

# Improving Pest Management for Wild Insect Welfare



## Table of Contents

### [Introduction](#)

### [Insect Sentience](#)

[What kinds of organisms might be sentient?](#)

[How should we apply what we learn about sentience?](#)

### [Impact of an Agricultural Insecticides Intervention](#)

[Why agricultural insecticides?](#)

[How many insects are there?](#)

[Box 1: Estimating global insect abundance](#)

[How many insects are affected by insecticides?](#)

[Box 2: Estimating insect abundance on U.S. agricultural land](#)

[Box 3: Using EILs to estimate pest management impacts](#)

### [Insecticide Practices](#)

[Recent U.S. insecticides market](#)

[Figure 1: Percentage of cropland treated with insecticides per county, 2017.](#)

[Table 1: Chemical pesticide use on U.S. agricultural lands, 1997-2017.](#)

[Table 2: Select metrics of U.S. agricultural land usage, 1997-2017.](#)

[Table 3: Most popular insecticides in each U.S. market sector \(2012\).](#)

[Overview of the major insecticide modes of action](#)

[AChE inhibitors](#)

[Table 4. Most commonly used organophosphate insecticides across all market sectors.](#)

[Sodium-channel modulators](#)

[Insect growth regulators](#)

[Integrated pest management](#)

[Biological control methods](#)

[Cultural control methods](#)

[Chemical control methods](#)

### [Considerations and Conclusions](#)

[Comparing insect pest management methods](#)

[Recommendations for future research](#)

[Conclusion](#)

### [Acknowledgments](#)

### [References](#)

## Introduction

This report lays a foundation for future research into projects to improve wild insect welfare by promoting more humane insect pest management practices. I summarize recent insect sentience literature and estimate the number of insects impacted by agricultural insecticide use in the United States. I then examine the usage and modes of action of a variety of common insecticides and non-insecticidal pest management practices, highlighting knowledge gaps and suggesting directions for future inquiry.

As a companion resource to this report, I have compiled a [database of insecticidal compounds](#)<sup>1</sup>, their modes of action, and their insecticidal mechanisms. This database is under development and may be expanded to include pests targeted, brand names, and chemical fact sheets where available. I have also developed a rough [impact estimate table](#), outlining a method for using a pest control literature review to calculate the minimum number of insects affected by U.S. agricultural insecticide use.

## Insect Sentience

The expected value of an intervention to improve the welfare of wild insects will depend on the confidence we have in insects being sentient, and how intense we think their experiences are. For the purpose of this report, I define sentience as primary (or phenomenal) consciousness: the capacity to have mental experiences ([Allen & Trestman 2017](#)). I refer to positive and negative mental experiences as affective states, which typically occur in response to pleasant or aversive stimuli. So defined, sentience can occur in the absence of secondary (or access) consciousness: the ability to reflect upon or report those experiences. While other mental experiences also contribute to a sentient individual's welfare, the type of experience that is particularly relevant to the use of insecticides is pain, or an "unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage" ([IASP 2017](#)). Determining whether or not an organism is likely to feel pain is important for understanding where we should focus our welfare efforts.

### What kinds of organisms might be sentient?

If we assume that sentience is a fundamentally biological phenomenon, then it will be subject to processes such as natural selection ([Mellor 2016](#), [Dawkins 2008](#)). One theory of sentience suggests that it may confer a selective advantage to organisms whose reproductive success depends on their ability to process a constant influx of complex information from their dynamic environments, and integrate that information into a mental map, comprising the environment and themselves in relation to it ([Klein & Barron 2016a](#), [Mallatt & Feinberg 2016](#), [Tebbich et al. 2016](#), [Morand-Ferron et al. 2015](#)). If this is true, then motile organisms and organisms with multiple sensory modalities or high sensory resolution are

---

<sup>1</sup> Adapted from the [IRAC Mode of Action Classification catalogue](#) to be more easily searchable and include additional information.

more likely to be sentient, as the capacity for first-order mental experiences would probably improve their reproductive success ([Klein & Barron 2016a](#), [Mallatt & Feinberg 2016](#)).

The principal anatomical evidence against insect sentience is their brain size. Insect brains have substantially fewer neurons than mammals; honey bee and cockroach brains have about 1 million neurons, whereas mouse brains have about 70 million neurons ([Giurfa 2007](#), [Herculano-Houzel et al. 2006](#), [Fox 2006](#)). Insect brains are certainly smaller than vertebrates', but they are also highly efficient, supporting complex behaviors with fewer neurons and less redundancy than vertebrate brain regions with analogous functions ([Giurfa 2007](#), [Herculano-Houzel et al. 2006](#), [Fox 2006](#), [Greenspan & van Swinderen 2004](#)). Although it seems likely that there is a lower limit to the number of neurons required to support sentience ([Adamo 2016](#)), research into learning capacities of small brains over the past twenty years suggests that the limit may be lower than previously thought. If so, at least some insect species (e.g., fruit flies, dragonflies, ants, and honeybees) meet the basic requirements ([Haberkern & Jayaraman 2016](#), [Greenspan & van Swinderen 2004](#)).

Despite their relatively low neuron count, some insects nevertheless show unexpected behavioral sophistication that suggests they are capable of internal representation and affective states, such as associative learning ([Haberkern & Jayaraman 2016](#), [Giurfa 2007](#))<sup>2</sup>. Long-term change in an individual's behavior in response to an aversive stimulus could be motivated by a negative affective state. On the other hand, it is possible for at least some instances of behavior change to occur without the individual being motivated by a mental experience. Nociceptor sensitization can have similar behavioral outputs without the associated mental state, and robots (which are presumed not to be sentient) can be programmed to respond to an aversive stimulus as a learning motivator that drives behavior change ([Sneddon et al. 2014](#)).

Like vertebrates, an insect's nervous system is centralized, meaning that information from all over the body is transmitted to a relatively dense concentration of neurons where it is filtered and integrated. Although insects lack a cerebral cortex, which some researchers consider a necessary feature for experiencing affective states, there is emerging evidence that subcortical structures play a role in vertebrate sentience ([Koch et al. 2016](#), [Klein & Barron 2016a](#) and [2016b](#), [Mallatt & Feinberg 2016](#)). While the cerebral cortex may be required for secondary (access) consciousness, the midbrain, basal ganglia, hippocampus, and cerebellum seem to be responsible for integrating external stimuli, past experiences, and proprioceptive feedback into a mental simulation of the organism in the environment ([Haberkern & Jayaraman 2016](#), [Merker 2006](#)). These subcortical structures are also thought to support emotion and memory in vertebrates, and regions of the insect brain (including the central complex and mushroom bodies) appear functionally analogous and perhaps even homologous to these parts of the vertebrate brain ([Barron & Klein 2016](#), [Haberkern & Jayaraman 2016](#), [Pfeiffer & Homberg 2014](#), [Strausfeld & Hirth 2013](#)). If insect brains are, in fact, functionally analogous to these subcortical structures, they may be complex enough to support sentience ([Barron & Klein 2016](#), [Mallatt & Feinberg 2016](#)).

---

<sup>2</sup> Examples have been previously compiled by Tomasik ([2009](#), [2017](#)), Ray ([2017b](#)), Schukraft ([2019](#)), and Waldhorn ([2019](#)).

## How should we apply what we learn about sentience?

The affective states of other individuals cannot be directly observed, and very few species seem capable of reporting their mental experiences. We have yet to find conclusive anatomical, physiological, or behavioral correlates of sentience. Many of the proxies currently used (but especially such measures as encephalization quotient, neuron count, and phylogenetic distance from humans) are vulnerable to taxonomic bias, since our concept of sentience and its indicators are based on humans and our close relatives. These traits may not be generalizable across taxa, or even across life stages of the same species ([Adamo 2017](#)). This means the best we can do is to accumulate as much information as possible on relevant measurable traits, and use that evidence to triangulate around the issue of sentience ([Sneddon et al. 2014](#)). The current case for insect sentience is not fully compelling, but it is plausible. Further behavioral studies of a wider variety of insect taxa are necessary in order for us to be more certain about their moral status. As it stands, the best strategy is to consider the expected value of our actions: our concern for beings about whose sentience we are uncertain should be weighted by the strength of the evidence and the size of the potential harm. This approach is consistent with the spirit of the arguments made by welfare-concerned philosophers ([Birch 2017](#), [Knutsson & Munthe 2017](#)), and the recommendations of the American Veterinary Medical Association ([AVMA 2013](#)).

## Impact of an Agricultural Insecticides Intervention

### Why agricultural insecticides?

If we think it is plausible that many insects are sentient, then their enormous abundance should compel us to try to alleviate the suffering they may experience ([Ray 2018](#), [Tomasik 2007](#)). Improving wild insect welfare by altering insecticide practices is a promising intervention for several reasons. While many open questions remain (principally: whether or not insects can experience pain, how painful different insecticidal methods are, and how painful non-insecticide-related deaths are), there are several reasons a welfare intervention for insects impacted by agriculture seems more tractable than one for insects in environments less-influenced by human activity. Crucially, reducing the pain of death without modifying the total number of deaths avoids introducing the new knock-on effects we would expect from interventions that change the total population of a species, making it easier to determine the net effects of the intervention on the system as a whole. Because agricultural lands are intentionally less diverse and less spatially variable than most wild systems, detecting unexpected knock-on effects should also be easier. Interventions on agricultural lands should also be less controversial than interventions in areas which are further from the sphere of direct human influence. Altering an existing practice (i.e. agricultural pest management) is probably more economically and socially tractable than introducing a new practice (e.g. providing food and shelter to insects within the borders of a wildlife reserve). Lastly, insecticide use is already experiencing a decline: the decrease in the amount of insecticidal compounds applied may be partially attributable to increased scrutiny about their environmental and human health impacts ([Atwood & Paisley-Jones 2017](#)). If it turns out that alternative insect pest management

techniques are expected to be more humane than these insecticidal compounds, advocating for more humane insecticide practices would dovetail with existing environmentalist and public health efforts.

The effectiveness of an intervention to improve wild insect welfare by reducing the painfulness of agricultural insect pest management methods depends on the likelihood that the affected insects are capable of suffering, the number of insects that would be impacted by the intervention, and how much the intervention would improve their welfare. Other considerations are the effects the intervention may have on the welfare of other beings, and the cost of the intervention. The scope of this report is limited to insecticide use on agricultural lands in the United States, and primarily U.S. cropland, which comprises 9% of the world's croplands ([USGS 2017](#)).

### How many insects are there?

Most available data about insect abundance only reflect species richness and biomass<sup>3</sup> as a measure of relative abundance among samples, and not the absolute number of individuals in an area. Existing estimates of the total number of insects alive on Earth at any given time range from  $10^{17}$  to  $10^{19}$  ([Ray 2017a](#), [Williams 1960](#)). Despite being widely cited in subsequent research on insect abundance, Williams' estimate is based on a 1935 sample of soil insects<sup>4</sup> in the United Kingdom, and was published in 1960 as more of an exercise in population modeling than a rigorous estimate. However, William's estimate falls within an order of magnitude of the results of a recent model ([Bar-On et al. 2018](#)). Bar-On et al. used two parallel approaches to estimate the global biomass of terrestrial arthropods (which includes but is not limited to insects). The first method extrapolates measurements of biomass densities to the global ice-free land area. The second combines Williams' estimate with the average biomass of an individual arthropod (Box 1). These approaches result in global terrestrial arthropod biomass estimates of 0.4 and 0.1 Gt C, respectively ([ibid.](#) p. 40). Considering the average biomass of an individual terrestrial arthropod (0.1 mg C; [ibid.](#)), the biomass estimate obtained through the first approach corresponds to  $4 \times 10^{18}$  terrestrial arthropods globally (Box 1). Williams' estimate of  $1 \times 10^{18}$  insects (a taxonomic subset of Bar-On et al.'s terrestrial arthropods) is consistent with this value. Of 7 million terrestrial arthropod species, an estimated 5.5 million are insects ([Stork 2018](#)). In the absence of data on the relative abundance of insects versus other arthropod groups, I take Bar-On et al.'s estimate of the number of terrestrial arthropods as being approximately equal to the number of insects. I use  $1 \times 10^{18}$  insects, a conservative rounding of their estimate, in my calculations below.

#### Box 1: Estimating global insect abundance

##### Biomass estimate 1:

$2.7 \times 10^{-3}$  kg/m<sup>2</sup> (average measured biomass density of terrestrial arthropods)  $\times$   $1.3 \times 10^{14}$  m<sup>2</sup> (global ice-free land surface area) =  $4 \times 10^{11}$  kg (0.4 Gt C) global biomass of terrestrial

<sup>3</sup> The mass of living material in an individual, community, or ecosystem. Bar-On et al. report biomass as the mass of carbon in an individual ([2018](#)).

<sup>4</sup> Williams' estimate includes terrestrial arthropods in the subclass Collembola (springtails), which are no longer considered insects; however, their brains do not seem substantially different from the brains of many smaller insects, and they should not be discounted from consideration based on this taxonomic reclassification alone ([Kollmann et al. 2011](#)).



arthropods ([Bar-On et al. 2018](#))

**Biomass estimate 2:**

$1 \times 10^{18}$  insects ([Williams 1960](#))  $\times 1 \times 10^{-7}$  kg C (average biomass of individual terrestrial arthropod) =  $1 \times 10^{11}$  kg (0.1 Gt C) global biomass of terrestrial arthropods ([Bar-On et al. 2018](#))

**Abundance estimate 1:**

$1 \times 10^{18}$  insects ([Williams 1960](#), extrapolated from English soil samples)

**Abundance estimate 2:**

$4 \times 10^{11}$  kg (biomass estimate 1) ([Bar-On et al.2018](#))  $\div 1 \times 10^{-7}$  kg C (average biomass of individual terrestrial arthropod) ([Bar-On et al. 2018](#)) =  $4 \times 10^{18}$  terrestrial arthropods  $\approx 1 \times 10^{18}$  insects (rounded down)

How many insects are affected by insecticides?

As of the last USDA Agricultural Census in 2017,  $3.6 \times 10^{12}$  m<sup>2</sup> of land was in agricultural use, and  $0.45 \times 10^{12}$  m<sup>2</sup> of that land was treated with insecticides and/or acaricides<sup>5</sup> ([USDA NASS 2019a](#)). The majority of agricultural land was used as pasture ( $1.6 \times 10^{12}$  m<sup>2</sup>) or for growing crops ( $1.6 \times 10^{12}$  m<sup>2</sup>). The remainder was woodland ( $0.29 \times 10^{12}$  m<sup>2</sup>) and other agricultural uses ( $0.11 \times 10^{12}$  m<sup>2</sup>)([ibid.](#)). The number of insects per land-use type is a critical knowledge gap: the density of insects and other terrestrial arthropods is likely to be different between a corn field and a potato field, and even more different between cropland and woodland. Setting this uncertainty aside, considering the number of terrestrial arthropods on earth and the amount of US crop land, there are approximately  $2.7 \times 10^{16}$  individual terrestrial arthropods living on all U.S. cropland, and  $0.35 \times 10^{16}$  individuals are potentially affected by U.S. agricultural insecticide use in 2017 (Box 2).

**Box 2: Estimating insect abundance on U.S. agricultural land**

**Density:**

$1 \times 10^{18}$  insects globally  $\div 1.3 \times 10^{14}$  m<sup>2</sup> global ice-free land surface =  $7.7 \times 10^3$  insects/m<sup>2</sup>

**Abundance on US agricultural land:**

$7.7 \times 10^3$  insects/m<sup>2</sup>  $\times 3.6 \times 10^{12}$  m<sup>2</sup> agricultural land in the U.S. =  $2.7 \times 10^{16}$  insects on U.S. agricultural land

**Abundance on insecticide-treated US agricultural land:**

<sup>5</sup> Acaricides are compounds used to kill mites and ticks. The USDA agricultural census groups insecticides and acaricides together, and separates both from nematicides, so I treat these categories the same way in my report.

$$7.7 \times 10^3 \text{ insects/m}^2 \times 4.5 \times 10^{11} \text{ m}^2 \text{ U.S. agricultural land treated with insecticides} = 0.35 \times 10^{16} \text{ insects on insecticide-treated U.S. agricultural land}$$

This approach to estimating the impact of an insecticides intervention relies on global generalizations about biomass and abundance across different species and landscapes. While it may be useful for grasping the approximate scale of the impact of agricultural insecticides on wild insects, it is too broad to be useful for prioritization between specific insecticide interventions (e.g. whether to focus on soy versus barley cultivation). One approach for generating a more accurate impact estimate would be to incorporate economic injury levels (EILs). An EIL estimate is a tool for determining when pesticide application is cost-effective ([Hunt et al. 2009](#)). It is expressed as the number of individual pests of a given species per plant, where the economic injury caused by the pest is equal to the cost of treating the crops with a given insecticide ([ibid.](#)). If the number of pest individuals per plant exceeds the EIL, it is cost-effective for the grower to apply insecticides ([ibid.](#)). Growers may actually apply insecticides before or after pest populations exceed the EIL (which would result in an over- or under-estimate of the number of insects affected, respectively), but if we assume they are choosing pest management practices that are both economically sound and in line with recommendations for reducing the risk of insecticide resistance, then EILs are an appropriate basis for impact estimates. This method does not incorporate non-target insects that may still be affected by the pest control program, so the estimate generated should be assumed to be the minimum number of affected individuals.

EILs have been published for some major pests of crops that are grown widely in the United States, and are quite specific to the location, pest species, and crop variety. Multiple insect species may be pests of the same crop, and the EIL would be different for each species. Below, I suggest a way in which EIL estimates may be used to approximate the number of insects impacted by a pest control program, based on the kinds of agricultural data that are normally available (Box 3). I have also outlined a [table](#) that may be used in conjunction with a review of pest control literature to generate impact estimates for particular agricultural insecticide interventions.

### Box 3: Using EILs to estimate pest management impacts

$$\text{Cultivated area (m}^2\text{)} \times \text{expected yield (kg/m}^2\text{)} \div \text{average plant mass (kg/plant)} = \text{plant count}$$

$$\text{Plant count} \times \sum_{i=a}^n \text{EIL estimate for pest } i \text{ (indiv./plant)} = \text{number of individuals affected across all targeted species}$$

## Insecticide Practices

Developing an effective intervention requires understanding current agricultural insecticide practices. The use of agricultural insecticides is of economic, environmental, and human health concern; therefore,



information about the amount and type of insecticides used in the United States is made publicly available by the Environmental Protection Agency (EPA) and the U.S. Department of Agriculture (USDA). The USDA produces reports following the U.S. Agricultural Census every five years which include data on the use and sale of pesticides in the United States. The reports are based on data collected by the U.S. Department of Agriculture National Agricultural Statistics Service (USDA NASS) and by private market research companies. The most recent EPA report was published in 2017 and covered market estimates from 2008 to 2012 ([Atwood & Paisley-Jones 2017](#)). The most recent USDA Agricultural Census was in 2017, and a report summarizing its findings was released earlier this year ([USDA NASS 2019a](#)). The USDA also provides an interactive [database](#) of all information from prior agricultural censuses since 1997.

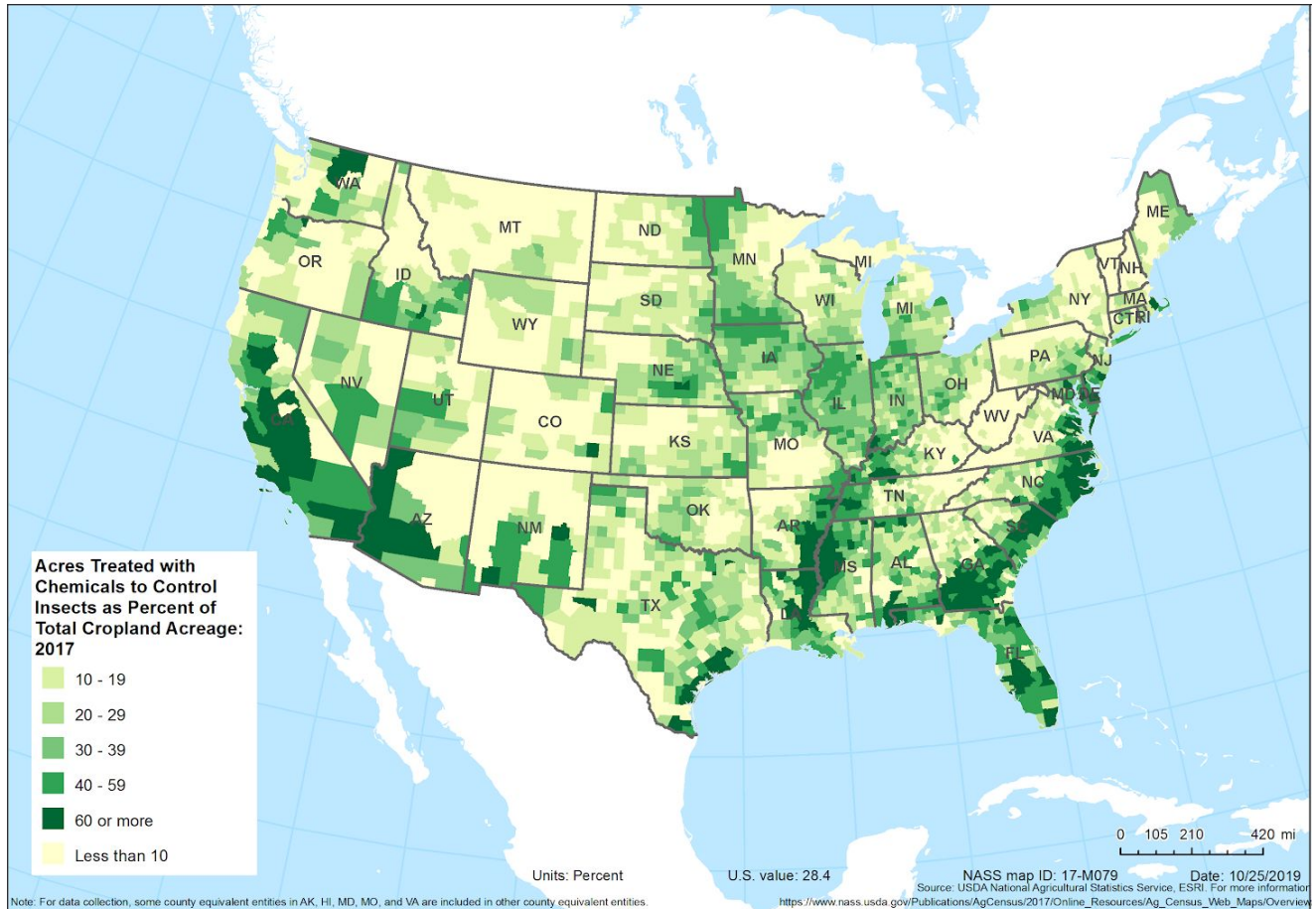
### Recent U.S. insecticides market

According to the EPA's 2017 market report on the pesticides industry, U.S. insecticide use comprised 6-7% by mass and 14% by expenditures of the global insecticides market from 2008 to 2012 ([Atwood & Paisley-Jones 2017](#)). Between 2008 and 2012, agricultural applications accounted for 55-57% by mass of the U.S. insecticides market (3-4% of the global market) ([ibid.](#)). Home and garden applications were 23-25%, and professional<sup>6</sup> applications were 17-20% by mass of total U.S. insecticide use ([ibid.](#)). The total mass of conventional (i.e. synthetic chemical) insecticides used in the U.S. has decreased by 39% between 2000 and 2012, from  $4.5 \times 10^7$  kg (99 million lbs) to  $2.7 \times 10^7$  kg (60 million lbs) ([Atwood & Paisley-Jones 2017](#)). This excludes biological control techniques that are popular in the integrated pest management approach, such as chemical insecticides derived from microorganisms (e.g. Bt), the genetic modification of crop plants to produce insecticidal or insect-averse compounds, and the use of "natural enemies" (predators, parasites, pathogens, and competitors) to reduce insect pest populations ([U.S. EPA 2016](#), [Landis & Orr 1996](#)). Between 2008 and 2012, agricultural applications accounted for approximately 60% by mass on average of insecticides used (Section 3.2 in [Atwood & Paisley-Jones 2017](#)). Across all U.S. market sectors (agricultural, home and garden, and professional), chlorpyrifos and acephate were the most commonly used insecticides by mass of active ingredient used, at  $2 \times 10^6$  to  $4 \times 10^6$  kg (5-8 million lb) each in 2012.  $2 \times 10^6$  to  $4 \times 10^6$  kg (4-8 million lb) of chlorpyrifos and  $1 \times 10^6$  to  $3 \times 10^6$  kg (2-6 million lb) of acephate were used in agriculture in 2012 ([Atwood & Paisley-Jones 2017](#)).

---

<sup>6</sup> The U.S. EPA 2017 market report defines this sector (also called the Industrial/Commercial/Governmental sector) as involving pesticide use (including pesticides restricted to use by licensed applicators) by professional applicators on industrial, commercial, and governmental property. It also includes professional pesticide application in homes and gardens (in contrast to the Home and Garden sector, which covers unlicensed laypersons using unrestricted pesticides on private property) ([Atwood & Paisley-Jones 2017](#)).

**Figure 1: Percentage of cropland treated with insecticides per county, 2017.** ([USDA NASS 2019b](#))



**Table 1: Chemical pesticide use on U.S. agricultural lands, 1997-2017.** Data are from an [inquiry of the USDA NASS Quick Stats database](#). “Other” refers to the domain “CHEMICAL, OTHER (TOTAL)” in the USDA NASS Quick Stats database, defined as chemicals used “to control growth, thin fruit, ripen, or defoliate” in the 2017 Census of Agriculture ([USDA 2019a](#)). Census respondents were not asked to specify what type of agricultural land they applied chemical pesticides to (Section 26 in [Form 17-A100](#)).

		1997	2002	2007	2012	2017
<b>Herbicides</b>	No. of farms	0.734 x 10 <sup>6</sup>	0.708 x 10 <sup>6</sup>	0.704 x 10 <sup>6</sup>	0.794 x 10 <sup>6</sup>	0.702 x 10 <sup>6</sup>
	Area (m <sup>2</sup> )	0.777 x 10 <sup>12</sup>	0.785 x 10 <sup>12</sup>	0.916 x 10 <sup>12</sup>	1.16 x 10 <sup>12</sup>	1.19 x 10 <sup>12</sup>
<b>Insecticides and/or acaricides</b>	No. of farms	0.392 x 10 <sup>6</sup>	0.357 x 10 <sup>6</sup>	0.354 x 10 <sup>6</sup>	0.361 x 10 <sup>6</sup>	0.306 x 10 <sup>6</sup>
	Area (m <sup>2</sup> )	0.262 x 10 <sup>12</sup>	0.266 x 10 <sup>12</sup>	0.368 x 10 <sup>12</sup>	0.408 x 10 <sup>12</sup>	0.455 x 10 <sup>12</sup>

<b>Fungicides</b>	No. of farms	0.124 x 10 <sup>6</sup>	0.092 x 10 <sup>6</sup>	0.097 x 10 <sup>6</sup>	0.122 x 10 <sup>6</sup>	0.121 x 10 <sup>6</sup>
	Area (m <sup>2</sup> )	0.057 x 10 <sup>12</sup>	0.050 x 10 <sup>12</sup>	0.092 x 10 <sup>12</sup>	0.142 x 10 <sup>12</sup>	0.179 x 10 <sup>12</sup>
<b>Nematicides</b>	No. of farms	0.046 x 10 <sup>6</sup>	0.036 x 10 <sup>6</sup>	0.035 x 10 <sup>6</sup>	0.059 x 10 <sup>6</sup>	0.047 x 10 <sup>6</sup>
	Area (m <sup>2</sup> )	0.028 x 10 <sup>12</sup>	0.024 x 10 <sup>12</sup>	0.031 x 10 <sup>12</sup>	0.059 x 10 <sup>12</sup>	0.059 x 10 <sup>12</sup>
<b>Other</b>	No. of farms	0.056 x 10 <sup>6</sup>	0.045 x 10 <sup>6</sup>	0.045 x 10 <sup>6</sup>	0.053 x 10 <sup>6</sup>	0.038 x 10 <sup>6</sup>
	Area (m <sup>2</sup> )	0.050 x 10 <sup>12</sup>	0.044 x 10 <sup>12</sup>	0.049 x 10 <sup>12</sup>	0.053 x 10 <sup>12</sup>	0.060 x 10 <sup>12</sup>

**Table 2: Select metrics of U.S. agricultural land usage, 1997-2017.** Farm number and area data reproduced from Table 1: Historical Highlights in the 2017 Census of Agriculture ([USDA NASS 2019a](#)).

	1997	2002	2007	2012	2017
<b>All agricultural land</b>					
Total area (m <sup>2</sup> )	3.86 x 10 <sup>12</sup>	3.80 x 10 <sup>12</sup>	3.73 x 10 <sup>12</sup>	3.70 x 10 <sup>12</sup>	3.64 x 10 <sup>12</sup>
No. of farms	2.22 x 10 <sup>6</sup>	2.13 x 10 <sup>6</sup>	2.20 x 10 <sup>6</sup>	2.11 x 10 <sup>6</sup>	2.04 x 10 <sup>6</sup>
Avg. farm area (m <sup>2</sup> )	1.74 x 10 <sup>6</sup>	1.78 x 10 <sup>6</sup>	1.69 x 10 <sup>6</sup>	1.76 x 10 <sup>6</sup>	1.78 x 10 <sup>6</sup>
<b>Cropland</b>					
Total cropland area (m <sup>2</sup> )	1.80 x 10 <sup>12</sup>	1.76 x 10 <sup>12</sup>	1.64 x 10 <sup>12</sup>	1.58 x 10 <sup>12</sup>	1.60 x 10 <sup>12</sup>
% total ag. land area	46.6%	46.3%	44.1%	42.6%	44.0%
No. of farms with cropland	1.86 x 10 <sup>6</sup>	1.75 x 10 <sup>6</sup>	1.69 x 10 <sup>6</sup>	1.55 x 10 <sup>6</sup>	1.48 x 10 <sup>6</sup>
% total no. of farms	83.8%	82.3%	76.4%	73.6%	72.3%
Avg. area cropland per farm having cropland (m <sup>2</sup> )	0.97 x 10 <sup>6</sup>	1.00 x 10 <sup>6</sup>	0.98 x 10 <sup>6</sup>	1.02 x 10 <sup>6</sup>	1.09 x 10 <sup>6</sup>
Cropland area harvested (m <sup>2</sup> )	1.29 x 10 <sup>12</sup>	1.22 x 10 <sup>12</sup>	1.25 x 10 <sup>12</sup>	1.27 x 10 <sup>12</sup>	1.30 x 10 <sup>12</sup>
% harvested of total cropland area	71.7%	69.7%	76.2%	80.8%	80.7%
<b>Woodland</b>					
Total woodland area (m <sup>2</sup> )	0.31 x 10 <sup>12</sup>	0.31 x 10 <sup>12</sup>	0.30 x 10 <sup>12</sup>	0.31 x 10 <sup>12</sup>	0.30 x 10 <sup>12</sup>
% total ag. land area	8.05%	8.09%	8.14%	8.42%	8.12%
No. of farms with woodland	0.86 x 10 <sup>6</sup>	0.82 x 10 <sup>6</sup>	0.84 x 10 <sup>6</sup>	0.84 x 10 <sup>6</sup>	0.79 x 10 <sup>6</sup>
% total no. of farms	38.7%	38.4%	38.2%	39.8%	38.9%
Avg. area in woodland per farm having woodland (m <sup>2</sup> )	0.36 x 10 <sup>6</sup>	0.38 x 10 <sup>6</sup>	0.36 x 10 <sup>6</sup>	0.37 x 10 <sup>6</sup>	0.37 x 10 <sup>6</sup>

<b>Pasture</b>					
Total pasture area (m <sup>2</sup> )	1.61 x 10 <sup>12</sup>	1.60 x 10 <sup>12</sup>	1.65 x 10 <sup>12</sup>	1.68 x 10 <sup>12</sup>	1.62 x 10 <sup>12</sup>
% total ag. land area	41.7%	42.1%	44.3%	45.4%	44.5%
No. of farms with pasture	0.65 x 10 <sup>6</sup>	0.85 x 10 <sup>6</sup>	1.13 x 10 <sup>6</sup>	1.178 x 10 <sup>6</sup>	1.13 x 10 <sup>6</sup>
% total no. of farms	29.1%	40.0%	51.4%	55.8%	55.3%
Avg. area in pasture per farm having pasture (m <sup>2</sup> )	2.50 x 10 <sup>6</sup>	1.88 x 10 <sup>6</sup>	1.46 x 10 <sup>6</sup>	1.43 x 10 <sup>6</sup>	1.44 x 10 <sup>6</sup>
<b>Other agricultural use</b>					
Total area in other ag. use (m <sup>2</sup> )	0.14 x 10 <sup>12</sup>	0.13 x 10 <sup>12</sup>	0.13 x 10 <sup>12</sup>	0.13 x 10 <sup>12</sup>	0.12 x 10 <sup>12</sup>
% total ag. land area	3.60%	3.51%	3.44%	3.56%	3.32%
No. of farms with land in other ag. use	1.33 x 10 <sup>6</sup>	1.17 x 10 <sup>6</sup>	1.13 x 10 <sup>6</sup>	1.34 x 10 <sup>6</sup>	1.18 x 10 <sup>6</sup>
% total no. of farms	59.9%	54.7%	51.1%	63.5%	57.9%
Avg. area in other ag. use per farm having land in other ag. use (m <sup>2</sup> )	0.11 x 10 <sup>6</sup>	0.12 x 10 <sup>6</sup>	0.11 x 10 <sup>6</sup>	0.10 x 10 <sup>6</sup>	0.10 x 10 <sup>6</sup>

**Table 3: Most popular insecticides in each U.S. market sector, by mass of active ingredient applied (2012).** Use rates and sales are presented as ranges in the USDA report, as the source data is proprietary information from private market research companies ([Atwood & Paisley-Jones 2017](#)).

<b>Insecticide</b>	<b>Class</b>	<b>Mode of action</b>	<b>Mechanism</b>	<b>Mass applied in sector (10<sup>6</sup> kg)</b>
<b>Agricultural</b>				
Chlorpyrifos	Organophosphates	Nerve & muscle	AChE inhibitor	2-4
Acephate	Organophosphates	Nerve & muscle	AChE inhibitor	1-3
<b>Home and Garden</b>				
Carbaryl	Carbamates	Nerve & muscle	AChE inhibitor	1-2
Acephate	Organophosphates	Nerve & muscle	AChE inhibitor	0.5-1
Permethrin and other pyrethroids	Pyrethroids, pyrethrins	Nerve & muscle	Sodium-channel modulator	0.5-1
Malathion	Organophosphates	Nerve & muscle	AChE inhibitor	0.5-1
<b>Professional</b>				

Sulfuryl fluoride	Fluorides	Unknown or non-specific	Multi-site inhibitor	0-1
Acephate	Organophosphates	Nerve & muscle	AChE inhibitor	0-1
<i>B. thuringiensis israelensis</i>	Microbial	Midgut	Insect midgut membrane disruptor	0-1
Bifenthrin	Pyrethroids, pyrethrins	Nerve & muscle	Sodium-channel modulator	0-1

## Overview of the major insecticide modes of action

### AChE inhibitors

Acetylcholinesterase (AChE) inhibitors are a kind of nerve and muscle agent. They are the most popular insecticide type in the U.S. by mass, both within the agricultural sector and across all market sectors. Organophosphate and carbamate insecticides operate through this mechanism ([IRAC 2019a](#)). AChE inhibitors prevent the enzyme AChE from breaking down acetylcholine, a neurotransmitter ([Čolović et al. 2013](#)). Acute exposure to organophosphates or carbamates therefore increases the bioavailability of acetylcholine, resulting in over-stimulation of the parasympathetic nervous system until the acetylcholine is depleted. This may manifest as pronounced muscle spasms before paralysis and death ([Čolović et al. 2013](#), [Fukuto 1990](#)). Sublethal effects have been observed in some insect species for several organophosphate and carbamate insecticides: carbaryl and parathion affect foraging and long-range pheromonal courtship behavior, diazinon affects foraging and fecundity, aldicarb and malathion affect locomotion, and parathion-methyl induces avoidance of treated host plants ([Haynes 1988](#)).

Organophosphates comprise a greater portion of the U.S. insecticides market than any other single chemical class. Of the  $3 \times 10^7$  kg (60 million lb) of all insecticidal active ingredients used in all US markets in 2012,  $1 \times 10^7$  kg (20 million lb) were organophosphates ([Atwood & Paisley-Jones 2017](#)). The two most commonly used insecticides by mass between 2008 and 2012, chlorpyrifos and acephate, are both organophosphate insecticides ([ibid.](#)). However, organophosphates have decreased in popularity in the past two decades: in 2000, 71% of the mass of all insecticidal active ingredients applied in the United States was organophosphates; in 2012, it was only 33% ([ibid.](#)). Other chemical classes, such as pyrethroids and pyrethrins, and neonicotinoids, have seen increased usage in this time period, although insecticide usage by mass has decreased by 39% overall ([ibid.](#)).

Because of their past widespread and heavy use, organophosphate insecticides have been a particular focus for EPA review, and this decrease in their popularity is likely attributable to the implementation of stricter regulations for organophosphate use. One example is chlorpyrifos, an organophosphate insecticide that was formerly sold in both the agricultural and home markets. In 2000, most forms of chlorpyrifos were banned from sale for home and garden use, and chlorpyrifos can now only be applied by certified pesticide applicators ([Vogel 2016](#), [U.S. EPA 2002](#)). The sale and possession of chlorpyrifos for any use, including agricultural, is currently or will soon be banned in Hawaii, New York, and California ([Rogers 2019](#)). Chlorpyrifos is still widely used in agricultural contexts, however, and in 2012

more chlorpyrifos was applied both across all markets and in the agricultural market than any other insecticide ([Atwood & Paisley-Jones 2017](#)). Acephate, another organophosphate, ranked second ([ibid.](#)).

In addition to increased regulatory oversight, another factor contributing to decreased organophosphate use may be the success of the Boll Weevil Eradication Program, a USDA integrated pest management program which has reduced reliance on the major organophosphate insecticide malathion for boll weevil control ([USDA APHIS 2006](#)). In 2005,  $5 \times 10^6$  to  $6 \times 10^6$  kg (10-13 million lb) of malathion were applied across all market sectors—as much as twice the mass of the next most common insecticide that year, chlorpyrifos. By 2012, malathion usage had declined to only  $0.5 \times 10^6$  to  $2 \times 10^6$  kg (1-4 million lb) applied ([Atwood & Paisley-Jones 2017](#)).

**Table 4. Most commonly used organophosphate insecticides across all market sectors, ranked by range in millions of pounds of active ingredient.** Reproduced from Table 3.8 in [Atwood & Paisley-Jones \(2017\)](#).

Active Ingredient	2012		2009		2007*		2005*	
	Rank	Range	Rank	Range	Rank	Range	Rank	Range
Chlorpyrifos	1	5-8	1	6-9	1	6-9	2	6-9
Acephate	2	5-8	2	3-6	3	3-6	3	3-5
Malathion	3	1-4	3	2-5	2	5-7	1	10-13
Naled	4	1-2	4	1-2	4	1-2	5	1-2
Phorate	5	1-2	6	<1	7	1-2	6	1-2
Dicrotophos	6	1-2	7	<1	5	1-2	7	1-2
Dimethoate	7	<1	8	<1	9	<1	9	<1
Terbufos	8	<1	9	<1	8	<1	—	—
Phosmet	9	<1	5	<1	6	1-2	4	1-3
Ethoprophos	10	<1	—	—	—	—	—	—

Source: Agricultural Market Research Proprietary Data (2005-2012).  
 Non-Agricultural Market Research Proprietary Data (2005-2012)  
 USDA/NASS Quick Stats ([http://www.nass.usda.gov/Quick\\_Stats/](http://www.nass.usda.gov/Quick_Stats/))

*Note:* A dash (—) indicates that the organophosphate pesticide was not one of the 10 most commonly used in the given year.

\* Updated values for 2007 and 2005 presented for continuity.

## Sodium-channel modulators

Another group of nerve and muscle agents is the sodium-channel modulators, which include DDT, methoxychlor, and the pyrethroids and pyrethrins. Similarly to AChE inhibitors, these compounds cause nerve hyperexcitation, although the mechanism differs: sodium-channel modulators alter the concentration of sodium ions to affect action potentials ([US EPA 2009](#)). As with AChE inhibitors, acute



toxicity from sodium-channel modulators results in muscle spasms and paralysis, which eventually leads to death ([Toynton et al. 2009](#), [US EPA 2009](#)). The two most commonly-used sodium-channel modulators are permethrin and bifenthrin, both belonging to the class pyrethroids and pyrethrins. In insects, pyrethroids may cause hyperexcitation of the central nervous system and convulsions, or ataxia and incoordination prior to death ([Bloomquist 2015](#), [Wolansky & Harrill 2007](#)). Their use is mostly confined to the home and garden markets, where they are used for mosquito, flea, and tick control. Sodium-channel modulators are sometimes used in crop cultivation, but not commonly, due to their toxicity to aquatic organisms ([US EPA 2009](#)). Other sodium-channel modulators include oxadiazines and semicarbazones. These compounds cause central nervous system depression resulting in ataxia and paralysis in insects, and convulsions when the unmoving insect is disturbed ([Bloomquist 2015](#)). Sublethal effects on insects of pyrethroids include reduced feeding, hyperactivity, and avoidance of pesticide residues ([Bradbury & Coats 1989](#)). In particular, sublethal toxicity from permethrin alters foraging behavior, impedes long-range pheromonal courtship behaviors and inhibits the flight reflex ([ibid.](#)).

### **Insect growth regulators**

Some insecticides (such as fenoxycarb, pyriproxyfen, and etoxazole) disrupt the growth processes of larval insects by preventing metamorphosis, stopping the biosynthesis of necessary proteins (such as chitin, for forming the exoskeleton) and lipids, or delaying or accelerating moults ([IRAC 2019a](#)). Affected insects are usually killed by the resulting malformations before reaching the adult instar ([Silva-Aguayo 2002](#)). Insect growth regulators are not among the most commonly used insecticides in any sector ([Atwood & Paisley-Jones 2017](#)).

### **Integrated pest management**

Integrated pest management (IPM) refers to a broad approach to controlling pest populations using a combination of biological, cultural, and chemical methods ([U.S. EPA 2019](#)). While some IPM methods, such as crop rotation, have been in practice in some form for centuries, it was not until the development of synthetic pesticides after World War II that IPM gained scientific attention ([Smith & Smith 1949](#)). A 1987 federal evaluation of the effectiveness of integrated pest management found that IPM practitioners were able to mitigate pest damage to crops and the resulting economic injury while reducing pesticide use ([USDA 1989](#)). Since the ratification of the 1972 Federal Environmental Pesticides Control Act, the USDA has undertaken a coordinated IPM initiative, providing recommendations and funding for IPM programs nationwide ([Jacobsen 1996](#), [USDA NIFA](#)). The goal of IPM is not to eradicate pest populations, but rather to reduce the population size to a point where the pests do not have a significant detrimental economic or public health impact, while minimizing negative effects of pest control practices on ecosystems or human health. While some non-chemical methods employed in IPM may be more humane alternatives to conventional insecticides, their more complicated population and community effects make it harder to determine the net impact of the intervention on non-target species.

#### *Biological control methods*

IPM often includes the use of natural enemies (predators, parasitoids, and pathogens) to suppress pest populations ([Shelton n.d.](#)). This can involve the importation of novel enemies or the conservation or

augmentation of existing ones ([Landis & Orr 1996](#)). Ideally, a natural enemy is specific enough to the target pest or pests that they have minimal impacts on desirable species, and either the pest is extirpated or the predator-prey relationship is stable enough to suppress pest populations long-term ([Obrycki et al. 1996](#)). Examples of natural enemies used for biological control include: lady beetles, a specialist predator whose larval and adult stages consume aphid pests ([Obrycki et al. 1996](#)); parasitoid wasps, which lay their eggs inside living larvae (and sometimes adults) of crop pests, later killing the host when the wasp larvae emerge ([Landis & Orr 1996](#)); and *Bacillus thuringiensis* (Bt), a bacterium which produces toxins that destroy insect larvae's midguts, leading to death by starvation or infection ([Perez et al. 2015](#), [Shelton n.d.](#)). Parasitoids and pathogens tend to take much longer to kill than predators or chemical insecticides, on the order of weeks compared to hours ([Shelton n.d.](#), [IRAC 2019b](#)).

Some biological control methods do not involve killing pests directly or intentionally manipulating their natural enemies, but instead alter their reproductive success. One such autocidal technique is the Sterile Insect Release Method (SIRM). Lab-reared individuals of the pest species are made sterile (usually chemically or with radiation) and released into the pest population. Sterile individuals compete with fertile individuals for mating opportunities, which causes the population to decline in subsequent generations ([Bartlett & Staten 1996](#)). Related techniques are encouraging hybridization that results in sterile offspring, and introducing mutations that alter sex ratio or change the number of reproductive cycles in an insect's lifetime ([ibid.](#)). Individuals in populations managed exclusively with autocidal methods still die of predation, starvation, exposure, or disease, but after several generations there should be fewer individuals killed than a chemical method which targets adult insects who may already have reproduced.

### *Cultural control methods*

Cultural control encompasses management techniques that operate on the production system rather than the pest. Like biological control methods, cultural control requires an understanding of the pest species' life cycles, diets, reproductive strategies, trophic relationships, and migration and dispersal habits. Cultural control methods fall into one or more of four functional categories: impeding colonization by pests, making the environment inhospitable to pests, altering the crop to reduce pests' impacts, and making the environment more hospitable to pests' natural enemies. For example, physical barriers such as row covers or plastic-lined trenches can prevent colonization ([Ferro 1996](#)). Alternating between crops that do not have mutual pests, or shifting planting times so that pests who hatch or emerge from dormancy lack their preferred nutrition and refuge, creates an inhospitable environment for perennial pests ([ibid.](#)). Non-crop volunteer plants can be recruited to act as alternate hosts for pests, or to provide supplementary nutrition or refuge for natural enemies. Alternatively, some volunteer plants provide supplementary nutrition and refuge for pests, and eliminating them can reduce pest populations ([ibid.](#)). Crops can be genetically modified to be less susceptible to pest damage, either through selective breeding (such as developing cultivars which have a more durable epidermis or produce unpleasant-tasting leaves), or through direct genetic manipulation (such as inserting new genetic material so crops produce plant-incorporated protectants, like Bt toxins) ([US EPA 2017](#), [Perez et al. 2015](#), [Teetes 1996](#)). Wild relatives of crop species are a rich source for beneficial mutations to be used in genetic modification of crops; the conservation of genetic diversity is therefore important for developing pest-resistant cultivars ([Eigenbrode 1996](#)).

### *Chemical control methods*

IPM encourages practitioners to be more efficient in their insecticide use and incorporate complementary techniques to reduce the total amount of insecticide applied. For instance, IPM practitioners may rotate through insecticides with different modes of action, which reduces the likelihood of pests developing resistance to any one mode of action ([IRAC 2019c](#)). To reduce the risk of resistance and minimize harm to non-target organisms, the use of broad-spectrum insecticides and insecticides which are toxic to fish, amphibians, birds, or mammals are discouraged. IPM practitioners prefer chemical control methods that are specific to the target pest, or at least to insects. For example, diatomaceous earth is lethal to arthropods and nematodes but non-toxic to other taxa. The amorphous silicon dioxide in diatomaceous earth abrades the insect digestive tract if ingested, and impedes respiration by blocking the spiracles and trachea. The primary insecticidal mechanism of diatomaceous earth is desiccation: silicon dioxide destroys the protective cuticle on an insect's exoskeleton that prevents water loss ([Faulde et al. 2006](#)). Apart from mild irritation from the abrasive particles in diatomaceous earth, silicon dioxide seems to be harmless to non-arthropods ([Bunch et al. 2013](#)).

Non-insecticidal chemical control methods are antifeedants, repellents, and confusants. These compounds are usually botanical in origin. Certain plant volatiles deter pest insects at a distance because they are noxious to pests or attractive to their natural enemies; pyrethroids (including pyrethrin and permethrin), which are neurotoxic insecticides derived from chrysanthemums, act as repellents at lower concentrations. Other volatiles may attract pests, and can be applied to nearby volunteer plants to confuse herbivorous insects that locate food by chemosensation ([Silva-Aguayo 2002](#)). Synthetic insect pheromones can be used to disrupt mating by inundating the chemical landscape with false signals and overwhelming genuine ones, or to bait lethal traps (the method of killing in pheromone-baited traps is usually contact with an insecticide, or sometimes drowning in standing water) ([Flint & Doane 1996](#)). Some plants produce noxious-tasting or toxic compounds which deter pests from feeding on that plant. Some of these antifeedants are insecticidal, such as terpenes (isolated from conifer resin), which cause the insect to cease feeding altogether and starve to death ([Silva-Aguayo 2002](#)).

## Considerations and Conclusions

There are several factors to consider when comparing the expected welfare impacts of different insect pest management techniques. Broadly, they are: the intensity of the negative experiences caused by a particular method, the duration of those experiences, and how many individuals are affected. A more humane insect pest management method would be less painful, faster, or affect fewer individuals than the original method. It is important to bear in mind that the individuals under consideration will die by some means, whether or not their deaths are the direct result of a pest management program. Insects on agricultural land may die of starvation, desiccation, freezing, drowning, disease, parasitism, predation, insecticide exposure, or trauma from harvesting and transport processes. It is unknown how common, how painful, or how quick each of these causes of death are. My comparisons between the insect pest

management methods covered in this report are therefore speculative and I would readily change them with new information.

## Comparing insect pest management methods

In theory, most agricultural pest management programs aim to eradicate the pest population from the managed area, as doing so would eliminate economic injury to the crop from pest activity. In practice, environmental and economic constraints mean that extirpation is rarely achieved. Pest insect populations may only be suppressed and later rebound, or if the population is entirely eliminated then the managed area may be recolonized. Managing pest insect populations in this way might result in many more insects being killed than if they were successfully extirpated from managed areas and prevented from recolonizing, as ongoing management would be required to reduce economic injury by successive generations of pest insects.

The disvalue of killing more insects in total over multiple generations must also be balanced with any negative repercussions that could arise from eradicating the population entirely from the managed area. If the harm caused by eradication would outweigh the harm done to future generations of insects, then a more humane insect pest management program would avoid manipulating the number of insects killed directly by a given method, and instead try to shorten or lessen the painful experience it causes. This approach may help skirt the issue of introducing new ripple effects in the managed area and its ecological context, as it minimizes changes to insect population size and existing trophic dynamics.

If a death by other causes (e.g. predation) is expected to be better than a death by exposure to an insecticide, then it would be more humane to use non-lethal pest insect management methods (e.g. applying sublethal concentrations of insecticidal compounds as repellants, installing physical barriers, providing alternate host plants, or genetically modifying crops to be unpalatable to pests). If, however, death by other causes (e.g. parasitism or predation, which may or may not be part of a pest management program) is expected to be worse than death by insecticide, then the most humane management strategy would be to apply the fastest-acting and least-painful insecticide. Among the major groups of insecticides reviewed in this report, I expect the nerve and muscle agents (AChE inhibitors and sodium-channel modulators) to be preferable to insect growth regulators, or insecticides acting on the midgut (namely, Bt toxins). In absence of information about how painful these respective methods might be, it would be better to use the faster-acting nerve and muscle agents (which kill over minutes to hours) than the slower-acting growth regulators or midgut disruptors (which kill over days to weeks) ([Shelton n.d., IRAC 2019b](#)).

If eradicating a pest insect population is unlikely to have outsized negative consequences for other individuals, then the more humane pest management option may be to prevent subsequent generations of that population from coming into existence. While the duration and intensity of the negative experiences involved in a particular cause of death are still relevant to this approach, the primary focus is on reducing the number of individuals affected over the long term. The most humane method used to prevent future generations of a pest insect population will depend on the expected painfulness of death caused directly by pest management versus the death expected otherwise (including indirect effects of

pest management, as well as causes independent of management). Extirpation of a pest insect could be achieved by combining physical barriers (to prevent the population being augmented through immigration) and either non-lethal methods for reducing reproductive rate, or lethal methods targeting pre-reproductive individuals. Techniques for non-lethal population control include inhibiting mating signals or releasing sterile individuals into the population (SIRM). Some insecticides or natural enemies primarily affect juvenile insects (such as insect growth regulators, or certain parasitoid wasps), killing them before they reach reproductive maturity. It may be that larval insects are less likely to be sentient than adults, in which case it would be better to reduce reproductive rates by targeting juvenile insects than by killing adults who have not mated yet.

In summary, the relevant considerations for determining the welfare impact of a particular pest insect management program are: the ultimate cause of death, its duration and painfulness, the number of individuals affected immediately by the program, the number of individuals expected to be subject to this program in the future, the life stage affected and the expectation of sentience at that stage, and non-target effects on other individuals in the agroecosystem and beyond. Using nonlethal cultural, physical, or chemical control or a faster-acting lethal method (such as nerve and muscle agents, or potentially predation) is probably a higher-welfare option than using slower-acting insecticides (e.g. chitin-synthesis disruptors or Bt toxins) or some biological control methods (pathogens and parasitoids).

### Recommendations for future research

There are many questions that I was unable to answer when researching the content of this report. The following stood out as especially important for any further progress on a pest management intervention to improve insect welfare:

1. What symptoms do insects show when exposed to lethal and nonlethal doses of particular insecticides? How long does it take an insect to die after being exposed to a given insecticide?
2. How common are each of the causes of death experienced by insects in agroecosystems not under any kind of pest management program? How painful and how long are those experiences expected to be?
3. What trophic relationships do pest insects have in agroecosystems? Would eradicating a particular population have negative ramifications for other individuals?
4. What evidence do we have for sentience in the kinds of insects affected by agricultural pest management, which are different species than the insects that are normally studied?
5. At what developmental stage do features indicative of sentience appear in the relevant insect species?
6. How do different pest management methods affect the reproductive rates of pest insect populations? Does preventing colonization of an agroecosystem by a pest insect affect the growth of that insect's population outside the management area?

7. What is the average density of insects and other terrestrial arthropods on different types of agricultural land? On what types of agricultural land are particular insecticides used?
8. What amount of the less-common insecticides not covered in the EPA report are applied annually?
9. What are the economic injury levels (EILs) for particular crop-pest pairs? Can this information be used to generate estimates of number of insects affected by pest management?
10. On which insect species and crops are particular insecticides or pest management methods used?

Questions 1 and 2 seem important to address first, as they play a significant role in determining the valence of pest management methods. I encountered very little research examining the symptoms of lethal toxicity or time until death in insects exposed to different insecticides. A more intensive and focused literature review may turn up answers, suggest experts to contact for anecdotal evidence of symptoms, or determine that there is a gap in the literature that should be addressed in future studies. A crucial consideration for a pest management intervention is the painfulness and duration of the average death of agricultural pest insects in the absence of any management. Knowing how likely and how bad a death by a cause such as disease, dehydration, predation, or starvation is could make the difference between advocating for a lethal or non-lethal management program.

Questions 3 through 6 are important for determining the best life stage to target with a pest management program, both in terms of the welfare of the insects killed, and in terms of how many individuals are affected over the entire management period. I feel there is enough evidence of sentience in some insects to make it worthwhile to consider the potential welfare impacts of insecticides and other pest insect management techniques; however, research into question 4 would be useful as a means of continually evaluating the value of insect welfare interventions, in agroecosystems and in general.

Questions 7 through 10 are intended to help prioritize the regions, crops, and insecticidal compounds or other pest management methods for intervention.

## Conclusion

1. The evidence supporting insect sentience is sufficient to argue that, in combination with the large number of insects, we should afford some consideration to insect welfare.
2. Agricultural pest insect management practices may be a particularly tractable avenue for improving the expected welfare of a large number of insects.
3. Chemical insecticides remain a major part of many agricultural pest management programs. Their effects vary depending on the insecticide's mode of action, and I did not find much information about the symptoms of toxicity in insects from particular compounds.



4. Non-insecticidal methods of pest control may be gaining popularity, and should be considered when developing more humane pest insect management practices. The net welfare impact of non-lethal methods is dependent on ecological factors and the specific organisms involved.
5. Key unknowns make it difficult to recommend a particular insecticide or non-insecticidal pest control method as more humane. However, nerve and muscle agents (such as organophosphates and carbamates, or pyrethroids and pyrethrins) are faster-acting than insecticides with other modes of action (such as insect growth regulators, or Bt toxins).

## Acknowledgments

I thank Cameron Meyer Shorb, Michelle Graham, and Abraham Rowe for their guidance and support throughout this research project. I also thank Jane Capozzelli, Simon Eckerström Liedholm, and Luke Hecht for their insightful advice and valuable feedback during the research and writing processes.

## References

- Adamo, S. A. (2017). The "Precautionary Principle": A work in progress. *Animal Sentience*. 16(4). <https://animalstudiesrepository.org/cgi/viewcontent.cgi?article=1222&context=animsent>.
- Adamo, S. A. (2016). Subjective experience in insects: Definitions and other difficulties. *Animal Sentience*. 9(15):1-4. <https://animalstudiesrepository.org/cgi/viewcontent.cgi?article=1153&context=animsent>.
- Allen, C. and Trestman, M. (2017) Animal Consciousness. In: E. N. Zalta (ed.), *The Stanford Encyclopedia of Philosophy* (Winter 2017 Edition). <https://stanford.library.sydney.edu.au/index.html>. Retrieved 10 October 2019. <https://plato.stanford.edu/archives/win2017/entries/consciousness-animal/>.
- Atwood, D. & Paisley-Jones, C. (2017). Pesticides industry sales and usage: 2008-2012 market estimates. U.S. EPA. [https://www.epa.gov/sites/production/files/2017-01/documents/pesticides-industry-sales-usage-2016\\_0.pdf](https://www.epa.gov/sites/production/files/2017-01/documents/pesticides-industry-sales-usage-2016_0.pdf).
- AVMA. (2013). AVMA guidelines for the euthanasia of animals: 2013 edition. <https://www.avma.org/KB/Policies/Documents/euthanasia.pdf>.
- Bar-On, Y. M., Phillips, R., & Milo, R. (2018). The biomass distribution on Earth. Supplementary information appendix. *PNAS*. 115(25):6506-6511. <https://www.pnas.org/content/pnas/suppl/2018/07/13/1711842115.DC1/1711842115.sapp.pdf>.
- Barron, A. B. & Klein, C. (2016). What insects can tell us about the origins of consciousness. *PNAS*. 113(18):4900-4908. <https://www.pnas.org/content/pnas/113/18/4900.full.pdf>.
- Bartlett, A. C. & Staten, R. T. (1996). The Sterile Insect Release Method and other genetic control strategies. In: E. B. Radcliffe, W. D. Hutchison, & R. E. Cancelado [eds.], *Radcliffe's IPM World Textbook*. <https://ipmworld.umn.edu>. Retrieved 5 August 2019. <https://ipmworld.umn.edu/bartlett>.
- Birch, J. (2017). Animal sentience and the precautionary principle. *Animal Sentience*. 16(1). <https://animalstudiesrepository.org/cgi/viewcontent.cgi?referer=http://animalstudiesrepository.org/&httpsredir=1&article=1200&context=animsent>.
- Bloomquist, J. R. (2015). Insecticides: Chemistries and characteristics. 2nd edition. In: E. B. Radcliffe, W. D. Hutchison, & R. E. Cancelado [eds.], *Radcliffe's IPM World Textbook*. <https://ipmworld.umn.edu>. Retrieved 31 October 2019. <https://ipmworld.umn.edu/bloomquist-insecticides>.
- Bradbury, S. P. & Coats, J. R. (1989). Comparative toxicology of the pyrethroid insecticides. *Reviews of Environmental Contamination and Toxicology*. 108:133-177. [https://www.researchgate.net/profile/Joel\\_Coats/publication/20508882\\_Comparative\\_Toxicology\\_of\\_the\\_Pyrethroid\\_Insecticides/links/55a9190a08aea3d086802d28.pdf](https://www.researchgate.net/profile/Joel_Coats/publication/20508882_Comparative_Toxicology_of_the_Pyrethroid_Insecticides/links/55a9190a08aea3d086802d28.pdf).
- Broom, D. M. (2007). Cognitive ability and sentience: Which aquatic animals should be protected? *Diseases of Aquatic Organisms*. 75:99-108. [https://www.int-res.com/articles/dao\\_oa/d075p099.pdf](https://www.int-res.com/articles/dao_oa/d075p099.pdf).
- Bunch, T. R., Bond, C., Buhl, K. & Stone, D. (2013). Diatomaceous earth general fact sheet. National Pesticide Information Center, Oregon State University Extension Services. Retrieved 15 August 2019. <http://www.npic.orst.edu/factsheets/degen.html>.

- Čolović, M. B., Krstić, D. Z., Lazarević-Pašti, T. D., Bondžić, A. M., & Vasić, V. M. (2013). Acetylcholinesterase inhibitors: Pharmacology and toxicology. *Current Neuropharmacology*, 11(3):315-335. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3648782/pdf/CN-11-315.pdf>.
- Dawkins, M. S. (2008). The science of animal suffering. *Ethology*, 114(10):937-945. <https://doi.org/10.1111/j.1439-0310.2008.01557.x>.
- Eigenbrode S. D. (1996). Host plant resistance and conservation of genetic diversity. In: E. B. Radcliffe, W. D. Hutchison, & R. E. Cancelado [eds.], *Radcliffe's IPM World Textbook*. <https://ipmworld.umn.edu>. Retrieved 15 August 2019. <https://ipmworld.umn.edu/eigenbrode>.
- Elwood, R. W., Barr, S., & Patterson, L. (2009). Pain and stress in crustaceans? *Applied Animal Behaviour Science*, 118(3):128-136. <https://www.sciencedirect.com/science/article/pii/S0168159109000409#aep-bibliography-id22>.
- Faulde, M. K., Tisch, M. & Scharninghausen, J. J. (2006). Efficacy of modified diatomaceous earth on different cockroach species (Orthoptera, Blatellidae) and silverfish (Thysanura, Lepismatidae). *Journal of Pesticide Science*, 79:155-161. <https://link.springer.com/content/pdf/10.1007%2Fs10340-006-0127-8.pdf>.
- Ferro, D. N. (1996). Cultural control. In: E. B. Radcliffe, W. D. Hutchison, & R. E. Cancelado [eds.], *Radcliffe's IPM World Textbook*. <https://ipmworld.umn.edu>. Retrieved 7 August 2019. <https://ipmworld.umn.edu/ferro>.
- Flint, H. M. & Doane, C. C. (1996). Understanding semiochemicals with emphasis on insect sex pheromones in Integrated Pest Management programs. In: E. B. Radcliffe, W. D. Hutchison, & R. E. Cancelado [eds.], *Radcliffe's IPM World Textbook*. <https://ipmworld.umn.edu>. Retrieved 15 August 2019. <https://ipmworld.umn.edu/flint>.
- Fox, D. (2007). Consciousness in a cockroach: The insect nervous system provides clues to attention, consciousness, and the origin of the brain. *Discover Magazine*, January 2007. Retrieved 4 September 2019. <http://discovermagazine.com/2007/jan/cockroach-consciousness-neuron-similarity>.
- Fukuto, T. R. (1990). Mechanism of action of organophosphorus and carbamate insecticides. *Environmental Health Perspectives*, 87:245-254. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1567830/pdf/envhper00420-0231.pdf>.
- Giurfa, M. (2007). Behavioral and neural analysis of associative learning in the honeybee: a taste from the magic well. *Journal of Comparative Physiology*, 193(8):801-824. <https://link.springer.com/article/10.1007/s00359-007-0235-9>.
- Greenspan, R. J. & van Swinderen, B. (2004). Cognitive consonance: Complex brain function in the fruit fly and its relatives. *TRENDS in Neurosciences*, 27(12):707-711. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.304.3883&rep=rep1&type=pdf>.
- Haberkern, H. & Jayaraman, V. (2016). Studying small brains to understand the building blocks of cognition. *Current Opinion in Neurobiology*, 37:59-65. <https://www.sciencedirect.com/science/article/pii/S0959438816000088#sec0010>.
- Haynes, K. F. (1988). Sublethal effects of neurotoxic insecticides on insect behavior. *Annual Review of Entomology*, 33:149-168. [https://www.researchgate.net/profile/Kenneth\\_Haynes/publication/19877837\\_Sublethal\\_Effects\\_Of\\_Neurotoxic\\_Insecticides\\_On\\_Insect\\_Behavior/links/0046351e92dbce78c0000000.pdf](https://www.researchgate.net/profile/Kenneth_Haynes/publication/19877837_Sublethal_Effects_Of_Neurotoxic_Insecticides_On_Insect_Behavior/links/0046351e92dbce78c0000000.pdf).
- Herculano-Houzel, S., Mota, B., & Lent, R. (2006). Cellular scaling rules for rodent brains. *PNAS*, 103(32):12138-12143. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1567708/>.

Hunt, T. E., Wright, R. J., & Hein, G. L. (2009). Economic thresholds for today's commodity values. *Proceedings of the UNL Crop Production Clinics (2009)*. 93-96. <https://cropwatch.unl.edu/documents/Economic%20Thresholds.pdf>.

IASP. (2017). IASP Terminology. Retrieved 9 December 2019. <https://www.iasp-pain.org/Education/Content.aspx?ItemNumber=1698#Nociception>.

IRAC. (2019a). IRAC Mode of Action Classification Scheme. Version 9.3. IRAC International MoA Working Group. Retrieved 17 June 2019. <https://www.irc-online.org/modes-of-action/>.

IRAC. (2019b). Test methods. IRAC Methods Team. Retrieved 7 August 2019. <https://www.irc-online.org/methods/>.

IRAC. (2019c). Resistance management. IRAC Outreach Team. Retrieved 15 August 2019. <https://www.irc-online.org/about/resistance/management/>.

Jacobsen, B. (1996). USDA integrated pest management initiative. In: E. B. Radcliffe, W. D. Hutchison, & R. E. Cancelado [eds.], *Radcliffe's IPM World Textbook*. <https://ipmworld.umn.edu>. Retrieved 1 July 2019. <https://ipmworld.umn.edu/jacobsen-usda>.

Klein, C. & Barron, A. B. (2016a). Insects have the capacity for subjective experience. *Animal Sentience*. 9(1). <https://animalstudiesrepository.org/cgi/viewcontent.cgi?referer=http://animalstudiesrepository.org/&httpsredir=1&article=1113&context=animsent>.

Klein, C. & Barron, A. B. (2016b). Reply to Adamo, Key et al., and Schilling and Cruse: Crawling around the hard problem of consciousness. *PNAS*. 113(27):E3814-E3815. <https://www.pnas.org/content/113/27/E3814>.

Knutsson, S. & Munthe, C. (2017). A virtue of precaution regarding the moral status of animals with uncertain sentience. *Journal of Agricultural and Environmental Ethics*. 30(2):213-224. [https://www.researchgate.net/profile/Christian\\_Munthe/publication/315836483\\_A\\_Virtue\\_of\\_Precautio\\_n\\_Regarding\\_the\\_Moral\\_Status\\_of\\_Animals\\_with\\_Uncertain\\_Sentience/links/59e76ae84585152d5f04edd2/A-Virtue-of-Precautio\\_n\\_Regarding-the-Moral-Status-of-Animals-with-Uncertain-Sentience.pdf](https://www.researchgate.net/profile/Christian_Munthe/publication/315836483_A_Virtue_of_Precautio_n_Regarding_the_Moral_Status_of_Animals_with_Uncertain_Sentience/links/59e76ae84585152d5f04edd2/A-Virtue-of-Precautio_n_Regarding-the-Moral-Status-of-Animals-with-Uncertain-Sentience.pdf).

Koch, C., Massimini, M., Boly, M., & Tononi, G. (2016). Neural correlates of consciousness: progress and problems. *Nature Reviews Neuroscience*. 17:307-321. [http://www.crm.cat/en/Activities/Curs\\_2017-2018/Documents/Consciousness1.pdf](http://www.crm.cat/en/Activities/Curs_2017-2018/Documents/Consciousness1.pdf).

Kollmann, M., Huetteroth, M., Schachtner, J. (2011). Brain organization in Collembola (springtails). *Arthropod Structure and Development*. 40(4):304-316. [http://kops.uni-konstanz.de/bitstream/handle/123456789/28911/Kollmann\\_289118.pdf?sequence=2&isAllowed=y](http://kops.uni-konstanz.de/bitstream/handle/123456789/28911/Kollmann_289118.pdf?sequence=2&isAllowed=y).

Landis, D. A. & Orr, D. B. (1996). Biological control: approaches and application. In: E. B. Radcliffe, W. D. Hutchison, & R. E. Cancelado [eds.], *Radcliffe's IPM World Textbook*. <https://ipmworld.umn.edu>. Retrieved 1 July 2019. <https://ipmworld.umn.edu/landis>.

Mallatt, J. & Feinberg, T. E. (2016). Insect consciousness: Fine-tuning the hypothesis. *Animal Sentience*. 9(10). <https://animalstudiesrepository.org/cgi/viewcontent.cgi?article=1141&context=animsent>.

Mellor, D. J. (2016). Updating animal welfare thinking: moving beyond the "five freedoms" towards "a life worth living." *Animals*. 6(3):21. <https://doi.org/10.3390/ani6030021>.

Merker, B. (2006). Consciousness without a cerebral cortex: A challenge for neuroscience and medicine. *Behavioral and Brain Sciences*. 30(1):63-81. <https://pdfs.semanticscholar.org/3db9/c2f8ca0bc9d73532f2e950a1ecfe7063064d.pdf>.

Morand-Ferron, J., Cole, E. F., & Quinn, J. L. Studying the evolutionary ecology of cognition in the wild: a review of practical and conceptual challenges. *Biological Reviews*. 2015:1-25. [https://www.researchgate.net/profile/John\\_Quinn13/publication/271538545\\_Studying\\_the\\_evolutionary\\_ecology\\_of\\_cognition\\_in\\_the\\_wild\\_A\\_review\\_of\\_practical\\_and\\_conceptual\\_challenges/links/5b72ca87299bf14c6da1efdc/Studying-the-evolutionary-ecology-of-cognition-in-the-wild-A-review-of-practical-and-conceptual-challenges.pdf](https://www.researchgate.net/profile/John_Quinn13/publication/271538545_Studying_the_evolutionary_ecology_of_cognition_in_the_wild_A_review_of_practical_and_conceptual_challenges/links/5b72ca87299bf14c6da1efdc/Studying-the-evolutionary-ecology-of-cognition-in-the-wild-A-review-of-practical-and-conceptual-challenges.pdf).

Obrycki, J. J., Tauber, M. J., Tauber, C. A., & Ruberson, J. R. (1996). Prey specialization in insect predators. In: E. B. Radcliffe, W. D. Hutchison, & R. E. Cancelado [eds.], *Radcliffe's IPM World Textbook*. <https://ipmworld.umn.edu>. Retrieved 2 July 2019. <https://ipmworld.umn.edu/obrycki-tauber-ruberson>.

Perez, J., Bond, C., Buhl, K. & Stone, D. (2015). *Bacillus thuringiensis (Bt) General Fact Sheet*. National Pesticide Information Center, Oregon State University Extension Services. Retrieved 7 August 2019. <http://npic.orst.edu/factsheets/BTgen.pdf>.

Pfeiffer, K. & Homberg, U. (2014). Organization and functional roles of the central complex in the insect brain. *Annual Review of Entomology*. 59:165-184. [https://www.annualreviews.org/doi/full/10.1146/annurev-ento-011613-162031?casa\\_token=Zk4\\_WBrBRgIAAAAA%3AWnI9dNv8oMwMvHDR3gX4u6jTCpTYutEWIPw8219K1e76sslW17cWaiaK4XfCx6w4BT\\_Pa9LTryp8#\\_i20](https://www.annualreviews.org/doi/full/10.1146/annurev-ento-011613-162031?casa_token=Zk4_WBrBRgIAAAAA%3AWnI9dNv8oMwMvHDR3gX4u6jTCpTYutEWIPw8219K1e76sslW17cWaiaK4XfCx6w4BT_Pa9LTryp8#_i20).

Ray, G. (2017a). How many wild animals are there? *Wild Animal Suffering Research Archives*. Retrieved 6 May 2019. <https://was-research.org/writing-by-others/many-wild-animals/>.

Ray, G. (2017b). Which invertebrate species feel pain? *Wild Animal Suffering Research Archives*. Retrieved 6 May 2019. <https://was-research.org/writing-by-others/invertebrate-species-feel-pain/#Insects>.

Ray, G. (2018). Invertebrate sentience: Urgent but understudied. *Wild Animal Suffering Research Archives*. Retrieved 6 May 2019. <https://was-research.org/paper/invertebrate-sentience-urgent-understudied/>.

Rogers, J. (2019). California bans pesticide linked to brain damage in children. *Associated Press*. 9 October 2019. [www.apnews.com](http://www.apnews.com). Retrieved 31 October 2019. <https://apnews.com/2b433b664d834f3faa4e39ff257cabb6>.

Schukraft, J. (2019). Invertebrate sentience: A useful empirical resource. *Effective Altruism Forum*. <https://forum.effectivealtruism.org>. Retrieved 22 August 2019. <https://forum.effectivealtruism.org/posts/AMFuSWrsutBFraZtE/invertebrate-sentience-a-useful-empirical-resource>.

Shelton, A. *Biological Control: A guide to natural enemies in North America*. Cornell University Department of Entomology. Retrieved 7 August 2019. <https://biocontrol.entomology.cornell.edu/index.php>.

Silva-Aguayo, G. (2002). Botanical insecticides. In: E. B. Radcliffe, W. D. Hutchison, & R. E. Cancelado [eds.], *Radcliffe's IPM World Textbook*. <https://ipmworld.umn.edu>. Retrieved 15 August 2019. <https://ipmworld.umn.edu/silva-aguayo-botanical>.

Smith, R. F. & Smith, G. L. (1949). Supervised control of insects utilizes parasites and predators and makes chemical control more efficient. *California Agriculture*. 3(5):3-12. <http://calag.ucanr.edu/archive/?type=pdf&article=ca.v003n05p3>.

- Sneddon, L. U., Elwood, R. W., Adamo, S. A., Leach, M. C. (2014). Defining and assessing animal pain. *Animal Behaviour*. 97:201-212.  
[https://animalstudiesrepository.org/cgi/viewcontent.cgi?referer=http://animalstudiesrepository.org/&httpsredir=1&article=1068&context=acwp\\_arte](https://animalstudiesrepository.org/cgi/viewcontent.cgi?referer=http://animalstudiesrepository.org/&httpsredir=1&article=1068&context=acwp_arte).
- Strausfeld, N. J. & Hirth, F. (2013). Deep homology of arthropod central complex and vertebrate basal ganglia. *Science*. 340(6129):157-161. <https://science.sciencemag.org/content/340/6129/157.abstract>.
- Stork, N. E. (2018). How many species of insects and other terrestrial arthropods are there on Earth? *Annual Review of Entomology*. 63:31-45. <https://doi.org/10.1146/annurev-ento-020117-043348>  
<http://ecologylabs.org/wp-content/uploads/2018/03/Estimate-of-insect-species.pdf>.
- Teetes, G. L. (1996). Plant resistance to insects: A fundamental component of IPM. In: E. B. Radcliffe, W. D. Hutchison, & R. E. Cancelado [eds.], *Radcliffe's IPM World Textbook*. <https://ipmworld.umn.edu>. Retrieved 15 August 2019.  
<https://ipmworld.umn.edu/teetes>.
- Tebbich, S., Griffin, A. S., Peschl, M. F., & Sterelny, K. (2016). From mechanisms to function: an integrated framework of animal innovation. *Philosophical Transactions of the Royal Society B*. 371(1690):1-11.  
<https://royalsocietypublishing.org/doi/10.1098/rstb.2015.0195>.
- Tomasik, B. (2017). Which stimuli are painful to invertebrates? *Essays on Reducing Suffering*.  
<https://reducing-suffering.org>. Updated 30 July 2018. Retrieved 22 August 2019.  
<https://reducing-suffering.org/which-stimuli-are-painful-to-invertebrates/>.
- Tomasik, B. (2009). Do bugs feel pain? *Essays on Reducing Suffering*. <https://reducing-suffering.org>. Updated 28 July 2017. Retrieved 22 August 2019. <https://reducing-suffering.org/do-bugs-feel-pain/>.
- Tomasik, B. (2007). Humane Insecticides. *Essays on Reducing Suffering*. <https://reducing-suffering.org>. Updated 12 November 2018. Retrieved 26 November 2019. <https://reducing-suffering.org/humane-insecticides/>.
- Toynton, K., Luukinen, B., Buhl, K., & Stone, D. (2009). Permethrin General Fact Sheet. National Pesticide Information Center, Oregon State University Extension Services. Retrieved 25 July 2019.  
<http://npic.orst.edu/factsheets/PermGen.pdf>.
- USDA APHIS. (2006). Boll Weevil Eradication Factsheet. Plant Protection and Quarantine. Retrieved 24 July 2019.  
[https://web.archive.org/web/20070204143907/http://www.aphis.usda.gov/publications/plant\\_health/content/printable\\_version/fsbollweevil.pdf](https://web.archive.org/web/20070204143907/http://www.aphis.usda.gov/publications/plant_health/content/printable_version/fsbollweevil.pdf).
- USDA NASS. (2019a). United States: Summary and state data. 2017 Census of Agriculture. Volume 1: Geographic Area Series; part 51.  
[https://www.nass.usda.gov/Publications/AgCensus/2017/Full\\_Report/Volume\\_1,\\_Chapter\\_1\\_US/usv1.pdf](https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf).
- USDA NASS. (2019b). Ag Census Web Maps. 2017 Census of Agriculture. Retrieved 29 October 2019.  
[https://www.nass.usda.gov/Publications/AgCensus/2017/Online\\_Resources/Ag\\_Census\\_Web\\_Maps/index.php](https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Ag_Census_Web_Maps/index.php).
- USDA NIFA. Integrated pest management program (IPM). Retrieved 2 July 2019.  
<https://nifa.usda.gov/program/integrated-pest-management-program-ipm>.



U.S. EPA. (2019). Integrated pest management (IPM) principles. Retrieved 2 July 2019.  
<https://www.epa.gov/safepestcontrol/integrated-pest-management-ipm-principles>.

U.S. EPA. (2017). Insect resistance management for Bt plant-incorporated protectants. Retrieved 15 August 2019.  
<https://www.epa.gov/regulation-biotechnology-under-tsca-and-fifra/insect-resistance-management-bt-plant-incorporated>.

U.S. EPA. (2009). Permethrin facts: Reregistration eligibility decision (RED) fact sheet. Retrieved 25 July 2019.  
[https://www3.epa.gov/pesticides/chem\\_search/reg\\_actions/reregistration/fs\\_PC-109701\\_1-Aug-09.pdf](https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-109701_1-Aug-09.pdf).

U.S. EPA. (2002). Chlorpyrifos facts. Retrieved 10 May 2019.  
[https://www3.epa.gov/pesticides/chem\\_search/reg\\_actions/reregistration/fs\\_PC-059101\\_1-Feb-02.pdf](https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-059101_1-Feb-02.pdf).

U.S. EPA. (2016). What are biopesticides? Retrieved 1 July 2019.  
<https://www.epa.gov/ingredients-used-pesticide-products/what-are-biopesticides>.

USGS. (2017). New map of worldwide croplands supports food and water security. Retrieved 9 December 2019.  
<https://www.usgs.gov/news/new-map-worldwide-croplands-supports-food-and-water-security>.

Vogel, D. (2016). Chlorpyrifos status update. EPA Pesticide Program Dialogue Committee. Retrieved 10 May 2019.  
<https://www.epa.gov/sites/production/files/2016-05/documents/session-2-chlorpyrifos-human-health-risk-assessment-approach.pdf>.

Waldhorn, D. (2019). Invertebrate sentience: Summary of findings, part 2. Effective Altruism Forum.  
<https://forum.effectivealtruism.org>. Retrieved 22 August 2019.  
<https://forum.effectivealtruism.org/posts/JtmiKxwCL7CQ4iL4p/invertebrate-sentience-summary-of-findings-part-2-1>.

Williams, C. B. (1960). The range and pattern of insect abundance. *The American Naturalist*. 94(875):137-151.  
[https://www.jstor.org/stable/pdf/2458376.pdf?casa\\_token=vMq0wVTqe10AAAAA:YbMo1x6UOypH9Qu\\_6FhGlnw4ndtK\\_Wey0oA4bJvrNJ\\_RYrJqbV24Wyi7qKFfaIz0aeTnv4wT9PLHQi\\_C99TOyAHobAKwPVzg4DuBo2n9cuGThLE7o1A](https://www.jstor.org/stable/pdf/2458376.pdf?casa_token=vMq0wVTqe10AAAAA:YbMo1x6UOypH9Qu_6FhGlnw4ndtK_Wey0oA4bJvrNJ_RYrJqbV24Wyi7qKFfaIz0aeTnv4wT9PLHQi_C99TOyAHobAKwPVzg4DuBo2n9cuGThLE7o1A).

Wolansky, M. J. & Harrill, J. A. (2007). Neurobehavioral toxicology of pyrethroid insecticides in adult animals: a critical review. *Neurotoxicology and Teratology*. 30(2):55-78.  
[http://www.latomeq.qb.fcen.uba.ar/imagenes/Review\\_Pyrethroids\\_Corrected\\_Proof.pdf](http://www.latomeq.qb.fcen.uba.ar/imagenes/Review_Pyrethroids_Corrected_Proof.pdf).