		(1.029)			(0.051)	
Cicada:Bushels			0.278			0.030
			(0.508)			(0.025)
County FE	X	X	X	X	X	X
Year FE	X	X	X	X	X	X
State-Yr Trend	X	X	X	X	X	X
Observations	118,232	118,232	118,232	105,746	105,746	105,746
R^2	0.617	0.617	0.617	0.735	0.735	0.735

Notes: Linear regression. Dependent variables are BEA county-level farm income per capita from 1969 to 2016. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Covariates include apple acreage, a dummy for the top decile apple production, and apple production in bushels in 1997. State-level annual time trends and county and year level fixed effect dummies included. Standard errors clustered at the state level. *p<0.1; **p<0.05; ***p<0.01

Table A9: Cicada Impact on Long-term Migration, 1960 to 1990

	Dependent variable:			
	Net Migration Rate		Net Migration (1,000s)	
	(1)	(2)	(3)	(4)
Cicada	0.029	0.057*	−1.704	6.869
	(0.047)	(0.028)	(5.218)	(4.399)
Cicada:Bushels(Decile)	0.046	0.012	2.178	6.124
	(0.042)	(0.031)	(7.758)	(9.463)
Constant	0.027		1.444	
	(0.044)		(4.021)	
State FE		X		
Observations	2,423	2,423	2,423	2,423
R^2	0.002	0.153	0.0001	0.044

Notes: Linear regression. County-level cross section. Dependent variable in Models (1)-(2) is long-term migration rates calculated as the sum of net migration in the four decades between 1960 and 1990 divided by the average county population during that period. Models (3)-(4) is the sum of net migration over that time in thousands of people. Cicada county is a dummy variable if cicadas are endemic to the county. Bushels(Decile) is a dummy for the top decile counties in apple production in 1964. Standard errors clustered at the state level. *p<0.1; **p<0.05; ***p<0.01

Table A10: Maternal characteristics in cicada years versus non-cicada years

Variable	Cicada.year	Non.cicada.year	t.value
Education	12.664	12.616	-0.788
Black proportion	0.071	0.074	0.664
Weight gain	30.713	30.638	-0.426
Age	26.346	26.388	0.485
Cigarettes	1.795	1.924	1.267

Notes: Notes: Analysis includes counties in the top decile of apple production averaged over 1964 and 1997 with endemic cidadas. Maternal characteristics for those giving birth one year after a cicada event.

Table A11: Cicada-Apple Interaction Impact on Birth Rates

	Dependent variable:					
	All people (Crude)			Female Age-Specific		
	(1)	(2)	(3)	(4)	(5)	(6)
Cicada	0.11^{***}	0.12^{***}	0.12^{***}	0.29	0.24	0.32
	(0.03)	(0.04)	(0.04)	(0.21)	(0.30)	(0.28)
Cicada:Bushels(Decile 1964)		-0.05			0.28	
		(0.05)			(0.60)	
Cicada:Bushels(Decile 1997)			-0.07			-0.17
			(0.06)			(0.61)
County FE	X	X	X	X	X	X
State-Year FE	X	X	X	X	X	X
Observations	142,212	142,212	142,212	142,193	142,193	142,193
R^2	0.84	0.84	0.84	0.73	0.73	0.73

Notes: Linear regression. Dependent variable is next-year birth rate. Models (1)-(3) show the crude birth rate (births per 1000 people). Models (4)-(6) show births per thousand women of child bearing age (ages 15-44). Cicada is a dummy variable taking the value of 1 if there is a cicada emergence in the county in that year. Covariates include a dummy for top decile apple production in 1964 and 1997. County and state by year fixed effect dummies included. Standard errors clustered at the state level. *p<0.1; **p<0.05; ***p<0.01

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