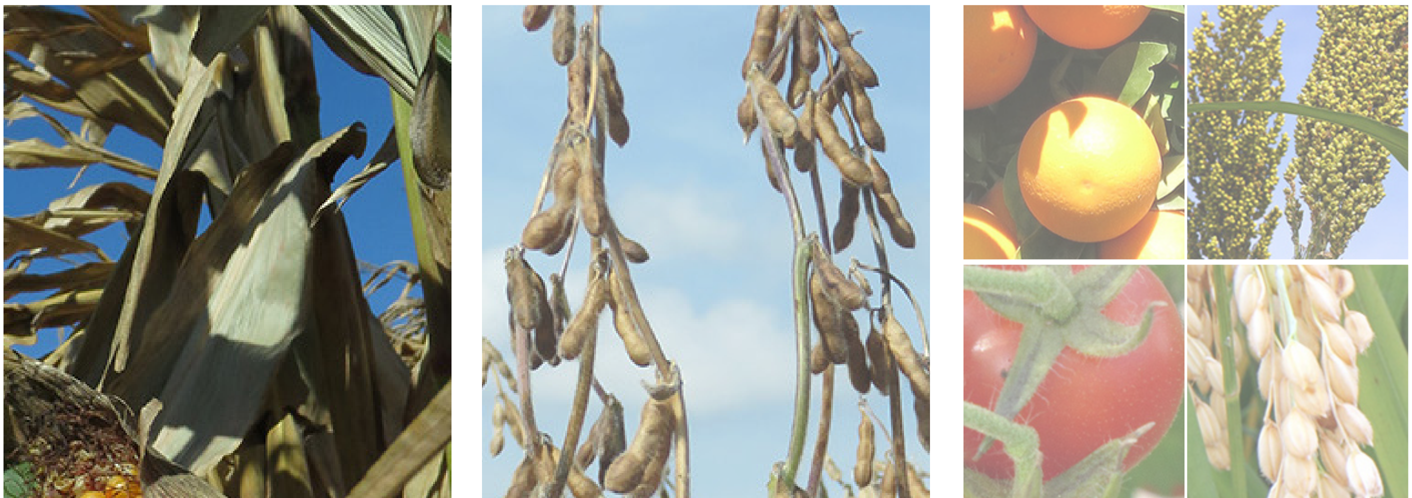
AgInfomatics

# The value of pyrethroids in U.S. agricultural and urban settings:



## Estimated yield benefits and efficacy of pyrethroid insecticides for major U.S. crops based on a meta-analysis of small plot data

2017

This report series, researched and produced by AgInfomatics, LLC, is an independent and comprehensive analysis of the economic and societal benefits of pyrethroid insecticides (bifenthrin, cyfluthrins, cyhalothrins, cypermethrins, deltamethrin, esfenvalerate, fenpropathrin, permethrin, and tefluthrin). The research was sponsored by the Pyrethroid Working Group, an informal association of firms marketing products based on the above pyrethroid active ingredients. These products are used in agricultural, structural and landscape applications.

AgInfomatics, an agricultural consulting firm established in 1995, conducted an analyses exploring the answer to the question: *What would happen if pyrethroids were no longer available or restricted beyond the current situation?* Comparing this hypothetical future to the economics associated with current applications allowed AgInfomatics to derive an estimate of the value of pyrethroids.

This estimated value was based on robust quantitative and qualitative study methods including econometrics, modeling of insecticide use, crop yield data, market impacts, surveys of growers, surveys of professional applicators and in-depth case studies. All these data sources and methods were used to triangulate on the above question.

## The value of pyrethroids in North American agriculture and urban settings

Reports include:

1. Executive summary
2. Methods and assumptions for estimating the impact of pyrethroid insecticides on pest management practices and costs for U.S. crop farmers
3. Summary of the use of pyrethroid insecticides by U.S. crop farmers and the impacts of non-pyrethroid scenario on insecticide use and farmer costs
4. Estimated yield benefits and efficacy of pyrethroid insecticides for major U.S. crops based on a meta-analysis of small plot data
5. Use and value of insect management practices in U.S. alfalfa corn, cotton and soybean production
6. Value of pyrethroid insecticides to urban pest management professionals
7. An economic assessment of the benefits of pyrethroid insecticides in the U.S.
8. Case studies of pyrethroid use patterns and potential impacts of regulatory changes on production of high value fruits and vegetables in primary U.S. production states
9. A case study of pyrethroid use patterns and potential impacts of regulatory changes on the control of mosquito vectors in Florida

*For more information, please contact: AgInfomatics@gmail.com*

## Contents

# Executive summary

This report summarizes the yield benefits and efficacy of pyrethroid insecticides for several major U.S. crops based on a meta-analysis of small plot data. The report contains three sections. Section 1.0 focuses on soybean, section 2.0 on corn and section 3.0 on the following 11 crops: alfalfa, citrus, cotton, potato, rice, sorghum, sugar beet, sunflower, sweet corn, tomato, and wheat. The meta-analyses for soybean and corn are described separately because different methods are used than for the crops in the third section, since more data were available. The focus of this executive summary of the full report is on the broad-level findings for each section, with each section providing more specific details.

Overall, this meta-analysis of small plot data finds that pyrethroid insecticides are among the most efficacious insecticide classes used commercially to manage a wide range of pests in a variety of crops. In most pest-crop systems examined here, pyrethroids are the most efficacious insecticide class or are equally efficacious to other classes used. Superior efficacy generally translates to higher yields, but this connection is highly variable due to the natural variability in pest-crop systems. Because pyrethroids are generally a lower cost insecticide class, they are typically economically competitive with other insecticide classes because of their efficacy and associated yield benefits. As a result, pyrethroids are an effective and economical insecticide class that provide monetary benefits for many farmers, and in the longer term, they provide low cost options for rotating or mixing insecticide classes for managing insect resistance to multiple modes of action.

## 1 Soybean

The meta-analysis of soybean small-plot data focused on the soybean aphid, the primary insect pest of soybean in the U.S. The meta-analysis found that foliar-applied pyrethroid insecticides are the most efficacious method for controlling soybean aphids in soybean in the U.S. A foliar application of a pyrethroid insecticide was the most effective treatment for reducing both the average and the variability of cumulative aphid days for soybean aphids. This increased efficacy also increased yields. The yield advantage of a foliar-applied pyrethroid for managing soybean aphids was 0.7% compared to a foliar-applied non-pyrethroid and 3.75% compared to a neonicotinoid seed treatment.

Focusing on farmer returns, analysis over a wide range of assumptions shows that reasonable ranges of soybean yield and price, treatment cost and aphid pressure exist for which farmers can find each of these management options the most profitable. As a result, farmers will find a portfolio of control options that provide managerial flexibility useful, as the most profitable management option for soybean aphids likely varies across fields and years. Foliar-applied pyrethroids will be a key part of this portfolio for many farmers to manage soybean aphids, but maintaining alternative methods and insecticide classes is important for rotating and mixing modes of action for managing insect resistance.

## 2 Corn

The meta-analysis of corn small-plot data focused on soil-applied insecticides for managing corn rootworm larvae, the primary insect pest of corn in the U.S. The meta-analysis found that the most effective soil-applied insecticide treatment for reducing the root injury from corn rootworm larval feeding was a pyrethroid-organophosphate insecticide premix. This premix reduced the average and the standard deviation of the node injury scale to levels comparable to a single toxin Bt corn before the development of rootworm resistance to Bt toxins. When used alone, pyrethroids were slightly less effective than the premix but provided comparable reductions in root injury as organophosphates used alone and significantly better than the other insecticide classes examined (diamides, neonicotinoids and phenylpyrazoles).

The corn yield advantage of soil-applied pyrethroid insecticides averaged about 12% relative to no control. The yield advantage of a pyrethroid-organophosphate premix relative to a pyrethroid used alone averaged about 1.0% and the yield advantage for a pyrethroid used alone relative to the other insecticide classes examined averages about 3.5%. These average yield advantages are for fields where average rootworm pressure is moderate to high, with the average node injury scale of 1.0; these averages will increase or decrease with average rootworm pressure.

## 3 Other crops

The meta-analysis of small plot data for the other 11 major crops found that pyrethroid insecticides substantially increase yields, reduce both pest abundance and crop damage, and improve crop health. These findings provide empirical support for the long-standing and widespread commercial use of pyrethroid insecticides in these and other crops. Furthermore, the benefits provided by pyrethroid insecticides are at least comparable to those provided by other commercially available insecticide classes, with the magnitude of the benefits tending to follow the same trends across crops.

Notable examples exist in which pyrethroids out-perform other insecticide classes. Most noteworthy is pest abundance, in which the average efficacy of pyrethroid treatments was generally larger than for non-pyrethroid treatments, with only a few exceptions (Colorado potato beetles in potato, non-lepidopteran cotton pests and all pests in wheat). Other notable examples of pyrethroids out-performing other insecticide classes included yield increases for sweet corn, potato and sunflower and for crop damages in cotton, potato, sugar beet, sunflower and tomato. The benefits of pyrethroids are often enhanced when insecticide treatments combine pyrethroids and non-pyrethroids, indicating the benefits from mixing or sequencing pyrethroids with other modes of action. Rotating or mixing modes of action not only increases yield and efficacy in the short-term but also in the long-term by helping manage insect resistance for multiple modes of action.

# **1.0** Pest pressure, control efficacy, yield benefits and farmer net returns for soybean aphid management

## 1.1 Executive summary

The soybean meta-analysis focused on soybean aphid (*Aphis glycines*), the primary insect pest of soybean in the U.S. Data were assembled from 118 site-years of small-plot studies conducted from 2002-2015 in 10 states. Observations of yield and cumulative aphid days for soybean aphid included 118 observations for the untreated control, 225 observations for insecticide seed treatments and 588 observations for foliar-applied insecticide treatments. None of the seed treatments were pyrethroids, but 386 observations of the foliar-applied insecticide treatments used a pyrethroid, either alone or as part of a mix. The meta-analysis specified a bio-economic model of pest pressure, control efficacy, yield impacts and farmer returns, and the small plot data were used to estimate parameters for all model components. The parametrized model was then used to estimate the average yield benefit of foliar-applied insecticides and seed treatments for controlling soybean aphid.

The meta-analysis found that foliar-applied pyrethroid insecticides are the most effective method for controlling soybean aphids in soybean in the U.S. A foliar application of a pyrethroid insecticide was the most effective treatment for reducing both the average and the variability of cumulative aphid days for soybean aphids. On average, 19.5% of the initial aphid pressure remains after a foliar application of a pyrethroid, which is an efficacy advantage of 12.3% compared to a foliar-applied non-pyrethroid and 35% compared to a neonicotinoid seed treatment. Similarly, the standard deviation of aphid days as a percentage of the initial aphid pressure is an additional 10% to 11.5% lower with a foliar-applied pyrethroid than with a foliar-applied non-pyrethroid insecticide or a seed treatment.

Based on Monte Carlo simulations with the estimated efficacy and yield benefit models, the average yield advantage of a foliar-applied pyrethroid for managing soybean aphids was 0.7% compared to a foliar-applied non-pyrethroid and 3.75% compared to a seed treatment. The estimated average yield benefit for a seed treatment ranged 1.5% to 3.0% across the regions and 2.4% when averaging over all regions. The average yield gain for a foliar-applied pyrethroid averaged 6.15% across the regions, for a relative yield advantage of 3.75% for a foliar-applied pyrethroid compared to a seed treatment (i.e., 6.15% — 2.4% = 3.75%). Similarly, the yield gain for a foliar-applied non-pyrethroid averages 5.45% across the regions, and so the relative yield advantage of a foliar-applied pyrethroid compared to a non-pyrethroid averages 0.7%. These average yield benefits are comparable to those reported in other meta-analyses, national surveys and multi-state small-plot data sets for seed treatments and foliar insecticide applications (e.g., North et al. 2016, Hurley and Mitchell 2016, Mitchell 2014c, Orlwoski et al. 2016).

Two key findings emerge from Monte Carlo simulations of farmer net returns for each treatment over a wide range of assumptions for soybean

yield and price, control costs and aphid pressure. First, the range of the average increase in farmer net returns for these control options relative to no control is at most about $50 per acre under appropriate assumptions, and the differences between the different insecticide treatments in many cases is not large. As a result, given the variability in soybean prices and yields and pest pressure between years and among fields, these average differences in net returns among the treatment options would be difficult for farmers to detect consistently.

Second, for reasonable ranges of soybean yield and price, control costs and aphid pressure, each one of these aphid control options can be optimal for a farmer based on the average increase in net returns. Assuming average costs for insecticides and scouting with low soybean yields, prices and aphid pressure, leaving a field untreated maximizes average net returns, while with high soybean yields, prices and aphid pressure, using a foliar-applied pyrethroid maximizes average net returns, with intermediate cases between these for which a seed treatment can maximize average net returns. Thus, under reasonable conditions, farmers can find each of these management options the profitable, so that the most profitable option can shift across fields and years as soybean prices and yields, control costs and aphid pressure varies.

Based on these results, farmers will find a portfolio of control options that provide managerial flexibility useful, as the most profitable management option for soybean aphids likely varies across fields and years for most farmers. Foliar-applied pyrethroids will be a key part of this portfolio for many farmers to manage soybean aphids.

Two important caveats apply to this analysis. First, this analysis focused solely on the soybean aphid, the primary insect pest of soybean in the U.S., even though farmers manage a wide variety of insect pests in soybean, both below-ground and above-ground. Key above-ground pests that are also managed with foliar-applied pyrethroids include several leaf beetles from the family Chrysomelidae (e.g., bean leaf beetle, flea beetle, adult rootworm beetle, Colorado potato beetle), plus various stink bugs (family Pentatomidae) and spider mites (family Tetranychidae). Though in aggregate and on average, these may be minor soybean insect pests; in specified years and for specific farmers, they can be major insect pests and cause economic losses. The benefits of pyrethroids for managing these pest are not included here. Second, the resistance management benefits of foliar applied pyrethroids are not explicitly accounted for in this analysis. Providing farmers with alternative methods and insecticide classes is important, since rotating and combining modes of action is a key part of managing insect resistance. Pyrethroids are generally a lower cost class of insecticides, and so are often a part of insecticide rotations and mixes with more costly insecticide classes to help preserve their efficacy.

## 1.2 Introduction

The U.S. is the world's largest soybean producer, growing about 30% of total global production, and soybean is the second largest crop in the U.S. in terms of planted acres and the value of farm production (USDA 2016, USDA-NASS 2017). In 2014, a total of 83.3 million soybean acres were planted in the U.S., producing 3.93 billion bushels and generating $39.7 billion in farm gate value based on a marketing year average price of $10.10/bu (USDA-NASS 2017). In 2015, 82.65 million soybean acres were planted, again producing 3.93 billion bushels, but with a somewhat lower total crop value expected due to lower market prices, though the 2015 marketing year does not end until August of 2016 (USDA NASS 2017).

The soybean aphid (*Aphis glycines*) is the primary insect pest of soybean in the U.S. Yield losses without control can often exceed 20% or more (Ragsdale et al. 2007; Hurley and Mitchell 2016). Besides direct yield loss due to feeding damage, soybean aphids also transmit viruses to crops, causing additional yield loss (Grau 2015). Farmers commonly use insecticides to control soybean aphid populations and reduce yield losses. The most common insecticide-based treatments used in the U.S. are insecticidal seed treatments and foliar insecticide applications. The U.S. average for 2010-2012 was 29.1 million soybean acres treated with an insecticidal seed treatment, with 40% of U.S. soybean planted acres on average using neonicotinoid seed treatments in 2010-2012 to control a variety of insect pests, including the soybean aphid (Mitchell 2014a, 2014b). For foliar insecticides, the U.S. average for 2012-2014 was 22.9 million acres treated with a foliar insecticide or about 29% of soybean planted acres (Mitchell 2017). Pyrethroid insecticides were the most commonly used foliar insecticide in soybeans with pyrethroids comprising 14.9 million acres of the 22.9 million acres of foliar insecticides used in soybean (Mitchell 2017).

Seed treatments are lower cost than foliar insecticides once the cost of application and scouting is included, but their efficacy is likely lower as well. Seed treatments are "applied" at the time of planting and become systemic throughout the growing plant, but in-plant concentrations begin to decline as the insecticide degrades and the plant increases in size. As a result, by the time soybean aphid populations typically become problematic in fields, in-plant concentrations are too low to be as efficacious as well-timed foliar applications, at least at current registered application rates for seed treatments. However, seed treatments also protect seeds and young plants from other pests, most commonly seedcorn maggots (*Delia platura*), wireworm larvae (*Melanotus* spp., *Agriotes mancus*, *Limonius dubitans*) and bean leaf beetle (*Cerotoma trifurcata*) and help establish a good stand and/or provide early-season foliar protection from insects. Neonicotinoids have also been shown to have plant growth regulator effects that enhance early season growth (Higley and Boethel 1994, Macedo and Camargo Castro, 2011).

For below-ground pests such as seed maggots and wireworms, developing scouting methods is difficult and even if such methods existed, making scouting-based insecticide applications in a newly seeded or just emerged crop is impractical. Furthermore, no soil-applied insecticides are registered for use in soybean in the U.S., and so U.S. farmers rely on neonicotinoid seed

treatments to control below-ground insect pests, based on their experience of stand loss in a field, treatment cost, seed prices and the crop prices. For managing soybean aphids, farmers can use a lower cost but less effective seed treatment for soybean aphids or rely on scouting to detect when aphid populations become problematic and then treat only those fields that need it with a more costly but more effective, foliar insecticide. Multiple trade-offs exist between cost and efficacy, between timing and risk and between risk-based IPM and scouting-based IPM; these trade-offs likely vary among regions.

To address these and other pest management questions, numerous small-plot experiments have been conducted at many locations over several years (e.g. North et al. 2016, Gaspar et al. 2014; Orlowski et al. 2016). This paper analyzes the available data from many of these experiments to examine the economics of managing soybean aphid in the U.S., comparing seed treatments and foliar-applied insecticides. To better identify the benefits of pyrethroid insecticides, the analysis of foliar-applied insecticides separates pyrethroid and non-pyrethroid insecticides. The overall goal of the analysis is to use small plot data to estimate the economic value of pyrethroid insecticides for managing soybean aphid as part of a comprehensive evaluation of the benefits of pyrethroid insecticides in U.S. crop production.

The remainder of this section first briefly overviews the history of the soybean aphid and its life cycle in the U.S. Next the available small plot data are briefly summarized, and then the analytical framework capturing the soybean aphid management problem is described. Model components include aphid pressure, control efficacy, yield benefits and finally, farmer net returns for each control option. Next estimation results are presented that use the small plot data to link the model components together. The economic analysis is described, which relies on Monte Carlo simulation parameterized with the estimation results to examine the expected farmer net returns for each control option. Finally, the economic results are presented with discussion of the implications of the findings for the value of pyrethroid insecticides for managing soybean aphid.

### 1.2.1 Soybean aphid in the U.S.

The soybean aphid is native to eastern Asia but has been spreading globally at an increasing rate. Between 1980 and 1990, the soybean aphid was newly confirmed in seven Asian nations, spreading from China primarily by cargo and baggage transport (Ragsdale et al. 2004). The soybean aphid was first confirmed in the U.S. in August of 2000 in Wisconsin and was documented in nine other states by the end of the season; at this time, it has been confirmed in 21 states (Venette and Ragsdale 2004).

The resilience of the soybean aphid is attributed in part to its lifecycle. Aphid females lay hard-shelled eggs that overwinter on buckthorn foliage. The first generations of aphids hatch as mature, wingless aphids known as fundatrices in early spring. The second generation produced on buckthorn is primarily wingless females. The third generation of aphids is predominantly winged, mature females that migrate to the secondary host, which in North America is primarily soybean (Ragsdale et al. 2004). The aphids typically begin migrating to soybean fields to feed in early June, depending on natural factors, including temperature. Throughout the summer, both winged and wingless females are produced. Because female aphids can reproduce asexually and bear live young, several generations can be produced quickly. Because of their lightweight bodies, aphid population can also use wind to migrate long distances in a short amount of time. Reduced light and temperatures in the autumn trigger aphid populations to produce both a winged female and a winged male, which migrate back to buckthorn where the females produce a sexual nymph known as oviparae. The oviparae mate with the male aphids and produce overwintering eggs that are deposited on buckthorn.

During the growing season, the soybean aphid causes damage to soybean crops by piercing plants and sucking sap. In the early growth stages, the aphids feed primarily on young leaves. As the growing season continues, aphid feeding expands to leaves, flowers, pods and stems, which result in shorter plants, fewer pods and small, lower quality seeds. Aphids also excrete honeydew onto the leaves, which can cause fungal growth to develop and inhibit photosynthesis. In addition, soybean aphids can cause significant damage by transmitting viruses. Within soybean crops, the aphid is a vector of the soybean mosaic virus (SMV) and the alfalfa mosaic virus (AMV) (Hill et al. 2001; Clark and Perry 2002). Virus symptoms include plant stunting, leaf distortion, mottling, reduced pod numbers and seed discoloration. Aphids also spread viruses to other plants. For example, though soybean aphid cannot colonize a potato crop, individuals visit potato fields and spread potato leafroll virus (PLV) to susceptible plants with a 6% to 9% efficiency and potato virus Y (PVY) with a 14% to 75% efficiency (Davis and Radcliffe 2008; Davis et al. 2005).

## 1.3 Small plot data

This section first briefly overviews the small plot data used for this analysis and then describes the analytical framework used to model farmer net returns for different aphid management options. The framework developed here begins with a model for the background pressure for soybean aphid and a model of control efficacy to describe how each control method reduces this pressure. Next, a yield benefit model describes the additional yield generated by reducing this aphid pressure, and then finally, a model of per acre revenue and costs captures the impact on farmer net returns.

The small plot data used for this analysis were from replicated and randomized trials that included an untreated control, with at least one treatment as an insecticide seed treatment, a foliar treatment or a combination of a seed and foliar treatment. The untreated control plots were categorized as *untreated*. However, all soybean seeds in these plots were treated with a fungicidal seed treatment, independent of the insecticide treatment (i.e., even the untreated controls), so that the only difference between untreated control plots and treated plots was the insecticide treatment. Plots planted with a neonicotinoid seed treatment were categorized as *seed*. Plots receiving a foliar insecticide application based on integrated pest management (IPM) were categorized as *foliar*. IPM involved scouting the plots throughout the season and applying a foliar insecticide only if aphid populations reached

the economic threshold (Ragsdale et al. 2007). For the analysis of the *foliar* yield benefit, only plots that were actually sprayed were included ( i.e., the foliar yield benefit is the yield gain if an insecticidal spray is actually made).

Table 1.1 summarizes the available data. Data were available from 2002-2015 from 10 states. A site-year is a set of replicated trials conducted at a single site in a single year that included an untreated control. Multiple observations were generated at a single site-year because multiple seed treatments or foliar sprays may be evaluated, plus multiple experiments may be conducted at the same site in a year. This analysis used five regions: Eastern Corn Belt (Illinois, Indiana, Ohio and Michigan), Great Plains (North Dakota, South Dakota and Nebraska), and three individual states: Iowa, Minnesota and Wisconsin. States grouped into regions were contiguous and were judged to have too few observations for separate estimation.

Based on Table 1.1, there are 34 site-years in the Eastern Corn Belt region, 16 site-years in the Great Plains region, 20 site-years in Iowa, 28 site-years in Minnesota and 20 site-years in Wisconsin for a grand total of 118 site-years of data, and so there are 118 observations for the untreated control. In addition, there are 225 observations for insecticide seed treatments and 588 observations for foliar-applied insecticide treatments. None of the seed treatments were pyrethroids, but 386 observations of the foliar-applied insecticide treatments used a pyrethroid, either alone or as part of a mix. Figure 1.1 shows the distribution of the site years by state/region and year and Figure 1.2 shows the distribution of the observations by year and insecticide application method. In terms of application method, most of the

**TABLE 1.1** Number of site-years and observations for each treatment by state and region

| | | ---------------- Observations ---------------- | | |
|---|---|---|---|---|
| **Region or State** | **Site-years*** | **Seed Treatment** | **Foliar Application** | **Total*** |
| Eastern Corn Belt | 34 | 73 | 149 | 256 |
| Illinois | 9 | 19 | 63 | 91 |
| Indiana | 8 | 15 | 19 | 42 |
| Michigan | 13 | 19 | 67 | 99 |
| Ohio | 4 | 20 | 0 | 24 |
| Great Plains | 16 | 8 | 126 | 150 |
| North Dakota | 3 | 0 | 10 | 13 |
| Nebraska | 6 | 3 | 60 | 69 |
| South Dakota | 7 | 5 | 56 | 68 |
| Iowa | 20 | 37 | 203 | 260 |
| Minnesota | 28 | 56 | 84 | 168 |
| Wisconsin | 20 | 51 | 26 | 97 |
| **Grand Total** | **118** | **225** | **588** | **931** |

*Each site year has one observation of an untreated control, so the total number of observations for a region or state also counts these observations.

observations are for foliar applications, and in terms of states, most of the observations are from Iowa and Minnesota. In terms of years, most of the data are from 2005 and 2007 to 2009, a few years after the initial invasion when widespread field research reached its peak.

## 1.4 Analytical framework

The analytical framework used for this analysis is illustrated in Figure 1.3. The analysis begins with pest pressure. If pest control is used, this pest pressure is reduced, with different control options having different effica-

**FIGURE 1.1** Number of site years by state/region and year (ECB = Eastern Corn Belt (Illinois, Indiana, Ohio, Michigan), GP = Great Plains (North Dakota, South Dakota, Nebraska), IA = Iowa, MN = Minnesota, WI = Wisconsin)

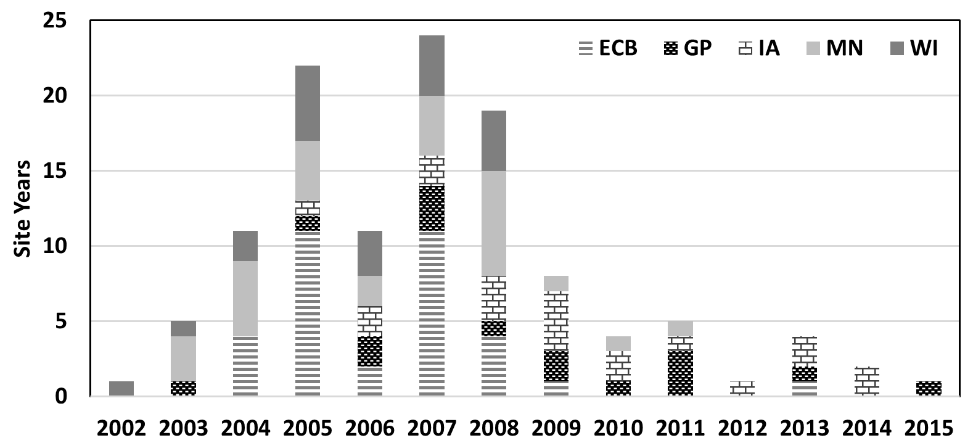



**FIGURE 1.2** Number of observations by year and insecticide application method

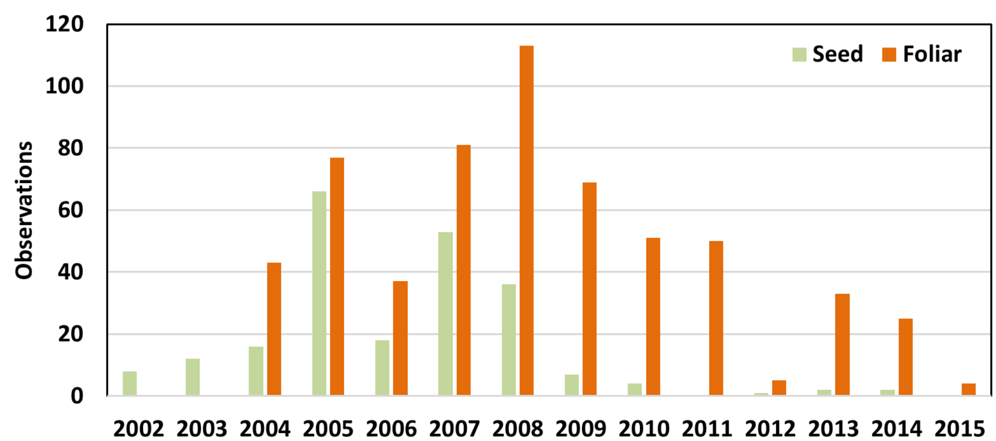
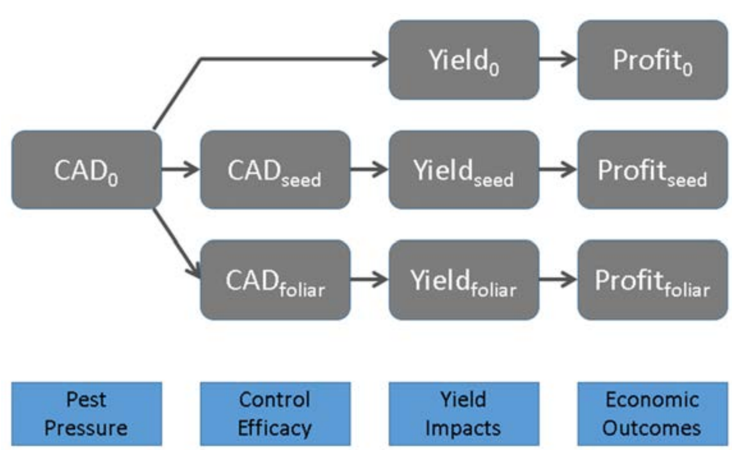



**FIGURE 1.3** Components of the bioeconomic model of soybean aphid management



cies. Based on this efficacy, yield is determined for each control option and then farmer net returns (profit). The reminder of this section describes the parametrization of the various components of this framework for soybean aphid using the small plot data.

### 1.4.1 Aphid pressure

Individual soybean aphids are quite small, and hundreds or even thousands can infest a single plant (Hodgson et al. 2012). Because their direct cause of damage is piercing the plant and sucking plant juices on a regular basis, and these effects on the plant accumulate over time, entomologists use cumulative aphid days (CAD) as measure of soybean aphid pressure (Ragsdale et al. 2007). Aphid populations per plant are sampled on different days, and CAD between any two days is the average aphid population for the two sample dates multiplied by the number of days between the two sample dates. More specifically, based on Hanafi et al. (1989), if $t$ indexes sample dates and $A_t$ is the per plant aphid population on sample data $D_t$, then CAD over all sample dates $t$ = 1 to $T$ is

(1.1)
$$\mathrm{CAD} = \sum_{t=1}^{T-1} \tfrac{1}{2}(A_{t+1} + A_t)(D_{t+1} - D_t)\ .$$

This analysis uses CAD as the fundamental measure of soybean aphid pressure.

Small plot experiments leave untreated plots as experimental controls and this analysis uses the CAD data from these plots to estimate unconditional probability density functions for CAD as a stochastic model of background pressure from soybean aphids. We use a two parameter gamma distribution to model the initial aphid pressure, $\mathrm{CAD}_0$ and the efficacy of the insecticide treatments. Following Pinder et al. (1978), preliminary analysis also examined the Weibull distribution. Both models fit the data fairly similarly, but based on the Bayesian Information Criterion (BIC), the gamma distribution fit the data better. As a further advantage, the gamma distribution can be re-parametrized in terms of the mean and standard deviation, allowing for a more intuitive comparison among regions.

The probability density function $f(x)$ for a random variable $x$ with a gamma distribution is

(1.2)
$$f(x \mid \gamma, \eta) = \frac{x^{(\gamma-1)}}{\Gamma(\gamma)\eta^{\gamma}} \exp(-x/\eta)\,,$$

where the parameters $\gamma$ and $\eta$ determine the skewness and the shape of the distribution, respectively, and $\Gamma(\cdot)$ is the gamma function. The parameters $\gamma$ and $\eta$ can be expressed as functions of the mean ($\mu$) and standard deviation ($\sigma$) (Evans et al. 2000):

(1.3)
$$\gamma = \frac{\mu^2}{\sigma^2} \text{ and } \eta = \frac{\sigma^2}{\mu}\,.$$

Substituting these expressions into equation (1.2) re-parameterizes the probability density in terms of the mean and standard deviation, which allows direct estimation of the mean and standard deviation using maximum likelihood and makes comparing regional differences and the efficacy of different treatments more intuitive.

For initial aphid pressure as measured by $CAD_0$, regional differences in the mean $\mu_0$ and standard deviation $\sigma_0$ are explored empirically by using maximum likelihood to estimate the following models with regional indicator variables:

(1.4) $$\mu_0 = \sum_r \mu_r D_r \text{ and } \sigma_0 = \sum_r \sigma_r D_r \,.$$

Here, *r* indexes regions, $\mu_r$ and $\sigma_r$ are the mean and standard deviation of $CAD_0$ for region *r*, and $D_r$ is an indicator variable equal to 1 for data from region *r* and 0 otherwise.

### 1.4.2 Aphid control efficacy

Use of an insecticide or other control method reduces soybean aphid pressure, which in the context of this framework implies a reduction in CAD. To measure of the efficacy of the treatment, the analysis here uses the CAD data from the small plot experiments to estimate probability density functions for CAD after each of the aphid control methods (seed treatment, foliar insecticide). Maximum likelihood is used to estimate the distribution of CAD with treatment ($CAD_{trt}$) conditional on the initial CAD ($CAD_0$), assuming a proportional reduction in CAD due to the treatment. Specifically, a gamma density function is estimated for $CAD_{trt}$ with the mean ($\mu_{trt}$) and standard deviation ($\sigma_{trt}$) as proportions of $CAD_0$:

(1.5) $$\mu_{trt} = (\lambda_{seed} D_{seed} + \lambda_{foliar} D_{foliar} + \lambda_{pyrethroid} D_{pyrethroid} D_{foliar}) CAD_0 \,,$$

(1.6) $$\sigma_{trt} = (\theta_{seed} D_{seed} + \theta_{foliar} D_{foliar} + \theta_{pyrethroid} D_{pyrethroid} D_{foliar}) CAD_0 \,.$$

Here the subscripts *seed* and *foliar* denote the aphid control method as either an insecticide seed treatment or a foliar insecticide application, and pyrethroid denotes insecticide. $D_{seed}$ and $D_{foliar}$ are indicator variables for each aphid control method ($D_i$ = 1 if the treatment *i* is used and 0 otherwise), and $D_{pyrethroid}$ is an indicator variable that equals 1 if a pyrethroid insecticide was used for the foliar application.

In equations (1.5) and (1.6), the parameter $\lambda$ determines average proportion of the initial CAD remaining after treatment and the parameter $\theta$ is the proportion of the standard deviation of CAD after treatment relative to the initial CAD. Thus the parameter $\lambda_{seed}$ is the average proportion of the initial CAD remaining after a seed treatment, and the parameter $\theta_{seed}$ is the proportion of the standard deviation of CAD after a seed treatment relative to the initial CAD. The parameters $\lambda_{foliar}$ and $\theta_{foliar}$ have similar interpretations, but for a foliar-applied insecticide that is not a pyrethroid.

Lastly, the parameters $\lambda_{pyrethroid}$ and $\theta_{pyrethroid}$ are the deviation of the $\lambda$ and $\theta$ parameters for a foliar-applied pyrethroid from the $\lambda_{foliar}$ and $\theta_{foliar}$ for a foliar-applied non-pyrethroid. Thus the average proportion of the initial CAD remaining after a foliar-applied pyrethroid is $\lambda_{foliar} + \lambda_{pyrethroid}$ and the proportion of the standard deviation of CAD after a foliar-applied pyrethroid is $\theta_{foliar} + \theta_{pyrethroid}$.

With this model, if aphid control method reduces the mean CAD, then $\lambda < 1$ and if aphid control method reduces the variability of CAD, then $\theta < 1$. Similarly, the relative efficacy and risk reduction of each control method can be evaluated by testing the magnitude of the $\lambda$ and $\theta$ parameters for each control method.

### 1.4.3 Yield Benefit

This analysis also uses small plot data to estimate the yield benefit provided by reducing soybean aphid pressure. Building on the previous analysis, the yield benefit depends on the reduction in CAD, with a larger benefit expected with a greater reduction in the aphid population. However, this yield benefit is uncertain due to a variety of factors affecting the crop, the pest, and control efficacy. Furthermore, these control methods can affect populations and crop damage from other pests, not only seedcorn maggot and wireworm larvae but also numerous scarab beetle larvae ("white grubs") (*Phyllophaga spp*.). Above-ground pests affected by these treatments include bean leaf beetle, Japanese beetle (*Popillia japonica*), spider mites (family Tetranychidae) and various stink bugs including the green stink bug (*Acrosternum hilare*) (Hurley and Mitchell 2016, Mitchell 2017). Furthermore, not only do the population densities of these pests vary regionally, but also the yield losses they cause vary across species.

The analysis uses CAD and yield data from small plot experiments to estimate a stochastic yield benefit model that also allows yield benefits from control of other pests besides soybean aphids. More specifically, the yield benefit (*YB*) for a pest control treatment at a single location in any given year is calculated as

$$YB_{trt} = (Y_{trt} - Y_0) / Y_0 , \tag{1.7}$$

where $Y_{trt}$ is average yield with the pest control treatment and $Y_0$ is yield for the untreated control plots. Equation (1.7) normalizes the yield benefit of each treatment by the untreated control yield in order to allow pooling data across treatments, locations and years.

For this analysis, the reduction in CAD for each pest control treatment is calculated as $\Delta\text{CAD}_{\text{trt}} = (\text{CAD}_0 - \text{CAD}_{\text{trt}}) / 1{,}000$, where dividing by 1,000 reduces the magnitude of variables for more manageable parameter estimates. This regression analysis assumes a linear relationship between the reduction in CAD by each treatment and the yield benefit, with normally distributed, independent errors:

(1.8) $$YB = \begin{cases} YB_{seed} = \alpha_{seed} + \beta_{seed}\Delta\text{CAD}_{seed} + \varepsilon_{seed} & \text{if } D_{seed} = 1 \\ YB_{foliar} = \alpha_{foliar} + \beta_{foliar}\Delta\text{CAD}_{foliar} + \varepsilon_{foliar} & \text{if } D_{foliar} = 1, \end{cases}$$

where $\alpha_{seed}$, $\alpha_{foliar}$, $\beta_{seed}$, and $\beta_{foliar}$ are parameters to estimate and $\varepsilon_{seed}$, and $\varepsilon_{foliar}$ are error terms. In equation (1.8), the intercept parameters $\alpha_{seed}$ and $\alpha_{foliar}$ capture the yield benefit from control of insect pests other than soybean aphids, while the slope parameters $\beta_{seed}$ and $\beta_{foliar}$ capture the yield benefit of controlling soybean aphids as mediated by the reduction in CAD. Thus equation (1.8) assumes that all the yield benefits of controlling soybean aphids are captured by the reduction in CAD and any other yield effects are absorbed into the intercept $\alpha$ or the error term ε. Equation (1.8) also pools data so that the estimated $\alpha$ and $\beta$ are the yield effects when averaged over all the regions and years, which is appropriate for a national level analysis.

Equation (1.8) essentially estimates a linear model $YB = \alpha + \beta\Delta\text{CAD} + \varepsilon$ for seed treatments and foliar-applied insecticides separately. Because seed treatments and foliar applications occur at different times, they could affect different pest species, which implies potentially different intercepts ($\alpha_{seed}$ and $\alpha_{foliar}$) for seed treatments and foliar-applied insecticides. Similarly, the yield impacts from controlling soybean aphids early in the season could be different than the yield impacts from controlling soybean aphids later in the season, which implies potentially different slopes ($\beta_{seed}$ and $\beta_{foliar}$) for seed treatments and foliar-applied insecticides. Finally, note that equation (1.8) does not distinguish between pyrethroid and non-pyrethroid foliar applications in terms of the yield benefit. In terms of this model, the only difference between pyrethroid and non-pyrethroid foliar applications is due to differences in their efficacy, which would imply different yield benefits due to a different $\Delta\text{CAD}$, not due to a different slope parameter $\beta_{foliar}$.

### 1.4.4 Farmer net returns

Farmer profit varies with each treatment since not only does the yield benefit vary but also the costs. With no soybean aphid treatment, farmer profit is simply revenue minus cost

(1.9) $$\pi_{untreated} = PY_0 - K.$$

Here $P$ is the soybean price ($/bu), $Y_0$ is yield without treatment (bu/A), and $K$ is all other costs of production unrelated to soybean aphid control ($/A). With a seed treatment, farmer profit is

(1.10) $$\pi_{seed} = PY_0(1 + YB_{seed}) - C_{seed} - K,$$

where $YB_{seed} = \alpha_{seed} + \beta_{seed}\Delta\text{CAD}_{seed} + \varepsilon_{seed}$ is the proportional yield benefit of a seed treatment and $C_{seed}$ is the seed treatment cost ($/A). The farmer gains the yield benefit of a seed treatment but pays an additional cost.

For a scouting-based foliar system, insecticide applications are only made if the aphid population exceeds the economic threshold $\mathrm{CAD}_T$. As a result, farmer profit depends on the aphid population relative to the economic threshold.

For farmers using a non-pyrethroid foliar-applied insecticide, profit is:

$$(1.11)\quad \pi_{foliar} = \begin{cases} PY_0 - C_{scout} - K & \text{if } \mathrm{CAD}_0 < \mathrm{CAD}_T \\ PY_0(1+YB_{foliar}) - C_{scout} - C_{foliar} - K & \text{if } \mathrm{CAD}_0 \geq \mathrm{CAD}_T. \end{cases}$$

Here $C_{scout}$ is the cost (\$/A) of regularly scouting the soybean crop to determine the aphid population, which is paid whether or not an application is made, $C_{foliar}$ is the cost of a foliar application and the insecticide active ingredient (\$/A), and the proportional yield benefit for a foliar application is $YB_{foliar} = \alpha_{foliar} + \beta_{foliar}\Delta\mathrm{CAD}_{foliar} + \varepsilon_{foliar}$.

For farmers using a foliar-applied pyrethroid insecticide, profit is:

(1.12)

$$\pi_{pyrethroid} = \begin{cases} PY_0 - C_{scout} - K & \text{if } \mathrm{CAD}_0 < \mathrm{CAD}_T \\ PY_0(1+YB_{pyrethroid}) - C_{scout} - C_{pyrethroid} - K & \text{if } \mathrm{CAD}_0 \geq \mathrm{CAD}_T. \end{cases}$$

Again $C_{scout}$ is the cost (\$/A) of regularly scouting to determine the aphid population, $C_{pyrethroid}$ is the cost (\$/A) of a foliar application and the pyrethroid active ingredient, and finally, $YB_{pyrethroid} = \alpha_{foliar} + \beta_{foliar}\Delta\mathrm{CAD}_{pyrethroid} + \varepsilon_{foliar}$ is the proportional yield benefit for a foliar-applied pyrethroid. Note that the pyrethroid yield benefit is essentially the same as for the foliar-applied non-pyrethroid except that it uses the change in CAD for the pyrethroid rather than the non-pyrethroid, which potentially differs depending on the difference in the efficacy function as estimated by equations (1.5) and (1.6).

## 1.5 Estimation results

Table 1.2 reports estimation results for the mean and standard deviation of $\mathrm{CAD}_0$ for each region and for all data pooled. Of the original 118 observations, 5 were dropped as extreme values based on a four-sigma criterion — the observations were more than four standard deviations above the sample mean. This criterion dropped observations with $\mathrm{CAD}_0$ exceeding 35,000, including the maximum observed value of 375,000. Wald tests strongly support that the means and standard deviations vary regionally, with a test statistic of 57.30 (p-value <0.0001) for the means and 50.04 (p-value <0.0001) for the standard deviations.

Results in Table 1.2 show that the Eastern Corn Belt has the lowest initial soybean aphid pressure and lower variability than the other regions, a mean of 1,932 and a standard deviation of 3,559. The "heart" of the soybean aphid region based on these results is in Iowa, Minnesota and Wisconsin, states with the highest estimated means for $\mathrm{CAD}_0$, ranging from 6,168 to

**TABLE 1.2** Estimated mean () and standard deviation () of initial cumulative aphid days ($CAD_0$) by region and for all data pooled (N = 113)

| Parameter | Estimate | Standard Error | t-statistic | p-value |
|---|---|---|---|---|
| **Mean $CAD_0$ ($\mu_0$) by Region** | | | | |
| Eastern Corn Belt | 1,932 | 619 | 3.121 | 0.002 |
| Great Plains | 3,967 | 1,690 | 2.348 | 0.019 |
| Iowa | 6,785 | 2,069 | 3.280 | 0.001 |
| Minnesota | 7,269 | 1,741 | 4.176 | <0.001 |
| Wisconsin | 6,168 | 2,199 | 2.805 | 0.005 |
| **Mean $CAD_0$ ($\mu_0$) Pooled** | **5,035** | **764** | **6.589** | **<0.001** |
| | | | | |
| **Standard Deviation of $CAD_0$ ($\sigma_0$) by Region** | | | | |
| Eastern Corn Belt | 3,559 | 1,191 | 2.988 | 0.003 |
| Great Plains | 6,323 | 2,861 | 2.210 | 0.027 |
| Iowa | 9,021 | 3,009 | 2.998 | 0.003 |
| Minnesota | 9,211 | 2,438 | 3.779 | <0.001 |
| Wisconsin | 9,586 | 3,643 | 2.631 | 0.009 |
| **Standard Deviation of $CAD_0$ $\sigma_0$) Pooled** | **8,124** | **1,308** | **6.120** | **<0.001** |

7,269. In addition, all data were pooled to estimate the mean and standard deviation of $CAD_0$ for the aphid population across these 10 states and over these 14 years. The estimated mean and standard deviation were 5,035 and 8,124 respectively.

To estimate the efficacy of the three insecticide treatments, observations were again dropped if $CAD_0$ exceeded 35,000, just as when estimating the regional initial soybean aphid pressure, leaving 113 site-years. In addition, observations were dropped that had an initial aphid pressure $CAD_0$ less than 500, since there was too little aphid pressure to obtain an accurate evaluation of any treatment's efficacy for these cases. Dropping these observations left a total of 550 observations — 142 for seed treatments, 408 for foliar treatments, of which 273 were pyrethroids.

Estimation results in Table 1.3 show a significant difference between the average efficacy of a seed treatment, a foliar application of non-pyrethroid insecticide and a foliar application of a pyrethroid insecticide. Seed treatments were the least effective, with 54.5% of the initial aphid pressure remaining on average after use. A foliar application of pyrethroid insecticide was the most effective, with 19.5% of the initial aphid pressure remaining after use that outperformed a foliar application of non-pyrethroid insecticide by 12.3 percentage points. Foliar-applied pyrethroid insecticides also outperformed seed treatments and foliar applications of non-pyrethroid insecticides in terms of reducing the variability of aphid pressure. The standard deviation of CAD after use of a seed treatment or a foliar-applied

**TABLE 1.3** Estimation results for parameters determining efficacy of each insecticide treatment at reducing the mean and standard deviation of initial cumulative aphid days ($CAD_0$) (N = 550)

| Parameter | Estimate | Standard Error | t-statistic | p-value |
|---|---|---|---|---|
| **Proportion of mean $CAD_0$ remaining (λ)** | | | | |
| Seed Treatment | 0.545 | 0.028 | 19.21 | <0.001 |
| Foliar Application: Non-Pyrethroid | 0.318 | 0.030 | 10.48 | <0.001 |
| Foliar Application: Pyrethroid* | 0.195 | 0.014 | 13.56 | <0.001 |
| **Proportion of standard deviation of $CAD_0$ remaining (θ)** | | | | |
| Seed Treatment | 0.338 | 0.026 | 13.09 | <0.001 |
| Foliar Application: Non-Pyrethroid | 0.353 | 0.038 | 9.188 | <0.001 |
| Foliar Application: Pyrethroid* | 0.238 | 0.020 | 12.16 | <0.001 |

*Estimation results for $\lambda_{foliar} + \lambda_{pyrethroid}$ and $\theta_{foliar} + \theta_{pyrethroid}$.

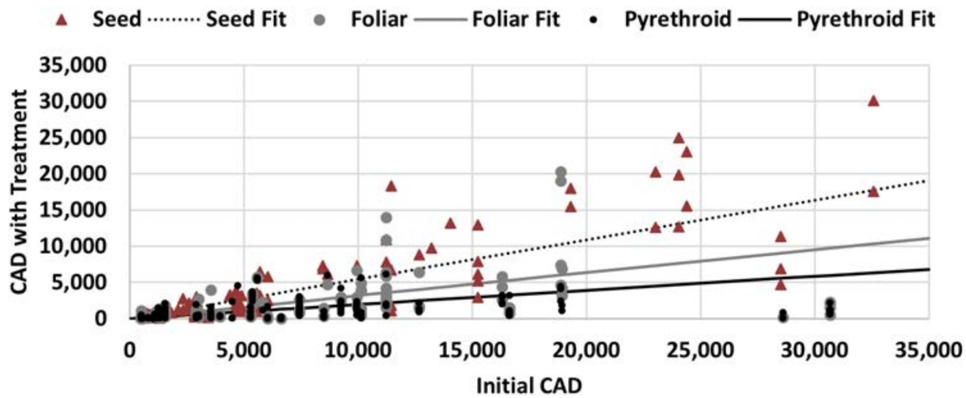
non-pyrethroid was roughly 33% of the initial aphid pressure but only 23.8% after a foliar-applied pyrethroid insecticide.

Figure 1.4 plots the observed data and estimated mean for CAD with each treatments versus the initial CAD without treatments ($CAD_0$). Visually, it is apparent that the observed CAD after a foliar-applied pyrethroid insecticide are noticeably lower than for the other treatments and have a smaller variation. Differences between a seed treatment and a foliar-applied non-pyrethroid are harder to discern since their variability seems roughly the same, but the statistical analysis finds that on average the CAD after a foliar-applied non-pyrethroid is lower than with a seed treatment.

Overall, these results show that foliar-applied pyrethroid insecticides are the most effective method for managing soybean aphid populations. Based on the impact on CAD, they reduce the average and variability of aphid pressure more than foliar-applied non-pyrethroid insecticides and seed treatments. Pyrethroids reduce average CAD by 12.3 percentage points more than foliar-applied non-pyrethroid insecticides and by 35 percentage points more than seed treatments. In addition, the variability of CAD as a percentage of the initial CAD pressure is 10 to 11.5 percentage points lower than with a foliar-applied non-pyrethroid insecticide or a seed treatment. These results indicate that foliar-applied pyrethroid insecticides are the most effective method for controlling soybean aphids in soybean in the U.S.

These results are consistent with expectations. Seed treatments are applied at planting and are effective during the early part of the growing season, generally before soybean aphid populations are high, and insecticide concentrations within the plant decline as the season progresses (Seagraves and Lundgren 2012). However, seed treatments can be effective if there is a high aphid population early in the season or if they prevent later aphid population from reaching the economic threshold (Magalhaes et al. 2009).

**FIGURE 1.4** Observed CAD after treatment for seed treatment (Seed), non-pyrethroid foliar-applied insecticide (Foliar), pyrethroid foliar-applied insecticide (Pyrethroid) and estimated mean (Fit) plotted against the initial CAD




Conversely, foliar insecticides used according to IPM guidelines are applied during the growing season, after soybean aphids have surpassed the economic threshold level (Ragsdale et al. 2007). By targeting high populations that have been confirmed by scouting and using an effective application rate, foliar insecticides should be more effective. In addition, pyrethroid insecticides are recognized as an effective broad-spectrum insecticide providing long-lasting control.

Table 1.4 reports estimation results for the yield benefit analysis, while Figure 1.5 plots the regression fits for both application methods. Yield benefits are quite variable when using only the observed reduction in CAD as a regressor, as Figure 1.5 illustrates. As a result, the intercept terms for both regressions have relatively high p-values, with the intercept for a seed treatment only significant at the 10% level. For both treatment methods, a positive intercept indicates a yield benefit independent of any reduction in aphid populations. The positive intercepts suggest benefits from control of non-aphid insects, such as seed maggots, white grubs and wireworm for seed treatments and other above-ground pests for foliar insecticide applications, such as bean leaf beetle (*Cerotoma trifurcate*), adult Japanese beetles and spider mites.

**TABLE 1.4** Estimation results for the yield benefit parameters

| Application Method and Parameter | Estimate | Standard Error | t-statistic | p-value |
|---|---|---|---|---|
| **Seed Treatment** | | | | |
| Intercept ( $\alpha_{seed}$ ) | 0.010 | 0.0058 | 1.66 | 0.097 |
| Slope ( $\beta_{seed}$ ) | 0.006 | 0.0011 | 5.65 | 0.024 |
| Regression Statistics: N = 221, $R^2$ = 0.127, standard error of regression = 0.077 | | | | |
| **Foliar Applied** | | | | |
| Intercept ( $\alpha_{foliar}$ ) | 0.014 | 0.0062 | 2.25 | <0.001 |
| Slope ( $\beta_{foliar}$ ) | 0.012 | 0.0008 | 15.2 | <0.001 |

Regression Statistics: N = 558, $R^2$ = 0.294, standard error of regression = 0.123

Slope estimates for both seed treatments and foliar applications were strongly significant and positive, implying yield benefits from reducing CAD. For each 1,000 unit reduction in CAD, the estimated average yield benefit is 0.6% for a seed treatment and 1.2% for a foliar-applied insecticide. For comparison, Ragsdale et al. (2007) derived an estimate of 0.7% yield loss for a 1,000 unit reduction in CAD for data from 2003-2005 from multiple locations in six states, indicating that the estimates here using data from more locations and more years are of similar magnitude. It is not surprising that the estimated slope for a foliar application exceeds the slope for a seed treatment, since foliar applications would only be made in these small plot experiments when the soybean aphid population exceeded the IPM treatment threshold. As a result, foliar applications would only have been made when there was substantial soybean aphid pressure, while seed treatments were used regardless of the initial aphid pressure.

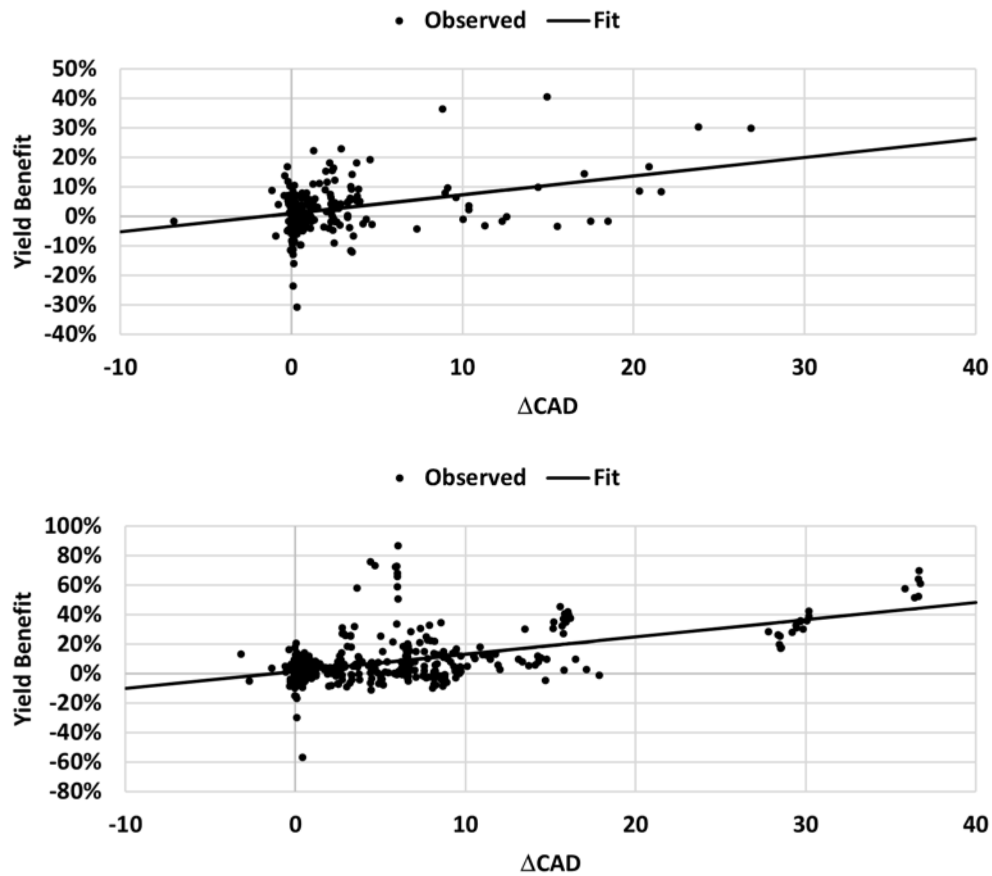
## 1.6 Economic analysis

The goal of this analysis is to determine expected profit as defined by equations (1.9)-(1.12) for each aphid control method in order to determine the farm value for each control method under different model parametrizations. However, given the linked gamma densities for aphid pressure and control efficacy as measured by CAD and the use of foliar insecticides only when the initial pest population exceeds the threshold, specific formulas of the analytical solutions cannot be determined for all treatment methods. As a result, Monte Carlo integration is used to numerically estimate the integrals required for determining the expected values. The process involves first generating many draws of pseudo-random variables and calculating CAD with treatment, the yield benefit and profit for each draw as defined by equations (1.9)-(1.12). Monte Carlo integration then uses sample counterparts to estimate integrals (e.g. the average over all simulated random draws of CAD after a foliar application to estimate the expected value of CAD when using a foliar insecticide if the population exceeds the threshold). This process has been used to estimate the value of lepidopteran Bt corn, federal crop insurance and proposed commodity support programs (Hurley et al. 2004; Seo et al. 2005; Mitchell and Knight 2008).

### 1.6.1 Monte Carlo simulations

The Monte Carlo simulation follows the conceptual framework illustrated in Figure 1.3, using the estimation results to parameterize the linkages between $\mathrm{CAD}_0$, CAD after treatment, the yield benefit and yield and then farmer profits. The process begins by drawing 20,000 pseudo-random draws of aphid pressure $\mathrm{CAD}_0$ from a gamma distribution with a mean and standard deviation for the appropriate region (Table 1.2) and the distribution's parameters calculated using equation (1.3). Next the aphid pressure for each aphid control method (seed treatment, foliar application of a non-pyrethroid and foliar application of a pyrethroid) is drawn from a gamma distribution, with a mean and standard deviation calculated using equations (1.5) and (1.6) and coefficient estimates in Table 1.3. The reduction in CAD for each aphid control method is calculated as $\Delta\mathrm{CAD}_{trt} = (\mathrm{CAD}_0 - \mathrm{CAD}_{trt})/1{,}000$ and then the intercept and slope parameters for the appropriate treatment are determined from Table 1.4 to cal-

**FIGURE 1.5** Observed and estimated yield benefit for seed treatments (top) and foliar-applied insecticides (bottom)




culate the yield benefit. To capture the uncertainty in the yield benefit, the error term ε is drawn from a mean zero normal distribution with a standard deviation equal to the standard error of the regression (Table 1.4).

Yield without an insecticide treatment ( $Y_0$ ) is drawn from a beta distribution (a commonly used distribution for crop yields), with a minimum of zero and a maximum of 2.5 times the standard deviation (Hurley et al. 2004; Seo et al. 2005; Mitchell and Knight 2008). Mean yield is varied systematically from 30, 40, 50 and 60 bushel per acre to capture the range of typical soybean productivities, with a yield coefficient of variation of 30%. To focus on uncertainty from aphid pressure, efficacy and the yield benefit, non-random price and cost assumptions are used. The soybean price *P* is varied systematically from \$8/bu, \$10/bu, \$12/bu and \$14/bu to capture a wide range of farm prices.

Costs for seed treatments, crop scouting and foliar applications are based on estimates developed for a previous analysis (Mitchell 2014a), just as for *Methods and Assumptions for Estimating the Impact of Pyrethroid Insecticides on Pest Management Practices and Costs for U.S. Crop Farmers* (Mitchell 2017). Original estimates were an average for 2010-2012, which was adjusted to a 2012-2014 average using USDA NASS annual prices paid index for services (USDA-NASS 2014, 2015). Specific index values were 98 for 2010, 100 for 2011, 103 for 2012, 105 for 2013 and 107 for 2014, giving a price index for 2010-2012 of 101.3 and for 2012-2014 of 105.0, which implies an inflation rate of 3.6% between the two periods.

The 2010-2012 cost for crop scouting based on custom rate surveys was \$7.44/A, which becomes $C_{scout}$ = \$7.71/A for 2012-2014 after a 3.6% adjustment for inflation. Similarly, the 2010-2012 average cost for a soybean seed treatment was \$7.67/A, which becomes $C_{seed}$ = \$7.95/A for 2012-2014 after a 3.6% adjustment for inflation. The 2010-2012 average cost for machinery and fuel for making foliar applications was \$7.20/A, which becomes \$7.46/A for 2012-2014 after a 3.6% adjustment for inflation. Average costs for foliar-applied insecticide active ingredients for 2012-2014 are acreage-weighted averages derived from GfK Kynetec data as reported in Soybean Table 11 in *Methods and Assumptions for Estimating the Impact of Pyrethroid Insecticides on Pest Management Practices and Costs for U.S. Crop Farmers* (Mitchell 2017). Specific values were \$4.77/A non-pyrethroids and \$3.56 for pyrethroids, so that final total costs (including application costs) were $C_{foliar}$ = \$7.46/A + \$4.77/A = \$12.23/A and $C_{pyrethroid}$ = \$7.46/A + \$3.56/A = \$11.02/A. Finally, the cost of production not including aphid control costs is K = \$400/A as a normalizing assumption that does not affect results.

The only remaining parameter to specify is the treatment threshold $\mathrm{CAD}_T$ indicating when foliar applications are to be made for profit equations (1.11) and (1.12). The traditional IPM treatment threshold is 250 aphids per plant (Ragsdale et al. 2007), which is expressed in terms of the observed population, not the accumulated population as measured by CAD (which is how the aphid population is modeled in this analysis). Furthermore, the actual threshold in terms of the CAD changes with the underlying yield, crop price, application cost and active ingredient cost, as well as the insecticide efficacy, yet IPM as practically applied usually does not use varying action thresholds. As a result, the impact of the threshold $\mathrm{CAD}_T$ on expected profit for the foliar-applied non-pyrethroid and pyrethroid was explored empirically with different prices, yields and costs using the Monte Carlo simulations. Results are not reported, but expected profit with foliar-applied insecticides was not very sensitive to the threshold but much more sensitive with the assumed soybean price and yield and foliar insecticide costs. Therefore, for this analysis, the threshold $\mathrm{CAD}_T$ is varied systematically from 500, 1,000 and 1,500.

Profit for each aphid control method is calculated using equations (1.9)-(1.12) for each random draw of the variables. The Monte Carlo estimate of the probability that $\mathrm{CAD}_0 >$ , which triggers a foliar insecticide application is the observed proportion of the 20,000 random draws of $\mathrm{CAD}_0$ that exceed the threshold. Similarly, the Monte Carlo estimate of expected profit is the observed average of profit for each control method. Based on these results, the net increase in expected profit measures the value of each control method based on an expected profit criterion and can be used to identify the economically optimal aphid control method for each region.

## 1.7 Economic results and discussion

Table 1.5 reports the estimated expected yield benefit by region. For a seed treatment, the benefit does not vary with the application threshold $\mathrm{CAD}_T$, and so only one value is reported for each region. However, for foliar-applied insecticides, the yield benefit varies with the threshold, and so separate results are reported for the three threshold used.

The average yield benefit for a seed treatment ranges from a low of 1.5% for the Eastern Corn Belt to a high of 3.0% in Minnesota, with an average of 2.4% using the pooled soybean aphid population parameters in Table 1.2. This result is slightly lower than the value derived by Hurley and Mitchell (2016) who reported 4.0% based on econometric analysis of farmer survey responses. This result is also slightly lower than the value of 3.6% derived by Mitchell (2014c) based on summarizing small plot data for soybeans. North et al. (2016) also report a 4.4% yield benefit for seed treatments in small plot data in the mid-South.

Results using the aphid population for the Eastern Corn Belt and Minnesota also define the range of yield benefits for non-pyrethroids and pyrethroids — from a low of about 3% for the Eastern Corn Belt to a high of a little more than 7% or 8% for Minnesota. These results are comparable to the yield benefits reported by Orlwoski et al. (2016) in their small plot study in several states for 2012-2014. They report a 1.5% average yield gain in Illinois, Indiana and Iowa, and 7.1% gain in Michigan, Minnesota and Wisconsin, but their foliar insecticide applications were made without use of an IPM treatment threshold and so should be lower than those reported here.

Note that the yield benefits for non-pyrethroids are less than for pyrethroids for all cases and yield benefits for both foliar applied insecticide cases exceed those for seed treatments. These results are as expected based on the efficacy results in Table 1.3 and yield benefit results in Table 1.4. Foliar-applied pyrethroids were more effective than foliar-applied non-pyrethroids and both were more effective than seed treatments at reducing CAD (Table 1.3). Furthermore, given the same reduction in CAD, foliar-applied insecticides had a larger intercept and larger slope than a seed treatment, and so would generate a larger yield benefit (Table 1.4).

An additional result in Table 1.5 to highlight is that the estimated yield benefit for non-pyrethroid insecticides is generally less than 1 percentage

**TABLE 1.5** Estimated expected yield benefit by region for seed treatment (Seed), non-pyrethroid foliar-applied insecticide (Foliar) and pyrethroid foliar-applied insecticide (Pyrethroid) with foliar application thresholds ($\mathrm{CAD}_T$) of 500, 1,000 and 1,500

| | | $\mathrm{CAD}_T = 500$ | | $\mathrm{CAD}_T = 1{,}000$ | | $\mathrm{CAD}_T = 1{,}500$ | |
|---|---|---|---|---|---|---|---|
| **Region** | **Seed** | **Foliar** | **Pyrethroid** | **Foliar** | **Pyrethroid** | **Foliar** | **Pyrethroid** |
| Eastern Corn Belt | 1.5% | 2.9% | 3.2% | 2.9% | 3.1% | 2.8% | 3.1% |
| Great Plains | 2.1% | 4.6% | 5.2% | 4.6% | 5.1% | 4.5% | 5.0% |
| Iowa | 2.9% | 6.9% | 7.9% | 6.9% | 7.8% | 6.8% | 7.7% |
| Minnesota | 3.0% | 7.3% | 8.4% | 7.3% | 8.3% | 7.2% | 8.2% |
| Wisconsin | 2.7% | 6.4% | 7.3% | 6.4% | 7.2% | 6.3% | 7.1% |
| **All** | **2.4%** | **5.5%** | **6.2%** | **5.4%** | **6.1%** | **5.4%** | **6.1%** |

point lower than for pyrethroids for each case, with the difference using the pooled population parameters at 0.7%. These values will be used in the subsequent economic analysis summarized in another report as the basis for the yield impact on soybeans if pyrethroid insecticides were no longer available.

In addition, the yield benefit in Table 1.5 varies only slightly in the application threshold, generally only 0.1 or 0.2 percentage points across the range used for $CAD_T$. The expected profit impacts of aphid control will largely depend on how these yield benefits compare to the costs. Because these yield benefits do not vary substantially with the threshold, results presented in subsequent tables use the threshold of $CAD_T$ = 1,000. Furthermore, to better understand how the foliar treatment threshold affects the likelihood of an insecticide application, Figure 1.6 summarizes the probability that $CAD_0 > CAD_T$ for a range of values for $CAD^T$. As expected, regions with a higher mean value for CAD0 have a higher probability of making an insecticide application and as the threshold increases, the probability that a foliar application is made decreases.

Tables 1.6, 1.7 and 1.8 report the same results — the expected profit ($/A) for each aphid control option for a range of assumptions for mean soybean yield and price — but each using different population parameters for CAD0. Table 1.6 uses the estimated parameters for the pooled data to capture the "average" case, while Table 1.7 uses the estimated parameters for the Eastern Corn Belt and Table 1.8 uses those for Minnesota, to capture the "low" and high" aphid pressure cases respectively.

The untreated cases in these tables all have the same values because there is no yield benefit from aphid control. As equation (1.9) shows, the expected profit is $\mathrm{E}[PY_0 - K] = P\mathrm{E}[Y_0] - K$ , since for this analysis, neither price P nor cost K = $400/A are random. As a result, the Monte Carlo estimated values of the untreated cases can be compared to their actual values to assess the accuracy of the simulations. For example, with P = $8/bu and a mean yield of 30 bu/A, the expect profit is —$160, which is very similar to the Monte Carlo estimate of —$159.95 reported in Table 1.6.

As expected, the results in Tables 1.6, 1.7, and 1.8 indicate that as the value of the crop increases due to a higher price or higher per acre yield, the value of pest control increases. In addition, comparing results in Table 1.6 to those in Tables 1.7 and 1.8, as pest pressure increases, the value of pest control also increases. Results for the same price and yield assumption and pest control method in Table 1.6 are greater than those in Table 1.7 and less than those in Table 1.8.

To help make sense of the extensive results in Tables 1.6, 1.7 and 1.8, Table 1.9 reports the net increase in expected profit for the three control options — a seed treatment (Seed), a foliar-applied non-pyrethroid (Foliar) and a foliar-applied pyrethroid (Pyrethroid) — relative to the untreated control option. This normalization allows all the results for these three aphid population assumptions to be displayed in one table, making comparisons easier. Finally, Table 1.10 uses the values in Table 1.9 to identify the economically optimal aphid control method based on which option has the greatest expected profit for a farmer for each assumption for mean soybean yield and

**TABLE 1.6** Estimated mean ($/A) of farmer profit by control method for different soybean prices, using the pooled mean parameters for initial aphid pressure and a foliar treatment threshold of 1,000*

| Control Method | Mean Yield | -------------------- Soybean Price -------------------- | | | |
|---|---|---|---|---|---|
| | | $8/bu | $10/bu | $12/bu | $14/bu |
| Untreated | 30 | -$159.95 | -$99.93 | -$39.92 | $20.10 |
| Seed | 30 | -$162.19 | -$100.75 | -$39.31 | $22.13 |
| Foliar | 30 | -$163.35 | -$100.45 | -$37.56 | $25.33 |
| Pyrethroid | 30 | -$161.14 | -$97.87 | -$34.60 | $28.67 |
| Untreated | 40 | -$79.93 | $0.09 | $80.11 | $160.13 |
| Seed | 40 | -$80.27 | $1.65 | $83.57 | $165.49 |
| Foliar | 40 | -$79.49 | $4.37 | $88.23 | $172.08 |
| Pyrethroid | 40 | -$76.78 | $7.58 | $91.93 | $176.29 |
| Untreated | 50 | $0.09 | $100.11 | $200.14 | $300.16 |
| Seed | 50 | $1.65 | $104.05 | $206.45 | $308.85 |
| Foliar | 50 | $4.37 | $109.19 | $214.01 | $318.83 |
| Pyrethroid | 50 | $7.58 | $113.02 | $218.47 | $323.92 |
| Untreated | 60 | $80.11 | $200.14 | $320.16 | $440.19 |
| Seed | 60 | $83.57 | $206.45 | $329.33 | $452.21 |
| Foliar | 60 | $88.23 | $214.01 | $339.80 | $465.58 |
| Pyrethroid | 60 | $91.93 | $218.47 | $345.00 | $471.54 |

*Based on results in Table 1.2, $CAD_0$ mean = 5,035 and standard deviation = 8,124 and $CAD_T$ = 1,000.

price. For example, with mean soybean yield of 30 bu/A and price of $8/bu, all the net increases in expected profit in Table 1.9 are negative, implying that leaving the field untreated would generate the greatest expected profit in this analysis, and so leaving the field untreated is the economically optimal aphid control option as reported in Table 1.10.

The net gains in Table 1.9 show the range of values for foliar-applied pyrethroids that can occur with high yields and/or prices. With the average soybean aphid pressure, the gains range from as small as $2/A to more than $31/A. As expected, the net gains for a foliar-applied non-pyrethroid are always less than for the pyrethroid. Seed treatments used alone have value in most cases, but never equal the value of a foliar-applied pyrethroid that is used when needed. As a result, Table 1.10 shows that with this average aphid pressure, the optimal control method is almost always a foliar-applied pyrethroid when needed.

In Table 1.9, with the low aphid pressure of the Eastern Corn Belt, the net gains are much smaller. At the highest yields and prices, pyrethroids are eventually the most valuable aphid control option, but only generate a maximum value of about $6/A. As Table 1.10 shows, in most cases examined, leaving the soybeans untreated is the most economical until sufficiently high prices and yields are obtained. Furthermore, for the right range

**TABLE 1.7** Estimated mean ($/A) of farmer profit by control method for different soybean prices, using Eastern Corn Belt parameters for initial aphid pressure and a foliar treatment threshold of 1,000*

| | | -------------------- Soybean Price -------------------- | | | |
|---|---|---|---|---|---|
| **Control Method** | **Mean Yield** | **$8/bu** | **$10/bu** | **$12/bu** | **$14/bu** |
| Untreated | 30 | -$159.95 | -$99.93 | -$39.92 | $20.10 |
| Seed | 30 | -$164.23 | -$103.30 | -$42.37 | $18.56 |
| Foliar | 30 | -$167.63 | -$106.44 | -$45.24 | $15.95 |
| Pyrethroid | 30 | -$166.74 | -$105.44 | -$44.13 | $17.17 |
| Untreated | 40 | -$79.93 | $0.09 | $80.11 | $160.13 |
| Seed | 40 | -$82.99 | -$1.75 | $79.50 | $160.74 |
| Foliar | 40 | -$86.04 | -$4.45 | $77.15 | $158.74 |
| Pyrethroid | 40 | -$85.00 | -$3.27 | $78.47 | $160.20 |
| Untreated | 50 | $0.09 | $100.11 | $200.14 | $300.16 |
| Seed | 50 | -$1.75 | $99.81 | $201.36 | $302.91 |
| Foliar | 50 | -$4.45 | $97.54 | $199.53 | $301.53 |
| Pyrethroid | 50 | -$3.27 | $98.90 | $201.07 | $303.24 |
| Untreated | 60 | $80.11 | $200.14 | $320.16 | $440.19 |
| Seed | 60 | $79.50 | $201.36 | $323.22 | $445.08 |
| Foliar | 60 | $77.15 | $199.53 | $321.92 | $444.31 |
| Pyrethroid | 60 | $78.47 | $201.07 | $323.68 | $446.28 |

*Based on results in Table 1.2, $CAD_0$ mean = 1,932 and standard deviation = 3,559 and $CAD_T$ = 1,000.

of prices and yields, seed treatments are the most economical aphid control option. With high aphid pressure of Minnesota, the net gains are noticeably larger — the lowest value for a foliar-applied pyrethroid is $2.75/A and the largest is more than $50/A. In addition, with this high aphid pressure, Table 1.10 shows that in all the cases examined, a foliar pyrethroid applied when needed is the most economical aphid control option.

Cost parameters were not varied in this analysis, but have effects as anticipated — increasing the cost of an aphid control option reduces the expected profit values in Tables 1.6 to 1.9 and reduces the range of prices and yields for which the practice is economically optimal, which may change results in Table 1.10. For a seed treatment, because the cost $C_{seed}$ = $7.95/A applies regardless of the outcomes, changes have a 1 for 1 impact on the values in Tables 1.6 to 1.9. For example, using $C_{seed}$ = $6.95 will increase all values by $1/A. The resulting numerical changes in Table 1.9 have no impact on the optimal control options in Table 1.10 except for when using the Eastern Corn Belt aphid population parameters. For this case, the range of prices and yields for which a seed treatment is economically optimal expands — three untreated cases in Table 1.10 switch to seed and two pyrethroid cases.

Changing the cost of scouting ($C_{scout}$) has a similar effect because it too applies regardless of the outcomes. Thus if it increases by $1/A, all values for

**TABLE 1.8** Estimated mean ($/A) of farmer profit by control method for different soybean prices, using Minnesota parameters for initial aphid pressure and a foliar treatment threshold of 1,000*

| | | -------------------- Soybean Price -------------------- | | | |
|---|---|---|---|---|---|
| **Control Method** | **Mean Yield** | **$8/bu** | **$10/bu** | **$12/bu** | **$14/bu** |
| Untreated | 30 | -$159.95 | -$99.93 | -$39.92 | $20.10 |
| Seed | 30 | -$160.72 | -$98.91 | -$37.10 | $24.71 |
| Foliar | 30 | -$160.39 | -$96.22 | -$32.04 | $32.13 |
| Pyrethroid | 30 | -$157.20 | -$92.45 | -$27.71 | $37.03 |
| Untreated | 40 | -$79.93 | $0.09 | $80.11 | $160.13 |
| Seed | 40 | -$78.30 | $4.11 | $86.52 | $168.93 |
| Foliar | 40 | -$74.83 | $10.74 | $96.31 | $181.88 |
| Pyrethroid | 40 | -$70.87 | $15.45 | $101.77 | $188.10 |
| Untreated | 50 | $0.09 | $100.11 | $200.14 | $300.16 |
| Seed | 50 | $4.11 | $107.12 | $210.13 | $313.15 |
| Foliar | 50 | $10.74 | $117.70 | $224.66 | $331.62 |
| Pyrethroid | 50 | $15.45 | $123.35 | $231.26 | $339.16 |
| Untreated | 60 | $80.11 | $200.14 | $320.16 | $440.19 |
| Seed | 60 | $86.52 | $210.13 | $333.75 | $457.37 |
| Foliar | 60 | $96.31 | $224.66 | $353.01 | $481.36 |
| Pyrethroid | 60 | $101.77 | $231.26 | $360.74 | $490.23 |

*Based on results in Table 1.2, CAD0 mean = 7,269 and standard deviation = 9,211 and CADT = 1,000.

foliar-applied pyrethroids and non-pyrethroids decrease by $1/A in Tables 1.6 to 1.9, which will decrease the range of prices and yields in Table 1.10 for which foliar-applied pyrethroids are the economically optimal aphid control method. Changing the cost assumption for application costs and active ingredient costs do not have 1 for 1 impacts because they only apply when a foliar application is made. Hence a $1/A increase in application costs will increase average costs by $1/A multiplied by the probability an application is made, which are summarized in Figure 1.6.

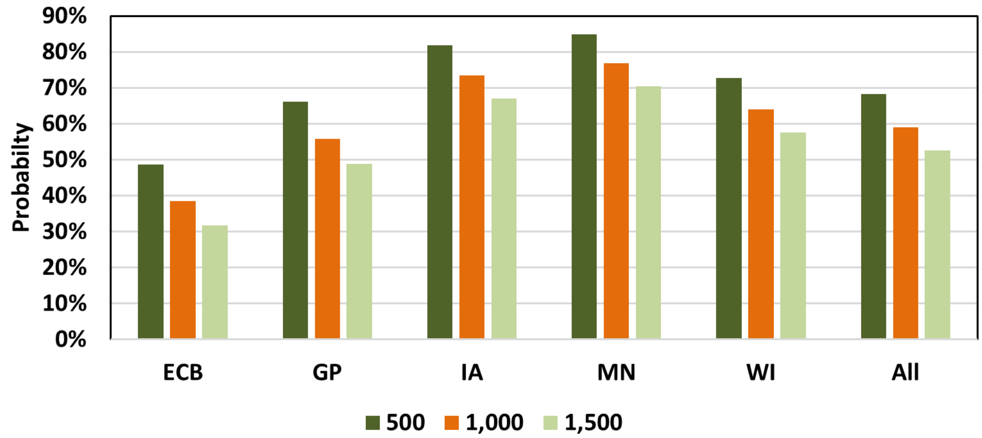
A primary implication of the results in Tables 1.6-1.10 and the summary of the cost sensitivity analysis is that for reasonable ranges of yields, prices, aphid pressure, and costs, any one of the aphid control options could be optimal for a farmer based on an expected profit criterion. The results presented in Tables 1.6-1.10 were developed based on data, but substantial variation exists for most of these parameters around their means for many farmers, even those geographically near one another. Crop budgets for Illinois report 55 bu/A as a typical yield for soybeans in central Illinois for low productivity farmland, but 61 and 63 for high productivity farmland, while the USDA-NASS (2017) county average yield for McLean County, IL in central Illinois was 64.6 in 2015. The marketing year average price for soybeans in Iowa was $14.40/bu in 2012, but $8.91 in 2015 (ISU Extension 2017), but

**TABLE 1.9** Value ($/A) of aphid control methods relative to untreated control by region

| | | -------------------- Soybean Price -------------------- | | | |
|---|---|---|---|---|---|
| **Control Method** | **Mean Yield** | **$8/bu** | **$10/bu** | **$12/bu** | **$14/bu** |
| | | ------------------ Pooled Parameters* ------------------ | | | |
| Seed | 30 | -$2.24 | -$0.82 | $0.61 | $2.04 |
| Foliar | 30 | -$3.40 | -$0.52 | $2.36 | $5.24 |
| Pyrethroid | 30 | -$1.19 | $2.06 | $5.32 | $8.57 |
| Seed | 40 | -$0.34 | $1.56 | $3.46 | $5.37 |
| Foliar | 40 | $0.44 | $4.28 | $8.12 | $11.96 |
| Pyrethroid | 40 | $3.15 | $7.49 | $11.83 | $16.16 |
| Seed | 50 | $1.56 | $3.94 | $6.32 | $8.69 |
| Foliar | 50 | $4.28 | $9.08 | $13.87 | $18.67 |
| Pyrethroid | 50 | $7.49 | $12.91 | $18.33 | $23.76 |
| Seed | 60 | $3.46 | $6.32 | $9.17 | $12.02 |
| Foliar | 60 | $8.12 | $13.87 | $19.63 | $25.39 |
| Pyrethroid | 60 | $11.83 | $18.33 | $24.84 | $31.35 |
| | | ------------Eastern Corn Belt Parameters* ------------ | | | |
| Seed | 30 | -$4.28 | -$3.37 | -$2.45 | -$1.53 |
| Foliar | 30 | -$7.69 | -$6.51 | -$5.33 | -$4.14 |
| Pyrethroid | 30 | -$6.79 | -$5.51 | -$4.22 | -$2.93 |
| Seed | 40 | -$3.06 | -$1.84 | -$0.61 | $0.61 |
| Foliar | 40 | -$6.11 | -$4.54 | -$2.96 | -$1.39 |
| Pyrethroid | 40 | -$5.08 | -$3.36 | -$1.64 | $0.08 |
| Seed | 50 | -$1.84 | -$0.31 | $1.22 | $2.75 |
| Foliar | 50 | -$4.54 | -$2.57 | -$0.60 | $1.37 |
| Pyrethroid | 50 | -$3.36 | -$1.21 | $0.94 | $3.08 |
| Seed | 60 | -$0.61 | $1.22 | $3.05 | $4.89 |
| Foliar | 60 | -$2.96 | -$0.60 | $1.76 | $4.12 |
| Pyrethroid | 60 | -$1.64 | $0.94 | $3.51 | $6.09 |
| | | ---------------- Minnesota Parameters* ---------------- | | | |
| Seed | 30 | -$0.77 | $1.02 | $2.82 | $4.61 |
| Foliar | 30 | -$0.45 | $3.71 | $7.88 | $12.04 |
| Pyrethroid | 30 | $2.75 | $7.48 | $12.21 | $16.93 |
| Seed | 40 | $1.62 | $4.02 | $6.41 | $8.80 |
| Foliar | 40 | $5.10 | $10.65 | $16.20 | $21.75 |
| Pyrethroid | 40 | $9.05 | $15.36 | $21.66 | $27.97 |
| Seed | 50 | $4.02 | $7.01 | $10.00 | $12.99 |
| Foliar | 50 | $10.65 | $17.59 | $24.52 | $31.46 |
| Pyrethroid | 50 | $15.36 | $23.24 | $31.12 | $39.00 |
| Seed | 60 | $6.41 | $10.00 | $13.59 | $17.18 |
| Foliar | 60 | $16.20 | $24.52 | $32.85 | $41.17 |
| Pyrethroid | 60 | $21.66 | $31.12 | $40.58 | $50.04 |

*Each region uses population parameter estimates in Table 1.2.

**FIGURE 1.6** Probability that a foliar insecticide application is made because initial aphid pressure exceeds the threshold ( $> \mathrm{CAD}_T$ ,) by region, with threshold of 500, 1,000, and 1,500 (ECB = Eastern Corn Belt (Illinois, Indiana, Ohio, Michigan), GP = Great Plains (North Dakota, South Dakota, Nebraska), IA = Iowa, MN = Minnesota, WI = Wisconsin)




these are state-wide average over 12 months — individual farmers would have had variation around these averages. Costs for application, active ingredients and scouting will also vary among farmers. Also, Figures 1.4 and 1.5 show the variation that exists in insect control efficacy and yield loss in more controlled small plot experiments. Finally, insect pressure also varies regionally within a state with many factors contributing to differences even for farmers geographically near one another. As a result, reasonable ranges of yields, prices, aphid pressure, and costs exist so that any one of the aphid control options could be optimal for a farmer based on an expected profit criterion.

Other findings emerge as well. Foliar-applied pyrethroid insecticides economically dominate non-pyrethroid insecticides based on the expected profit criterion. On average, pyrethroids are more effective for controlling soybean aphids and cost less than non-pyrethroid alternatives. The key qualifier is "on average" since individual exceptions likely exist for specific pyrethroid and non-pyrethroid active ingredients. In addition, seed treatments used alone are not as effective for controlling soybean aphid as foliar-applied insecticides used when needed. Furthermore, the yield benefit was larger for a foliar-applied insecticide than a seed treatment used alone for an equal reduction in aphid pressure. Nevertheless, there were yield, price and cost scenarios for which a seed treatment used alone was still the most economical method for managing soybean aphids.

Several caveats and qualifications also apply to these results. First, the analysis requires many parameter assumptions and substantial variation exists among these values, which changes the results. Nevertheless, the largest average net gain for using a foliar-applied pyrethroid when needed was about $50/A under high aphid pressure, with high yield and price assumptions. In addition, this analysis uses an expected profit criterion, which averages over all the variation, focusing just on the mean. However, farmers consider many other factors when making pest management decisions. Reducing income risk is one factor, but also human and environmental safety, multiple agronomic concerns, as well as time and ease of control (Hurley and Mitchell 2016). Furthermore, this analysis focuses on soybean aphid, but farmers also manage a wide range of other soybean insect pests, both above-ground and below-ground; soybean aphid is just the most important (Hurley and Mitchell 2016). In addition, this analysis does not account

**TABLE 1.10** Optimal aphid control method by region based on an expected profit criterion

| | | Soybean Price | | | |
|---|---|---|---|---|---|
| **Region*** | **Mean Yield** | **$8/bu** | **$10/bu** | **$12/bu** | **$14/bu** |
| All | 30 | Untreated | Pyrethroid | Pyrethroid | Pyrethroid |
| | 40 | Pyrethroid | Pyrethroid | Pyrethroid | Pyrethroid |
| | 50 | Pyrethroid | Pyrethroid | Pyrethroid | Pyrethroid |
| | 60 | Pyrethroid | Pyrethroid | Pyrethroid | Pyrethroid |
| Eastern Corn Belt | 30 | Untreated | Untreated | Untreated | Untreated |
| | 40 | Untreated | Untreated | Untreated | Seed |
| | 50 | Untreated | Untreated | Seed | Pyrethroid |
| | 60 | Untreated | Seed | Pyrethroid | Pyrethroid |
| Minnesota | 30 | Pyrethroid | Pyrethroid | Pyrethroid | Pyrethroid |
| | 40 | Pyrethroid | Pyrethroid | Pyrethroid | Pyrethroid |
| | 50 | Pyrethroid | Pyrethroid | Pyrethroid | Pyrethroid |
| | 60 | Pyrethroid | Pyrethroid | Pyrethroid | Pyrethroid |

*Each region uses population parameter estimates in Table 1.2.

for yield losses or extra treatment costs due to "flare ups" of mites or other secondary pests as a result of a foliar application of a pyrethroid to control soybean aphids. Also, the resistance management benefits of foliar-applied pyrethroids are not explicitly accounted for in this analysis. Providing farmers with alternative methods and insecticide classes is important, since rotating and combining modes of action is a key part of managing insect resistance. Pyrethroids are generally a lower cost class of insecticides, and so are often a part of insecticide rotations and mixes with more costly insecticide classes to help preserve their efficacy.

Finally, the analysis compares seed treatments used alone with foliar-applied insecticides used alone when needed. This analysis assumed each system was used in isolation, but some farmers use a seed treatment and then continue to scout and make a foliar application as needed for soybean aphid or other above-ground pests. For the perspective of this analysis, farmers would receive the yield benefit from the seed treatment, plus some portion of the yield benefit from the foliar application used when needed. This analysis already captures the distribution of CAD remaining after use of a seed treatment, but the yield benefit is unclear when both treatments are used. Would the seed treatment reduce the efficacy of foliar applications because some insects were already removed or would it enhance efficacy because the insects were in some way already weakened by the seed treatment? This question bears investigation, but is beyond the scope of this report.

## 1.8 References

Clark, A.J., and K.L. Perry. 2002. *Transmissibility of field isolates of soybean viruses by Aphis glycines.* Plant Disease 86: 1219-1222.

Davis, J.A., and E.B. Radcliffe. 2008. *The importance of an invasive aphid species in vectoring a persistently transmitted potato virus: Aphis glycines is a vector of potato leafroll virus.* Plant Disease 92: 1515-1523.

Davis, J.A., E.B. Radcliffe, and D.W. Ragsdale. 2005. *Soybean aphid, Aphis glycines Matsumura, a new vector of potato virus Y in potato*. American Journal of Potato Research 82: 197-201.

Evans, M., N. Hastings, and B. Peacock. 2000. *Statistical distributions.* John Wiley and Sons, New York.

Gaspar, A.P., D.A. Marburger, S. Mourtzinis, and S.P. Conley. 2014. Soybean Seed Yield Response to Multiple Seed Treatment Components across Diverse Environments. Agron. J. 106:1955-1962.

Grau, C.R. 2015. P*otential for Yield Loss Caused by Soybean Viruses.* Proceedings of the 2005 Crop Pest Management Shortcourse. University of Minnesota Extension, St. Paul, MN. Online: http://www.extension.umn.edu/agriculture/ag-professionals/cpm/2005/Grau_YieldLossSoyViruses.pdf.

Hanafi, A., E.B. Radcliffe, and D.W. Ragsdale. 1989. *Spread and control of potato leafroll virus in Minnesota*. J. Econ. Entomol. 82: 1201-1206.

Higley, L.G., and D.J. Boethel. 1994. *Handbook of soybean insect pests.* Entomological Society of America, Lanham, MD.

Hill, J.H., R. Alleman, D.B. Hogg, C.R. Grau. 2001. *First report of transmission of soybean mosaic virus and alfalfa mosaic virus by Aphis glycines in the New World.* Plant Disease85: 561-561.

Hodgson, E.W., B.P. McCornack, K. Tilmon, and J.J. Knodel. 2012. *Management recommendations for soybean aphid (Hemiptera: Aphididae) in the United States.* Journal of Integrated Pest Management 3: E1-E10.

Hurley, T.M., and P.D. Mitchell. 2016. Value of Insecticide Seed Treatments to U.S. Soybean Farmers. Pest Management Science DOI: 10.1002/ps.4424.

Hurley, T.M., P.D. Mitchell, and M.E. Rice. 2004. *Risk and the Value of Bt Corn*. American Journal of Agricultural Economics 86: 345-358.

Iowa State University (ISU) Extension. 2017. *Iowa Cash Corn and Soybean Prices.* Ames, IA. Online: https://www.extension.iastate.edu/agdm/crops/pdf/a2-11.pdf

Macedo, W.R., and P.R. Camargo e Castro. 2011. *Thiamethoxam: molecule moderator of growth, metabolism and production of spring wheat.* Pesticide biochemistry and physiology100: 299-304.

Magalhaes, L.C., T.E. Hunt, and B.D. Siegfried. 2009. *Efficacy of neonicotinoid seed treatments to reduce soybean aphid populations under field and controlled conditions in Nebraska.* Journal of Economic Entomology 102: 187-195.

Mitchell, P.D. 2014a. *Estimated Impact of Neonicotinoid Insecticides on Pest Management Practices and Costs for U.S. Corn, Soybean, Wheat, Cotton and Sorghum* Farmers. AgInfomatics, Madison, WI.

Mitchell, P.D. 2014b. *Methods and Assumptions for Estimating the Impact of Neonicotinoid Insecticides on Pest Management Practices and Costs for U.S. Corn, Soybean, Wheat, Cotton and Sorghum Farmers*. AgInfomatics, Madison, WI.

Mitchell, P.D. 2017. *Methods and Assumptions for Estimating the Impact of Pyrethroid Insecticides on Pest Management Practices and Costs for U.S. Crop Farmers*. AgInfomatics, Madison, WI.

Mitchell, P.D. and T. Knight. 2008. *Economic Analysis of Supplemental Deductible Coverage in the USDA's 2007 Farm Bill Proposal.* Agricultural and Resource Economics Review 37:117-131.

North, J.H., J. Gore, A.L. Catchot, S.D. Stewart, G.M. Lorenz, F.R. Musser, D.R. Cook, D.L. Kerns, and D.M. Dodd. 2016. *Value of neonicotinoid insecticide seed treatments in mid-South soybean (Glycine max) production systems.* J Econ. Entomol. 109: 1156-1160.

Orlowski, J.M., B.J. Haverkamp, R. G. Laurenz, D.A. Marburger, E.W. Wilson, S.N. Casteel, S.P. Conley, S.L. Naeve, E.D. Nafziger, K.L. Roozeboom, W.J. Ross, K.D. Thelen, and C.D. Lee. 2016. *High-Input Management Systems Effect on Soybean Seed Yield, Yield Components, and Economic Break-Even Probabilities*. Crop Sci. 56:1988-2004.

Pinder, J.E., J.G. Wiener, and M.H. Smith. 1978. *The Weibull distribution: a new method of summarizing survivorship data.* Ecology 59: 175-179.

Ragsdale, D.W., D.J. Voegtlin, and R.J. O'Neil. 2004. *Soybean Aphid Biology in North America*. Annals of the Entomological Society of America 97:204-208.

Ragsdale, D. W., B. P. McCornack, R. C. Venette, E. W. Hodgson, B. D. Potter, I. V. MacRae, M. E. O'Neal, K. D. Johnson, R. J. O'Neil, C. D. DiFonzo, et al. 2007. *Economic threshold for soybean aphid (Hemiptera: Aphididae)*. Journal of Economic Entomology 100:1258-1267.

Schnitkey. G. 2016. *Crop Budgets, Illinois, 2017.* Department of Agricultural and Consumer Economics, University of Illinois, Urbana-Champaign, IL. Online: http://www.farmdoc.illinois.edu/manage/2017_crop_budgets.pdf.

Seagraves, M. P., and J.G. Lundgren. 2012. *Effects of neonicotinoid seed treatments on soybean aphid and its natural enemies.* Journal of Pest Science 85: 125-132.

Seo, S., P.D. Mitchell, and D. Leatham. 2005. *Effects of Federal Risk Management Programs on Optimal Acreage Allocation and Nitrogen Use in a Texas Cotton-Sorghum System.* Journal of Agricultural and Applied Economics 37:685-699.

United States Department of Agriculture (USDA). *2016. World Agricultural Supply and Demand Estimates.* December 9, 2016, Washington, DC. Online: http://usda.mannlib.cornell.edu/usda/current/wasde/wasde-12-09-2016.pdf.

United States Department of Agriculture, National Agricultural Statistics Service (USDA-NASS). *2014. Agricultural Prices (January)*. USDA-NASS, Washington, DC. Online: http://usda.mannlib.cornell.edu/usda/nass/AgriPric//2010s/2014/AgriPric-01-31-2014_revision.pdf.

United States Department of Agriculture, National Agricultural Statistics Service (USDA-NASS). *2015. Agricultural Prices (February).* USDA-NASS, Washington, DC. Online: http://usda.mannlib.cornell.edu/usda/nass/AgriPric//2010s/2015/AgriPric-02-27-2015.pdf.

United States Department of Agriculture — National Agricultural Statistics Service (USDA NASS). 2017. *Quick Stats.* Online database: https://quickstats.nass.usda.gov/.

Venette, R.C., and D.W. Ragsdale. 2004. *Assessing the invasion by soybean aphid (Homoptera: Aphididae): Where will it end?* Annals of the Entomological Society of America 97: 219-226.

# 2.0 Efficacy and yield benefits of soil-applied pyrethroids for managing corn rootworm larvae

## 2.1 Executive summary

The corn meta-analysis focused on the efficacy of soil-applied insecticides for reducing the node injury scale, the standard measure of root injury due to larval feeding by corn rootworm (*Diabrotica spp.*), the primary pest complex for corn in the U.S. In total, 669 observations from replicated small plot experiments were assembled from 89 locations in four states over 11 years. Data consisted of paired observations of the average node injury scale with a soil-applied insecticide and without treatment. Small plot data for yield and other rootworm management options (Bt corn, seed treatments) were not assembled because meta-analyses have already been published (Dun et al. 2010, Tinsley et al. 2013, 2015).

The most effective soil-applied insecticide treatment for reducing the root injury was a pyrethroid-organophosphate premix, which reduced the average and the standard deviation of the node injury scale to levels comparable to a single toxin Bt corn before the development of rootworm resistance to Bt toxins. When used alone, pyrethroids were slightly less effective than the premix but provided comparable reductions in root injury as organophosphates and significantly better than the other insecticide classes examined (diamides, neonicotinoids and phenylpyrazoles). The average node injury scale with a premix was 20% of the node injury scale without treatment, which is a damage reduction advantage of almost 7% compared to a pyrethroid or organophosphate used alone and almost 30% compared to the other insecticide classes examined. Similarly, the standard deviation of the node injury scale with the pyrethroid-organophosphate premix as a percentage of node injury scale without treatment was 3.5 percentage points lower than with a pyrethroid or organophosphate used alone and 10.5 percentage points lower than for the other insecticide classes examined.

The yield advantage of soil-applied pyrethroid insecticides averages about 12% relative to no control, while the yield advantage of a pyrethroid-organophosphate premix relative to the pyrethroid used alone averages about 1.0% and the yield advantage for a pyrethroid used alone relative to the other insecticide classes examined averages about 3.5%. These yield advantages vary with the average node injury scale without treatment, the measure of pest pressure used.

Two important caveats apply to this analysis. First, this analysis focused only on corn rootworm larvae, the most important insect pest of corn in the U.S., even though farmers manage other insects in corn. Key below-ground pests include wireworm, seed maggots and various beetle larvae (“grubs”), while various lepidopteran larvae are key above-ground pests (e.g., European corn borer, corn earworm, cutworms, armyworms), plus mites, adult corn rootworm, stink bugs, aphids, flea beetles and grasshoppers. This analysis does not include yield benefits from using pyrethroids to manage any of these pests. Second, this analysis does not account for the resistance management benefits of soil-applied pyrethroids. Providing farmers with

alternative methods and insecticide classes is important, since rotating and combining modes of action is a key part of managing insect resistance. Pyrethroids and other soil-applied insecticides have become important alternatives to rootworm Bt corn with the development of resistance among rootworm population to Bt toxins.

## 2.2 Introduction

The U.S. is the world's largest corn producer, growing more than 35% of total global production, and corn is the largest crop in the U.S. in terms of planted acres and the value of farm production (USDA 2017). For example, a total of 90.6 million corn acres were planted in the U.S. in 2014, producing 14.2 billion bushels and generating $52.6 billion in farm gate value based on a marketing year average price of $3.70/bu (USDA-NASS 2017). The next largest U.S. crop in terms of farm gate value was soybeans at $39.7 billion (USDA-NASS 2017).

U.S. farmers report two major insect pests for corn: corn rootworm and European corn borer (*Ostrinia nubilalis*). In the U.S., corn rootworm is a complex of four related insect species: the western corn rootworm (*Diabrotica virgifera virgifera*), the northern corn rootworm, (*Diabrotica barberi*), the Mexican corn rootworm (*Diabrotica virgifera zeae*) and the southern corn rootworm (*Diabrotica undecimpunctata howardi*), with western and/or northern corn rootworms the most problematic species in most regions. In a survey of U.S. corn farmers in 2014, 38.5% reported corn rootworm as their most important pest, while 25% reported European corn borer; the next most important was black cutworm, reported by only 1.4% of respondents (Hurley and Mitchell 2014). In a 2016 survey of U.S. corn farmers, 61% report actively managing corn rootworm and 58% report the same for European corn borer, with corn earworm and cutworm reported by 11% and 8%, respectively (Hurley and Mitchell 2017).

Other than corn rootworm and European corn borer, U.S. corn farmers also manage other below-ground pests, including wireworm larvae, seed maggots and various grubs. In addition, several other lepidopteran larvae are managed as above-ground pests, including cutworms, earworms, and armyworms. Other important above-ground pests commonly managed are mites, adult corn rootworm and stink bugs, with aphids, flea beetles and grasshoppers and other orthopteran pests as minor but important pests for some growers (Hurley and Mitchell 2014, 2017; Mitchell 2017).

Rootworm larvae live below-ground, with thousands potentially infesting individual corn plants and feeding on the roots; this root injury disrupts several plant functions and increases the potential for crop lodging, all of which contribute to yield loss (Dun et al. 2010, Tinsley et al. 2013). The adults feed on corn pollen and silks and can cause loss in their own right, but the primary cause of crop injury and yield loss, and thus the focus of management, are below-ground larvae (Spencer et al. 2009). On the other hand, European corn borer as pests in Midwestern corn have multiple generations per year depending on latitude, with the larval phase causing crop injury by boring through leaves and into stalks or ear shanks, which not only disrupts plant functions but also causes lodging and yield loss (Mason et al. 1996).

Bt corn is the primary method farmers use to manage corn rootworm and European corn borer, with adoption rates at around 80% of planted acres from 2014 to 2016 (USDA-ERS 2016). A survey of U.S. corn farmers regarding Bt adoption in 2014 found that 82% used some type of Bt corn, with almost 65% using traits for controlling both corn borers and rootworm, almost 34% using traits for corn borer only and more than 13% using traits only for rootworm (Hurley and Mitchell 2014). An emerging problem for rootworm Bt corn is the development and spread of resistance to various Bt traits individually and more broadly (Gassman et al. 2011, 2014, Wangila 2015, Jakka et al. 2016).

The other primary methods used for managing corn rootworm include insecticidal seed treatments, soil-applied insecticides and crop rotation, while foliar-applied insecticides are the major alternative control option for European corn borer management. Seed treatments generally do not provide adequate control when rootworm larval populations are high but are effective for managing other below-ground pests, such as wireworm, seed maggots and grubs (Tinsley et al. 2015; Gray 2011). Seed treatments are widely used in corn, with roughly 90% of corn acres treated (Mitchell 2014). All Bt corn with traits for controlling rootworm is sold with a low rate of an insecticidal seed treatment, plus seed treatments are used without Bt corn to manage wireworm, seed maggots and grubs and in fields with low to moderate rootworm pressure to reduce crop injury.

Historically, crop rotation worked as an effective means of controlling rootworm since larvae feed almost exclusively on corn roots and adults lay eggs the summer/fall before crops are planted (Spencer et al. 2009). However, the two main rootworm species have evolved resistance to crop rotation. Females of the western corn rootworm soybean variant also lay eggs in other crops, which in areas dominated by a corn-soybean rotation means the eggs are laid in existing soybean fields that are planted to corn the following crop year (Onstad et al. 1999, Levine et al. 2002, Gray et al. 2009). Northern corn rootworm eggs exhibit extended diapause, with some eggs not hatching until after two or more winters, so that in areas dominated by a corn-soybean rotation, eggs hatch in fields that are again planted to corn (Levine et al. 1992). The geographic range of the northern corn rootworm has been expanding in recent years, with the prevalence of extended diapause growing among these populations (Unglesbee 2016a, 2016b). As a result of the soybean variant and extended diapause, first-year corn acres in many areas can suffer economic losses that justify rootworm management (Gray et al. 2009; Rice 2001). Further complicating the issue is that soybean variant populations have been confirmed to also be resistant to rootworm Bt corn (Unglesbee 2016a, 2016b).

The remaining alternative for managing below-ground and above-ground insects in corn are foliar and soil-applied insecticides. Based on 2012-2014 averages using GfK Kynetec data (Mitchell 2017), 68% of the total 19.4 million insecticide product acres in corn (not including insecticidal seed treatments or Bt corn) were soil-applied and 32% were foliar-applied.

Pyrethroids are the most commonly used insecticide class in corn (not including Bt corn or seed treatments), 74% of the 19.4 million insecticide product acres in corn (both soil-applied and foliar-applied) were pyrethroids. For foliar insecticides, pyrethroids constituted 62% of the product acres, while for soil-applied insecticides, pyrethroids constituted 79% of the product acres. These data show that below-ground insect pests are the primary focus of insect management in corn and that pyrethroids dominate among these insecticides, with soil-applied insecticides most commonly targeted at corn rootworm and foliar-applied insecticides targeted most commonly at lepidopteran pests of corn.

This section of the meta-analysis uses small plot data to examine the benefits of pyrethroids for managing corn rootworm larvae, the most important insect pest of corn in the U.S. Small plot field studies have been conducted to evaluate the efficacy and yield benefits of different rootworm control methods for several years. Before rootworm Bt corn, field studies experimentally examined the efficacy and yield benefits of soil-applied insecticides for controlling rootworm (e.g., Gray and Steffey 1998), and then with the commercialization of rootworm Bt corn in 2003, studies compared soil-applied insecticides to the new traits.[1] More recently with the emergence of rootworm resistance to Bt corn (Gassman et al. 2011, 2014, Wangila 2015, Jakka et al. 2016), studies were conducted to document the declining efficacy of rootworm Bt corn and the continued efficacy of soil-applied insecticides.[1] The goal here was to assemble data from these studies to evaluate the efficacy of soil-applied pyrethroid insecticides relative to non-pyrethroid alternatives.

Meta-analyses have already been published using small plot data to examine different aspects of rootworm management. Dun et al. (2010) used small plot data from Illinois and Iowa to examine the relationship between the increase in the node injury scale (NIS) and yield loss. The node injury scale of Oleson et al. (2005) is the widely used measure of root injury by corn rootworm larvae. Tinsley et al. (2013) used additional small plot data from Illinois and slightly different analysis methods to also examine the relationship between the increase in the NIS and yield loss. Both Dun et al. (2010) and Tinsley et al. (2013) found similar results — each one unit increase in the NIS on average increased yield loss by about 15%. More recently, Tinsley et al. (2015) used small plot data from Illinois and Nebraska to examine the efficacy of different rootworm control methods: insecticidal seed treatments used alone, soil-applied insecticides, single toxin Bt and double toxin Bt (both with a low rate of an insecticidal seed treatment) and single toxin Bt and double toxin Bt each with a soil-applied insecticide (again plus the low rate of an insecticidal seed treatment). However, no studies were found that examined the efficacy of different soil-applied insecticide classes. Hence, the goal here was to assemble data from small-plot experiments to evaluate the efficacy of soil-applied pyrethroid insecticides relative to non-pyrethroid alternatives.

The remainder of this section is organized as follows. First, the data collected for the analysis are described. Next, the statistical model is described,

1 For example, see http://www.ent.iastate.edu/dept/faculty/gassmann/rootworm or https://ipm.illinois.edu/ontarget/pastissues.html.

and then the analysis results are reported. Finally, the discussion explains the implications of this meta-analysis in terms of the yield benefits of soil-applied pyrethroid insecticides relative to non-pyrethroid alternatives for managing corn rootworm larvae and presents several caveats for and qualifications of these results and implications.

## 2.3 Small plot data

Some small plot data were available from Illinois locations from a previous study (Tinsley et al. 2015), with additional small plot data assembled from Iowa, Indiana and Wisconsin. Faculty and/or staff at the land grant university in each state conducted these studies. The reports for the Illinois and Iowa data are available online at the sites in footnote 1. The Indiana data are also available online (Bledsoe et al. 2008, Krupke et al. 2009). The Wisconsin data were obtained from academic staff at the University of Wisconsin for research conducted on a university research farm (Bryan Jensen, personal communication). To be included, the small plot study had to have replicated trials with untreated control plots and treatments that included only soil-applied insecticides. Data from treatment using insecticidal seed treatments and/or Bt corn were not included, just treatments that only used soil-applied insecticides. As the focus here was on corn rootworm, the collected data for each plot was the node injury scale (NIS) measuring root injury from rootworm larval feeding. Furthermore, the insecticide active ingredient(s) had to be noted.

Table 2.1 and Figures 2.1 and 2.2 summarize the data assembled for analysis. Overall, data were available from 2005 to 2015 (11 years) and from 16 different locations in 4 states. In total, there were 689 observations from 89 different site-years. A site-year is a set of replicated trials conducted at a single site in a single year with an untreated control. Multiple observations were generated at a single site-year because multiple soil-applied insecticides may be evaluated, plus multiple experiments may be conducted at the same site in a year. Most of the data are from Illinois and Iowa and from 2005, 2006, 2008 and 2009 (Figure 2.1).

Table 2.2 summarizes the data by insecticide class. Most of the observations (271) are for pyrethroids (class 3A), the most commonly used soil-applied insecticide in corn for rootworm control (IRAC 2016). The next most common is a mixture of a pyrethroid and an organophosphate insecticide (212 observations), and then an organophosphate (class 1B) insecticide used alone

**TABLE 2.1** Number of site-years and observations

| State | Number of Site-Years | Number of Observations |
|---|---|---|
| Illinois | 37 | 310 |
| Indiana | 5 | 73 |
| Iowa | 45 | 262 |
| Wisconsin | 2 | 24 |
| **Total** | **89** | **669** |

(153 observations). The remaining observations are 13 for phenylpyrazoles (class 2B), 11 for neonicotinoids (class 4A) and 8 for diamides (class 28).

Table 2.2 also reports the mean and standard deviation of the node injury scale for the untreated controls ($NIS_0$) and the treated plots ($NIS_t$) by insecticide class. As expected, the mean NIS with treatment is less than without treatment, implying that on average these insecticides reduce root injury from rootworm larval feeding. The average decrease in the NIS across all insecticide classes is 1.57 — 0.39 = 1.18 units. Similarly, in most cases the standard deviation deceases with use of the soil-applied insecticide, implying that these insecticides reduce the variability of root injury from rootworm larval feeding. The average decrease in the standard deviation across all insecticide classes is 0.44. The only exceptions are the diamide and phenylpyrazole classes, which do not show this trend due to the small sample sizes. Though the NIS without treatment ($NIS_0$) shows variation across insecticide classes, implying variation in initial rootworm pressure, most of the soil-applied insecticides generate an average NIS with treatment ($NIS_t$) in the 0.30 to 0.41 range. Again, the only exceptions are the diamide and phenylpyrazole classes, which have small sample sizes.

Note that care must be used when interpreting the statistics for $NIS_0$. First, the common protocol for rootworm field trials is to plant a trap crop of pumpkins and/or a late planting of corn the season before to attract egg-laying females to the plots in order to increase rootworm larval populations for the trial.[2] The implication is that the reported averages for the untreated control plots are likely higher than would occur for fields without treatment. Second, sites that evaluated multiple soil-applied insecticide treatments will have repeat observations of $NIS_0$ when calculating the statistics in Table 2.2, while sites that only evaluated one soil-applied insecticide treatment will only have one observation of $NIS_0$. As a result, the more treatments a site evaluated, the more weight its value of $NIS_0$ will receive when calculating the statistics for $NIS_0$ reported in Table 2.2.

Figure 2.2 plots each observed $NIS_t$ versus the associated $NIS_0$. The data show clear heteroscedasticity — with the variability $NIS_t$ increasing as the value of $NIS_0$ increases. In addition, Figure 2.2 plots the 45-degree line, which shows the value of $NIS_t$ that would result if $NIS_t = NIS_0$, i.e., that the soil-applied insecticide had zero efficacy. Almost all observations are below the 45-degree line, implying that $NIS_t$ is almost always less than the associated $NIS_0$, implying that the soil-applied insecticides usually reduce root injury to some extent.

In total, 16 observations had $NIS_t \geq NIS_0$. Of these, half had very low pressure, $NIS_0 < 0.10$, so that the experimental and measurement error in small plots likely caused the observed $NIS_t$ to exceed the $NIS_0$. The remaining observations are visible in Figure 2.2 as the points above the 45-degree line. In these cases, experimental and measurement error was likely larger than average. Furthermore, rootworm larval populations are "clumpy" in fields and so some variation in pressure should be expected, even at the scale of replicated small plots (Ellsbury et al. 1998, Toepfer et al. 2007), and the

2 For example, see http://www.ent.iastate.edu/dept/faculty/gassmann/rootworm or https://ipm.illinois.edu/ontarget/pastissues.html.

**FIGURE 2.1** Number of observations by year for the small plot data

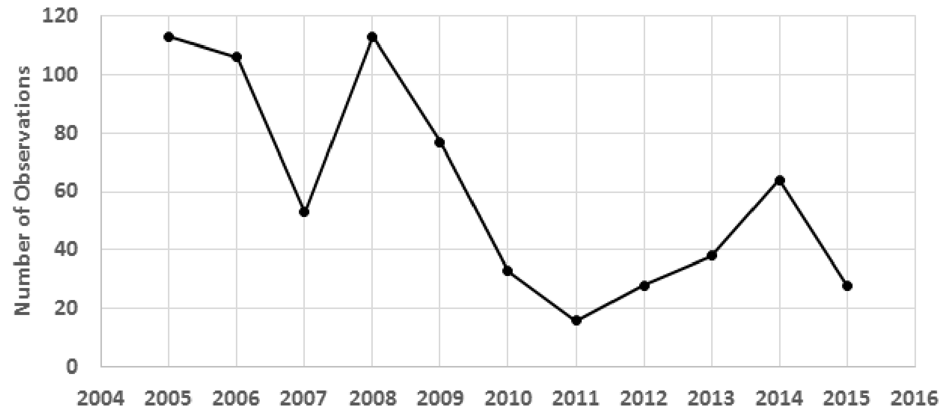



**FIGURE 2.2** Plot of the observed NIS with treatment ($NIS_t$) versus the NIS without treatment ($NIS_0$) for all insecticide classes, plus the 45-degree line

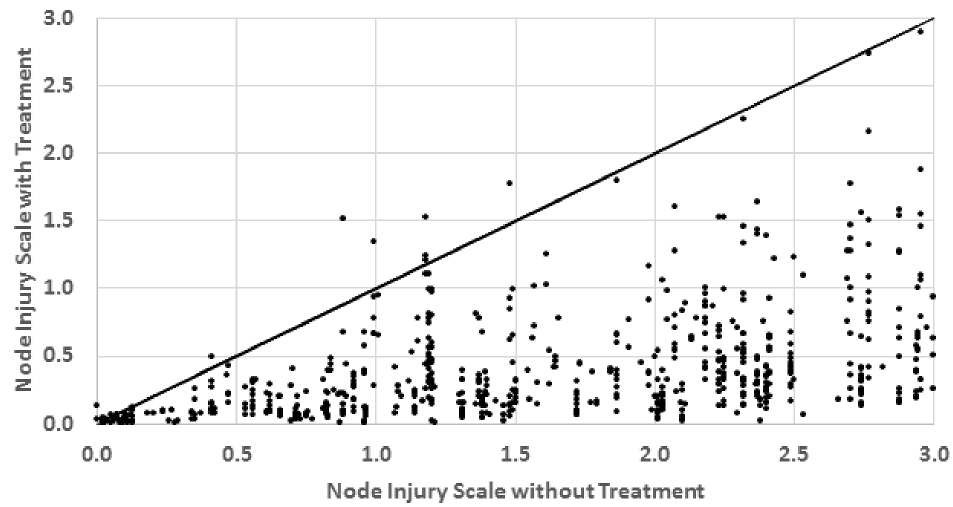



**TABLE 2.2** Sample statistics for the untreated node injury scale ($NIS_0$) and the node injury scale with a soil-applied insecticide ($NIS_t$)

| | | --------- $NIS_0$ --------- | | --------- $NIS_t$ --------- | |
|---|---|---|---|---|---|
| **Class** | **Observations** | **Mean** | **St. Dev.** | **Mean** | **St. Dev.** |
| Diamide | 9 | 1.14 | 0.19 | 0.96 | 0.38 |
| Neonicotinoid | 11 | 0.85 | 0.84 | 0.30 | 0.31 |
| Organophosphate | 153 | 1.77 | 0.81 | 0.41 | 0.39 |
| Phenylpyrazole | 13 | 2.03 | 0.61 | 1.13 | 0.81 |
| Pyrethroid | 271 | 1.41 | 0.86 | 0.39 | 0.38 |
| Pyrethroid+Organophosphate | 212 | 1.66 | 0.82 | 0.30 | 0.33 |
| **All** | **669** | **1.57** | **0.84** | **0.39** | **0.40** |

efficacy of soil-applied insecticides varies with environmental and management factors, also at the scale of replicated small plots (Musick and Fairchild 1967, Sutter et al. 1989; Levine and Oloumi-Sadeghi 1991).

## 2.4 Statistical model to analyze efficacy

Use of an insecticide or other control method reduces root injury from rootworm larvae, which in the context here implies a reduction in the NIS with treatment relative to the NIS without treatment at the same site-year. To measure of the efficacy of each insecticide class treatment, the analysis here uses the NIS data from the small plot experiments to estimate a probability density function for the NIS after application of the soil-applied insecticide. Maximum likelihood is used to estimate the distribution of the NIS with treatment ($NIS_t$) conditional on the NIS without treatment for the same site and year ($NIS_0$), assuming a proportional reduction in the NIS due to the soil-applied insecticide. Specifically, a beta density function is estimated for $NIS_t$ with the mean $\mu$ and standard deviation $\sigma$ as proportions of $NIS_0$:

(2.1) $$\mu = (\beta_{Pyrethroid} D_{Pyrethroid} + \beta_{OP} D_{OP} + \beta_{Both} D_{Both} + \beta_{Other} D_{Other}) \mathrm{NIS}_0 \,,$$

(2.2) $$\sigma = (\theta_{Pyrethroid} D_{Pyrethroid} + \theta_{OP} D_{OP} + \theta_{Both} D_{Both} + \theta_{Other} D_{Other}) \mathrm{NIS}_0 \,.$$

Here the subscripts *Pyrethroid*, *OP*, and *Both* respectively denote the insecticide class of the soil-applied insecticide as a pyrethroid, an organophosphate or a pre-mix of a pyrethroid and an organophosphate combined, while *Other* denotes either a diamide, a neonicotinoid or a phenylpyrazole, which had too few observations to stand alone (Table 2.2). The variables *Di* are indicator variables that equal 1 is the soil-applied insecticide is class *i* and 0 otherwise and the *bi* and *qi* are parameters to estimate.

Equation (2.1) assumes the mean of $NIS_t$ depends linearly on $NIS_0$ with a different slope coefficient for each insecticide class, while equation (2.2) assumes the standard deviation of $NIS_t$ also depends linearly on $NIS_0$, again with a different slope coefficient for each insecticide class. The expectation is that the *bi* and *qi* parameters are less than one, meaning that the NIS mean and standard deviation with each treatment are less than the mean and standard deviation of the NIS without treatment. The lower in value each *bi* and *qi*, the more effective the treatment is in reducing the mean or variably of the NIS with treatment.

In some sense, equations (2.1) and (2.2) are like a linear regression model with key differences. First, no intercept is used since if no rootworm pressure occurs, then $NIS_0$ equals zero and so the expected level of $NIS_t$ would also be zero. Imposing this logical restriction implies an intercept of zero. Second, the model uses a heteroscedastic error, with the variability increasing linearly as the initial pressure $NIS_0$ also increases. Figure 2.2 plots the observed $NIS_t$ versus $NIS_0$, showing the obvious increase in variability in $NIS_t$ as $NIS_0$ increases. Third, the model assumes a beta distribution for $NIS_t$, while regression assumes a normal error term. A beta density is appropriate distribution for $NIS_t$ because a beta density has set lower and upper limits, while a normal density ranges from negative to positive infinity. Because by definition, a NIS can range between 0 and 3, maximum likelihood estimation of the model here sets the minimum and maximum of the estimated beta density for $NIS_t$ to 0 and 3 as well.

Based on preliminary analysis, a restricted model is also specified that jointly estimates a single value for β and θ for treatments using either a pyrethroid alone or an organophosphate alone.

(2.1a) $$\mu = (\beta_{Pyr/OP} D_{Pyrethroid} + \beta_{Pyr/OP} D_{OP} + \beta_{Both} D_{Both} + \beta_{Other} D_{Other})\mathrm{NIS}_0\,,$$

(2.2a) $$\sigma = (\theta_{Pyr/OP} D_{Pyrethroid} + \theta_{Pyr/OP} D_{OP} + \theta_{Both} D_{Both} + \theta_{Other} D_{Other})\mathrm{NIS}_0\,.$$

In this model, the subscript *Pyr/OP* indicates that the soil-applied insecticide was either a pyrethroid or an organophosphate. Equation (2.1a) is the same as equation (2.1), except it assumes $\beta_{Pyrethroid} = \beta_{OP}$ with the new coefficient labelled $\beta_{Pyr/OP}$. Similarly, equation (2.2a) is the same as equation (2.2), except it assumes $\theta_{Pyrethroid} = \theta_{OP}$ with the new coefficient labelled $\theta_{Pyr/OP}$. The statistical support for each model will be tested using likelihood ratio tests (Greene 2003, p. 484).

The probability density function *f* ($NIS_t$) for a random variable $NIS_t$ with a beta distribution is

(2.3) $$f(\mathrm{NIS_t} \mid \alpha, \omega) = \frac{(\mathrm{NIS_t} - \min)^{\alpha-1}(\max - \mathrm{NIS_t})^{\omega-1}\Gamma(\alpha +}{(\max - \min)^{\alpha+\omega+1}\Gamma(\alpha)\Gamma(\omega)},$$

where the parameters *α* and *ω* determine the shape of the distribution, *Γ*(·) is the gamma function, and min and max are the minimum and maximum of the distribution (i.e., 0 and 3). The parameters *α* and *ω* can be expressed as functions of the mean μ and standard deviation *σ* (Evans et al. 2000):

(2.4) $$\alpha = \frac{(\mu - \min)^2(\max - \mu) - (\mu - \min)\sigma}{\sigma^2(\max - \min)},$$

(2.5) $$\omega = \frac{(\mu - \min)(\max - \mu)^2 - (\max - \mu)\sigma}{\sigma^2(\max - \min)}.$$

Substituting these expressions into equation (2.3) re-parameterizes the probability density in terms of the mean *μ* and standard deviation *σ*, then substituting equations (2.1) and (2.2) into that function parametrizes the density function in terms do the parameters *bi* and *qi* and the indicator variables *Di* for each insecticide class and $NIS_0$ as independent variables. Based on this density function, maximum likelihood is used to estimate the parameters *bi* and *qi* for each insecticide class, which makes comparing the efficacy of different insecticide classes more intuitive.

## 2.5 Estimation results

Table 2.3 reports estimation results for the *bi* and *qi* for each insecticide class for both the full model defined by equations (2.1) and (2.2) and the restricted models defined by equation (2.1a) and (2a). Of the original 669 observations, the 15 observation with $NIS_t \geq NIS_0$ were dropped since they

caused numerical errors for the statistical model (specifically the natural logarithm of a number less than or equal to zero) since they were not consistent with a beta probability density function. As discussed previously, these observations occurred due to experimental, measurement and sampling errors dominating treatment effects inherent in small plot work and with rootworm larvae. These dropped observations were 9 for *Pyrethroid*, 1 for *OP*, 1 for *Both* and 4 for *Other*, leaving a total of 654 observations.

Results in Table 2.3 show that the estimated *bi* and *qi* for each insecticide class are strongly significant whether using equations (2.1) and (2.2) or equations (2.1a) and (2.2a), even for the *Other* classes, which had few observations. In terms of mean effects, the estimated coefficients imply that using a pyrethroid and organophosphate premix (*Both*) was the most effective control method — on average, the mean NIS with treatment was 20.1% of the NIS without treatment for this case, regardless of whether the full or restricted model is used. Similarly, using one of the *Other* insecticide classes examined (diamide, neonicotinoid, phenylpyrazole) implied that the NIS with treatment was on average, 49.8% of the NIS without treatment, regardless of whether the full or restricted model is used. For a pyrethroid or an organophosphate soil-applied insecticide used alone, the mean effects are similar in magnitude to each other for the full model, 0.245 and 0.283 for the pyrethroid and organophosphate effects respectively, and only slightly greater than for the pyrethroid-organophosphate premix. The restricted model estimates a single coefficient for both of these treatments, with the estimate of 0.269 intermediate between the two coefficients when estimated separately.

In terms of effects on variability, the estimated $\theta$ parameters show similar relationships among the treatments, though the magnitudes differ. The most effective treatment for reducing the variably of the NIS is the pyrethroid-organophosphate premix (*Both*) treatment, with the standard deviation with treatment on average 20.1% of the NIS without treatment, regardless of whether the full or restricted model is used. Similarly, using one of the *Other* insecticide classes was the least effective for reducing the variability of the NIS with treatment, with the standard deviation of the NIS with treatment on average 26.2% of the NIS without treatment, regardless of whether the full or restricted model is used. Again, for a pyrethroid or an organophosphate used alone, the effects were similar in magnitude to each other for the full model, 0.193 and 0.186 for the pyrethroid and organophosphate effects respectively, and only slightly greater than for the pyrethroid-organophosphate premix. The single coefficient estimated for both treatments for the restricted model was 0.192, intermediate between the coefficients when estimated separately.

The statistical support for the restricted model relative to the full model is tested using a likelihood ratio test (Greene 2003, p. 484). The test statistic is two times the difference between the maximized value of the likelihood function for the full model and the restricted model, which has a chi-squared distribution with degrees of freedom equal to the number of parameter restrictions. In the case here, the test statistic is 2(157.439 — 154.709) = 5.46 with 2 degrees of freedom, which has a p-value 0.0652 to support the null hypothesis of $\beta_{Pyrethroid} = \beta_{OP}$ and $\theta_{Pyrethroid} = \theta_{OP}$. The

**TABLE 2.3** Maximum likelihood estimation results for the efficacy of soil-applied insecticides for reducing root injury by insecticide class

| Parameter | Estimate | Standard Error | t Statistic | p Value |
|---|---|---|---|---|
| **Full Model: Equation (2.1) and (2.2)*** | | | | |
| $\beta_{Pyrethroid}$ | 0.283 | 0.012 | 24.07 | <0.001 |
| $\beta_{OP}$ | 0.245 | 0.015 | 16.20 | <0.001 |
| $\beta_{Both}$ | 0.201 | 0.011 | 18.60 | <0.001 |
| $\beta_{Other}$ | 0.498 | 0.046 | 10.91 | <0.001 |
| $\theta_{Pyrethroid}$ | 0.193 | 0.009 | 20.35 | <0.001 |
| $\theta_{OP}$ | 0.186 | 0.012 | 14.97 | <0.001 |
| $\theta_{Both}$ | 0.157 | 0.009 | 16.52 | <0.001 |
| $\theta_{Other}$ | 0.262 | 0.031 | 8.38 | <0.001 |
| **Restricted Model: Equation (2.1a) and (2.2a)*** | | | | |
| $\beta_{Pyr/OP}$ | 0.269 | 0.009 | 28.70 | <0.001 |
| $\beta_{Both}$ | 0.201 | 0.011 | 18.60 | <0.001 |
| $\beta_{Other}$ | 0.498 | 0.046 | 10.91 | <0.001 |
| $\theta_{Pyr/OP}$ | 0.192 | 0.008 | 25.25 | <0.001 |
| $\theta_{Both}$ | 0.157 | 0.009 | 16.52 | <0.001 |
| $\theta_{Other}$ | 0.262 | 0.031 | 8.38 | <0.001 |

*Maximized value of the log-likelihood function is 157.439 for the Full model and 154.709 for the Restricted model.

interpretation is that we fail to reject the null hypothesis at the traditional 5% level of significance. Alternatively, there is statistical support at the 5% level of significance for the restricted model, which estimates a single coefficient for the mean effect of a pyrethroid and an organophosphate and a single standard deviation coefficient as well. In other words, from a statistical perspective, the efficacy of a pyrethroid and an organophosphate soil-applied insecticide are equivalent for reducing root injury from corn rootworm larvae.

To be thorough, two other restricted models were tested, though results are not reported. First, a restricted model that estimated a single coefficient for the pyrethroid, organophosphate and the pyrethroid-organophosphate premix ($\beta_{Pyrethroid} = \beta_{OP} = \beta_{Both}$ and $\theta_{Pyrethroid} = \theta_{OP} = \theta_{Both}$), and a second model that estimated a single coefficient for the

pyrethroid, organophosphate and the other insecticide classes examined ( $\beta_{Pyrethroid} = \beta_{OP} = \beta_{Other}$ and $\theta_{Pyrethroid} = \theta_{OP} = \theta_{Other}$ ). Both models were strongly rejected, the first with a p-value of 0.00002 and the second with a p-value < 0.00001. The implication is that, though the efficacy of a pyrethroid and an organophosphate soil-applied insecticide are equivalent for reducing root injury from corn rootworm larvae, they are more effective than the other classes examined (*Other*) and less effective than the pyrethroid-organophosphate premix (*Both*).

Overall, the results in Table 2.3 show that the pyrethroid-organophosphate premix provides the greatest reduction in the mean and standard deviation of the NIS with treatment relative to the NIS without treatment, i.e., the least root injury on average and the lowest variability for that injury. A pyrethroid or an organophosphate soil insecticide used alone do not provide quite as effective control of root injury as the premix, but they do provide a similar level of control. Finally, using one of the other insecticide classes examined (diamide, neonicotinoid, phenylpyrazole) provides noticeably less effective control, with a much higher mean and standard deviation of the NIS with treatment for any given level of NIS without treatment.

Figures 2.4 and 2.5 were developed to better illustrate the model and the differences between the soil insecticide treatments. Figure 2.4 shows the beta probability density function for the NIS with treatment ($NIS_t$) for the three soil-applied insecticide treatments, given that the NIS without treatment ($NIS_0$) is 2.0, based on the estimated coefficients in Table 2.3. Because using a pyrethroid-organophosphate premix is the most effective treatment, that probability density function is shifted the most to the left, implying greater probability of lower values and the lowest probability of higher values of the NIS with treatment. On the other hand, because the other insect classes examined had the least efficacy, that probability density function is shifted most to the right, implying greater probability of higher values of the NIS with treatment. Finally, the probability density function when using either a pyrethroid or organophosphate is intermediate between these two probability density functions. These three probability density functions will shift to the right as the NIS without treatment increases, implying greater probabilities of higher values for the NIS with treatment for all three treatments, but the three will retain their relative relationships as in Figure 2.4. Similarly, they will shift to the left as the NIS without treatment decreases, implying greater probabilities of lower values for the NIS with treatment for all three treatments, and again, they will retain their relative relationships as in Figure 2.4.

Figure 2.5 plots the probabilities that the NIS with treatment will be less than or equal to 0.25 for each insecticide treatment as the NIS without treatment varies from 0 to 3. In general, the lower the NIS without treatment, the greater the probability that the NIS with each treatment increases, which is consistent with expectations. Because the pyrethroid-organophosphate premix is the most effective treatment, the probabilities with that treatment of having low NIS are always the greatest for all levels of the NIS without treatment, again consistent with expectations. Similarly, because the other insecticide classes examined were the least effective treatment, the probabilities with that treatment of having low NIS are always the lowest for all levels of the NIS without treatment. Overall, these plots are different ways to illustrate the efficacy of the three different treatments for reducing root injury by rootworm larval feeding.

## 2.6 Discussion

The results of this analysis of the efficacy of soil-applied insecticides are generally consistent with the findings of Tinsley et al. (2015), who analyzed the effect of different rootworm control practices on the NIS with a similar model using some of the same data. Their analysis used ordinary least squares and a linear model comparable to equations (2.1) for the mean and controlled for heteroscedasticity as well. The primary difference between the analyses is the distributional assumption — the analysis here used beta density for the NIS and the Tinsley et al. (2015) analysis used a normal error term. The analysis here also had observations from Iowa, Indiana and Wisconsin that Tinsley et al. (2015) did not have, while the Tinsley et al. (2015) analysis had observations from Nebraska unavailable for this analy-

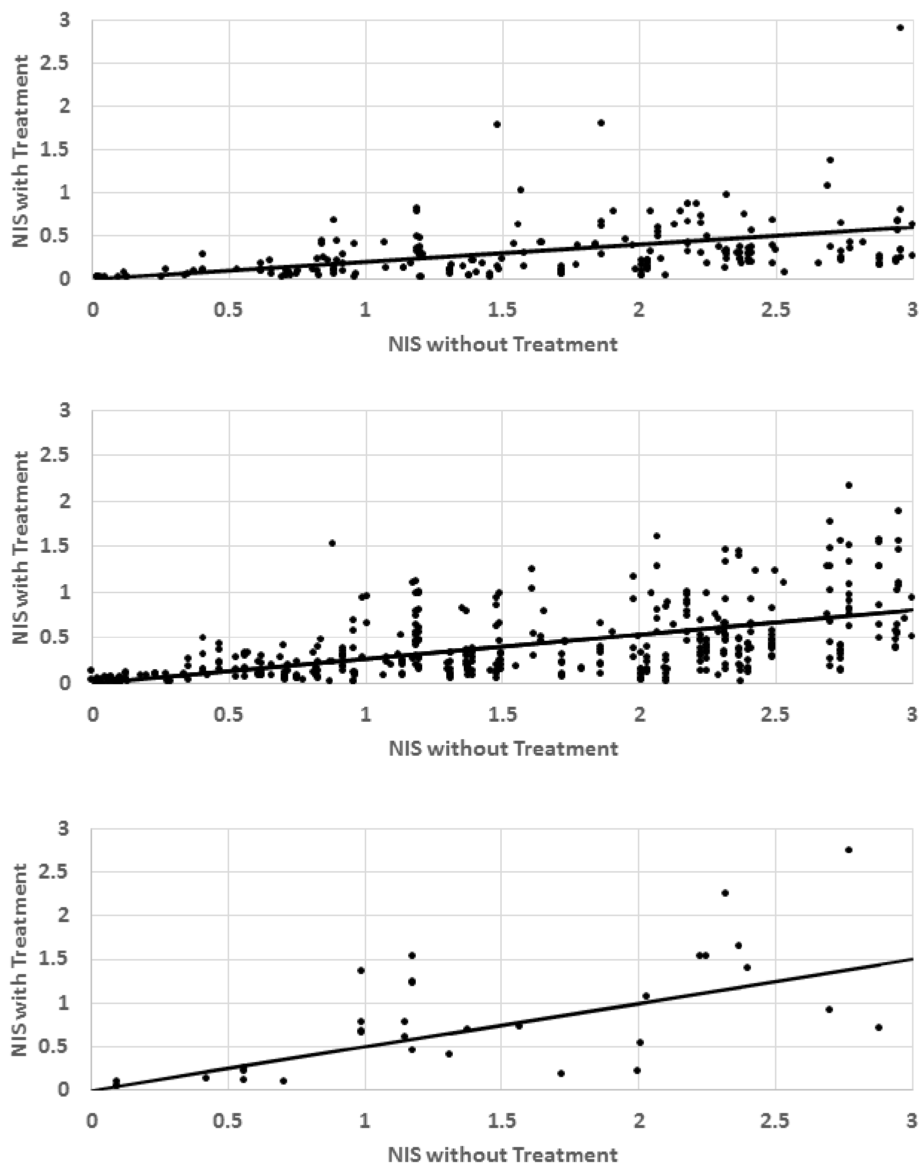



**FIGURE 2.3** Plot of the observed NIS with treatment (NISt) versus the NIS without treatment ($NIS_0$) (points) and the estimated mean NIS with treatment (line) by insecticide class

sis. Finally, the Tinsley et al. (2015) analysis combined all soil-applied insecticides into a single treatment group, while the analysis here separated them by insecticide class. Despite these differences, the two analyses have similar estimates for the mean effect of soil-applied insecticides on the NIS with treatment relative to the NIS without treatment. Here the estimated slope coefficient for the mean was 0.269 for a pyrethroid or organophosphate insecticide used alone, 0.201 for a pyrethroid-organophosphate premix, and 0.498 for a diamide, neonicotinoid or phenylpyrazole. For the data and model here, combining all the soil-applied insecticide treatments into one group gives a $\beta$ coefficient estimate of 0.259 with a standard error of 0.0075. The Tinsley et al. (2015) estimate for the slope coefficient of soil-applied insecticides was 0.28 with a standard error of 0.011 (see their Table 2). Based on these standard errors, these two estimates do not differ statistically, implying that the two analyses give generally consistent results despite their differences.

In terms of the value of pyrethroid insecticides, these results show that pyrethroids are quite effective for controlling corn rootworm larval damage. Mitchell (2017) shows that U.S. farmers predominately use pyrethroids for the soil-applied insecticides, with organophosphates being the only other major insecticide class used. These results are consistent with that practice. Pyrethroids are quite effective at reducing root injury from rootworm larval feeding, providing an equivalent reduction in root injury from rootworm larval feeding as organophosphates, and based on Mitchell (2017), pyrethroids cost less. Based on the findings of Tinsley et al. (2015), only pyramided hybrids with two rootworm Bt toxins provide more effective control than the pyrethroid-organophosphate premix. Among the soil-applied insecticides, a pyrethroid-organophosphate premix was the most effective control of rootworm larval feeding, with a $\beta$ coefficient of 0.201, compared to 0.22 for single toxin Bt corn as reported by Tinsley et al. (2015). The fact that few farmers use other classes of soil-applied insecticides is not surprising, since these results show that pyrethroids and organophosphates out-perform diamides, neonicotinoids and phenylpyrazoles for controlling rootworm larval feeding on corn roots. Indeed, the $\beta$ coefficient for these other insecticide classes estimated here was 0.498, which is comparable to the $\beta$ coefficient estimate of 0.52 that Tinsley et al. (2015) report for using a neonicotinoid seed treatment alone (see their Table 2).

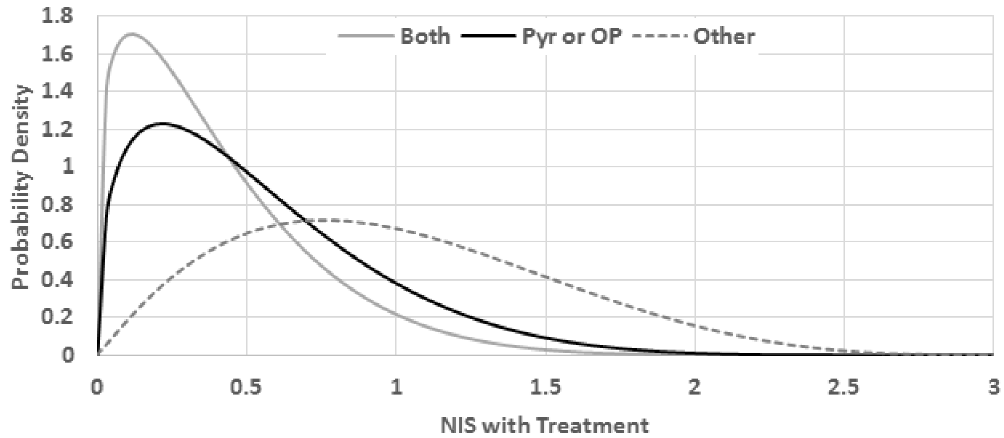
### 2.6.1 Yield benefits

A major reason for using soil-applied insecticides and other insecticides to reduce corn root injury from rootworm larval feeding is to increase yield. The relationship between the node injury scale and corn yield has been examined using small plot data (Dun et al. 2010; Tinsley et al. 2013). Results from this work will be used here to estimate the $\gamma$, proportional yield gain from using a rootworm treatment. Both Dun et al. (2010) and Tinsley et al. (2013) estimate this yield gain as a proportion of the difference in the node injury scale with a model that can be expressed as:

(2.6) $$\gamma = \eta(\mathrm{NIS}_0 - \mathrm{NIS}_t) + \varepsilon .$$

Both models use different but related methods to estimate the variance components of $\varepsilon$ using a composed error model in order to "purge" the es-

**FIGURE 2.4** Probability density for the NIS with treatment ($NIS_t$) when th NIS without treatment ($NIS_0$) is 2.0 by insecticide class used
Both = pyrethroid-organophosphate premix, Pyr or OP = pyrethroid or organophosphate, Other = diamide, neonicotinoid or phenylpyrazole



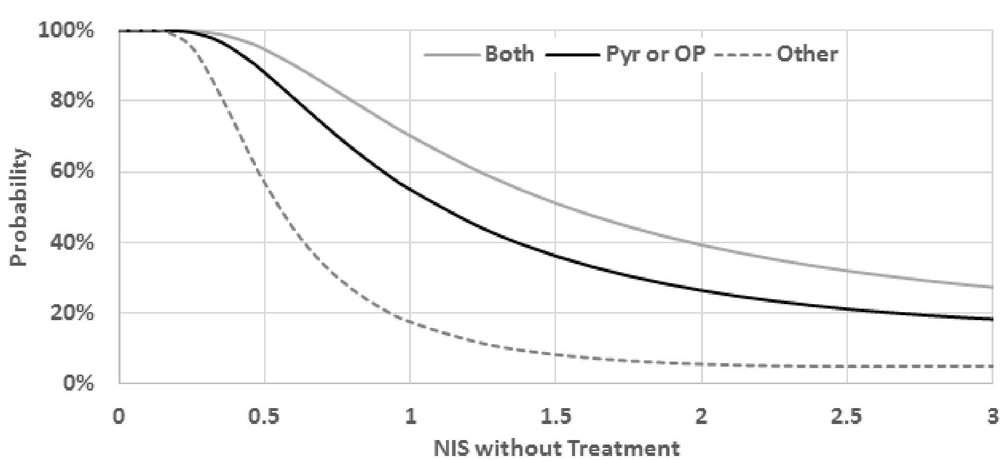

timated mean effect (the parameter $\eta$) of contributions from location, year and other factors. Focusing on the mean effect, which is of interest here, Dun et al. (2010) reported $\eta = 0.179$ for small plot data from Illinois, while Tinsley et al. (2013) report 0.152 for small plot data from Illinois and Nebraska. These estimates imply that for a one unit difference in the NIS (e.g., $NIS_0 = 1.5$ and $NIS_t = 0.5$), corn yield with the treatment would be 17.9% greater than yield without the treatment using the Dun et al. (2010) estimate and 15.2% greater using the Tinsley et al. (2013) estimate. To be more conservative in the yield advantage estimates, the lower value of $\eta = 0.152$ from Tinsley et al. (2013) is used for subsequent calculations.

This yield loss model is combined with the estimated efficacy model to determine the proportional yield gain as a function of the NIS without control ($NIS_0$). The efficacy model implies that for any given level of $NIS_0$, $NIS_t = \beta_t NIS_0$, where $\beta_t$ is the $\beta$ coefficient for the appropriate treatment $t$. The change in the NIS is $NIS_0 — NIS_t$, and then substituting in $NIS_t = \beta_t NIS_0$ and simplifying gives $NIS_0 — NIS_t = NIS_0 — \beta_t NIS_0 = (1 — \beta_t)NIS_0$. Finally, the proportional yield gain for treatment $t$ relative to no control is then:

(2.7) $$\gamma_t = \eta(1-\beta_t)\mathrm{NIS}_0 \,.$$

Note that each of these steps are actually the expected value or mean, i.e., $E[NIS_t] = \beta_t E[NIS_0]$, $E[NIS_0 — NIS_t] = (1 — \beta_t)E[NIS_0]$, and

**FIGURE 2.5**. Probability that NIS with treatment ($NIS_t$) will be ≤ 0.25 based on the NIS without treatment ($NIS_0$) by insecticide class used
Both = pyrethroid-organophosphate premix, Pyr or OP = pyrethroid or organophosphate, Other = diamide, neonicotinoid or phenylpyrazole



$\mathrm{E}[\gamma_t] = \eta(1-\beta_t)\mathrm{E}[\mathrm{NIS}_0]$, which implicitly ignores the variability. This assumption is appropriate, in the sense that these models are estimated with small plot data from multiple years and locations, and a field is a set of small plots that the farmer averages over spatially, the farmer manages multiple fields in different locations over multiple years. The yield gain implied by equation (2.7) averages over all of this variability.

Table 2.4 reports the expected yield gain for each rootworm control treatments examined here, plus three examined by Tinsley et al. (2015): double-toxin Bt, single-toxin Bt and a neonicotinoid seed treatment used alone. These yield gains are relative to using no rootworm control and are linear functions of the NIS without treatment ($\mathrm{NIS}_0$) based on equation (2.7). The columns are ordered from the largest to the smallest gains. Using Table 2.4 requires assuming an average level of rootworm pressure as measured by the NIS without treatment.

The average value for the NIS without treatment for the data summarized in Table 2.1 is 1.33, with the average for the Illinois plots equal to 1.46 and the average for the Iowa plots equal to 1.23; the respective averages for the Indiana and Wisconsin plots were 1.32 and 1.22. However, as noted before, these averages are skewed upward, because the standard protocol for rootworm field trials is to plant a trap crop of pumpkins and/or a late planting of corn the season before to attract egg-laying females to the plots to increase rootworm larval populations for the trial.[3] As a result, these averages are likely an upper bound on the "average" rootworm pressure to assume. In addition, the average rootworm pressure needs to be sufficient to justify use of a soil-applied insecticide. In areas with low rootworm pressure, lower cost and less efficacious control methods such as a seed treatment or even no control would be more appropriate. Based on this logic, a NIS without treatment of $\mathrm{NIS}_0 = 1.0$ is used as the average, consistent with a moderate to high level of rootworm pressure and justifying a soil-applied insecticide. Note that this value is the average; across years, locations and different parts of fields, the actual NIS without treatment would be higher and lower. For example, the standard deviation for all the untreated plots was 0.85, ranging from a low of 0.79 to a high of 0.97 across the four states.

With a $\mathrm{NIS}_0$ of 1.0, the average yield gain is 12.1% for a pyrethroid-organophosphate premix, 11.1% when using a pyrethroid or an organophosphate alone and 7.6% for the other insecticide classes. These average yield gains decrease slightly if the average pressure is $\mathrm{NIS}_0 = 0.8$, to 9.7%, 8.9% and 6.1% respectively and increase slightly if the average pressure is $\mathrm{NIS}_0 = 1.2$, to 14.6%, 13.3% and 9.2% respectively. With a $\mathrm{NIS}_0$ of 1.0, these values imply an average yield advantage of 1.0% for the premix over a pyrethroid or an organophosphate alone and 4.5% over one of the other classes and of 3.5% for a pyrethroid or an organophosphate alone compared to one of the other insecticide classes. These average yield advantage decrease slightly if the average pressure is $\mathrm{NIS}_0 = 0.8$, to 0.8%, 3.6% and 2.8% respectively and increase slightly if the average pressure is $\mathrm{NIS}_0 = 1.2$, to 1.3%, 5.5% and 4.2% respectively.

3 For example, see http://www.ent.iastate.edu/dept/faculty/gassmann/rootworm or https://ipm.illinois.edu/ontarget/pastissues.html.

**TABLE 2.4** Expected yield gain for each rootworm control treatment relative to using no rootworm control over the full range of values for the node injury scale without treatment ($NIS_0$)

| $NIS_0$ | Double Toxin Bt* | Pyrethroid and OP (Both) | Single Toxin Bt* | Pyrethroid or OP (Pyr/OP) | Other Class (Other) | Seed Treatment* |
|---|---|---|---|---|---|---|
| 0.0 | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| 0.1 | 1.4% | 1.2% | 1.2% | 1.1% | 0.8% | 0.7% |
| 0.2 | 2.7% | 2.4% | 2.4% | 2.2% | 1.5% | 1.5% |
| 0.3 | 4.1% | 3.6% | 3.6% | 3.3% | 2.3% | 2.2% |
| 0.4 | 5.5% | 4.9% | 4.7% | 4.4% | 3.1% | 2.9% |
| 0.5 | 6.8% | 6.1% | 5.9% | 5.6% | 3.8% | 3.6% |
| 0.6 | 8.2% | 7.3% | 7.1% | 6.7% | 4.6% | 4.4% |
| 0.7 | 9.6% | 8.5% | 8.3% | 7.8% | 5.3% | 5.1% |
| 0.8 | 10.9% | 9.7% | 9.5% | 8.9% | 6.1% | 5.8% |
| 0.9 | 12.3% | 10.9% | 10.7% | 10.0% | 6.9% | 6.6% |
| 1.0 | 13.7% | 12.1% | 11.9% | 11.1% | 7.6% | 7.3% |
| 1.1 | 15.0% | 13.4% | 13.0% | 12.2% | 8.4% | 8.0% |
| 1.2 | 16.4% | 14.6% | 14.2% | 13.3% | 9.2% | 8.8% |
| 1.3 | 17.8% | 15.8% | 15.4% | 14.4% | 9.9% | 9.5% |
| 1.4 | 19.2% | 17.0% | 16.6% | 15.5% | 10.7% | 10.2% |
| 1.5 | 20.5% | 18.2% | 17.8% | 16.7% | 11.5% | 10.9% |
| 1.6 | 21.9% | 19.4% | 19.0% | 17.8% | 12.2% | 11.7% |
| 1.7 | 23.3% | 20.7% | 20.2% | 18.9% | 13.0% | 12.4% |
| 1.8 | 24.6% | 21.9% | 21.3% | 20.0% | 13.7% | 13.1% |
| 1.9 | 26.0% | 23.1% | 22.5% | 21.1% | 14.5% | 13.9% |
| 2.0 | 27.4% | 24.3% | 23.7% | 22.2% | 15.3% | 14.6% |
| 2.1 | 28.7% | 25.5% | 24.9% | 23.3% | 16.0% | 15.3% |
| 2.2 | 30.1% | 26.7% | 26.1% | 24.4% | 16.8% | 16.1% |
| 2.3 | 31.5% | 27.9% | 27.3% | 25.5% | 17.6% | 16.8% |
| 2.4 | 32.8% | 29.2% | 28.5% | 26.7% | 18.3% | 17.5% |
| 2.5 | 34.2% | 30.4% | 29.6% | 27.8% | 19.1% | 18.2% |
| 2.6 | 35.6% | 31.6% | 30.8% | 28.9% | 19.9% | 19.0% |
| 2.7 | 36.9% | 32.8% | 32.0% | 30.0% | 20.6% | 19.7% |
| 2.8 | 38.3% | 34.0% | 33.2% | 31.1% | 21.4% | 20.4% |
| 2.9 | 39.7% | 35.2% | 34.4% | 32.2% | 22.1% | 21.2% |
| 3.0 | 41.0% | 36.4% | 35.6% | 33.3% | 22.9% | 21.9% |

*Calculated using $\beta$ coefficients of 0.10 for double-toxin Bt, 0.22 for single toxin Bt and 0.52 for a neonicotinoid seed treatment from Table 2 in Tinsley et al. (2015).

## 2.7 Conclusion

This meta-analysis used small plot data from four states, 11 years and 89 locations for a total of 669 observations to examine the efficacy of different soil-applied insecticides for reducing root injury from corn rootworm larval feeding. The meta-analysis found that pyrethroid insecticides are a relatively effective method for controlling rootworm larval injury to corn roots. When used alone, pyrethroids provide control equivalent to organophosphates and significantly better than the other classes examined (diamides, neonicotinoids, phenylpyrazoles). Pyrethroids are particularly effective when used as a premix with an organophosphate, providing control comparable to single-toxin Bt corn before the emergence of rootworm resistance. The data for this meta-analysis were collected mostly before the development and spread of rootworm resistance and cross resistance to Bt toxins (Gassman et al. 2011, 2014, Wangila 2015, Jakka et al. 2016). As a result, the efficacy of soil-applied pyrethroid-organophosphate premixes and pyrethroids used alone has likely grown relative to single toxin Bt corn and potentially may have become comparable double-toxin Bt corn as its efficacy has declined.

Based on the analysis of Tinsley et al. (2015), the efficacy of the other insecticide classes examined (diamides, neonicotinoids, phenylpyrazoles) is comparable to neonicotinoid seed treatments. Given the results here and those of Tinsley et al. (2015), it seems that these other classes are not alternatives to pyrethroids, organophosphates or Bt corn, but for seed treatments.

These changes and relative advantages of pyrethroids in reducing corn root injury as measured by the node injury scale (NIS) (Oleson et al. 2005) were transformed to yield gains and relative yield advantages using the yield loss model of Tinsley et al. (2013). Based on an average NIS without treatment of 1.0, the yield gain from using a pyrethroid is 11.1% when used alone and 12.1% when combined with an organophosphate, noticeably greater than the 7.6% yield gain for using the other insecticide classes examined. These yield gains increase as the average $NIS_0$ increases and decrease as the average $NIS_0$ decreases. Overall, the yield gain from using soil-applied insecticides likely ranges between 9% and 14.5%, with yield gains from pyrethroid-organophosphate premix comparable to those for single-toxin Bt corn before rootworm populations developed resistance to Bt toxins.

Several caveats and qualifications also apply to these results. First, resistance is an important issue for corn rootworm. Rootworm populations have developed resistance to many control tactics, not only to Bt toxins but also to crop rotation and multiple insecticide classes (Levine et al. 1992, 2002; Wright et al. 1999; Gassman et al. 2011, 2014; Wangila 2015; Jakka et al. 2016). Recently, Pereira et al. (2015) have documented increased resistance to a pyrethroid insecticide in populations of western corn rootworm adults in Nebraska and Kansas. Based on this history, resistance management is extremely important for corn rootworm and maintaining tactics with different modes of action is important. The reported efficacies and associated yield gains and advantages of the different classes and traits and comparisons between them are contingent on the data. If the data are prior to the development of resistance or from locations where resistance is not a problem, then they no longer are accurate for areas where resistance has become a problem.

A second caveat is that there are many pests of corn other than corn rootworm and the efficacies, yield gains and advantages presented here only focus on corn rootworm. Other below-ground pests that farmers commonly mention that are also controlled by soil-applied insecticides include wireworm, seed maggots and white grubs (Mitchell 2017). The yield benefits for controlling these pests with pyrethroids is not included in this analysis. In addition, pyrethroids are used to manage several above-ground, with farmers commonly mentioning lepidopteran larvae (European corn borer, corn earworm, cutworms, armyworms) and pests such as mites, adult corn rootworm, stink bugs, aphids, flea beetles and grasshoppers (Mitchell 2017). This analysis does not include any yield benefits from using pyrethroids to manage any of these pests. Among these pests, the most important are various larvae of lepidopteran species, such as European corn borer and corn earworm (*Helicoverpa zea*). The analysis of the sweet corn data in section 3.0 of this report shows the yield benefits of pyrethroids for managing lepidopteran pests of corn. Bt corn traits are currently used to manage most lepidopteran pests of corn (USDA-ERS 2016). However, the yield benefits of pyrethroids are likely to increase, given the recent documentation of corn earworm resistance to some Bt traits (Dively et al. 2016).

## 2.8 References


Bledsoe, L.W., E. Kraus, A. McKLinnis, N. Seiter, J. Oswalt, R. Swartz, L.P. Liu, R. Boles, and B. Coakes. 2008. *Corn and Soybean Insecticide Evaluations: 2008.* Department of Entomology, Purdue University, West Lafayette, IN. Online: https://extension.entm.purdue.edu/fieldcropsipm/pubs/INDfinal08.pdf.

Dively, G.P., P.D. Venugopal, and C. Finkenbinder. 2016. *Field-Evolved Resistance in Corn Earworm to Cry Proteins Expressed by Transgenic Sweet Corn.* PloS one 11.12 (2016): e0169115.

Dun, Z., P.D. Mitchell, and M. Agosti. 2010. *Estimating Diabrotica virgifera virgifera damage functions with field trial data: applying an unbalanced nested error component model.* J Appl Entomol 134:409-419 doi: 10.1111/j.1439-0418.2009.01487.x.

Ellsbury. M.M., W.D. Woodson, S.A. Clay, D. Malo, J. Schumacher, D.E. Clay, and C.G. Carlson. 1998. Geostatistical *Characterization of the Spatial Distribution of Adult Corn Rootworm (Coleoptera: Chrysomelidae) Emergence.* J Econ Entomol 27:910-917.

Gassmann, A.J., J.L. Petzold-Maxwell, R.S. Keweshan, and M.W. Dunbar. 2011. *Field-evolved resistance to Bt maize by western corn rootworm.* PLoS ONE 6, E22629.

Gassmann, A.J., J.L. Petzold-Maxwell, E.H. Clifton, M.W. Dunbar, A.M. Hoffmann, D.A. Ingber, and R.S. Keweshan. 2014. *Field-evolved resistance by western corn rootworm to multiple Bacillus thuringiensis toxins in transgenic maize.* Proc Natl Acad Sci USA 111:5141-5146.

Gray, M.E., and K.L Steffey. 1998. *Corn rootworm (Coleoptera: Chrysomelidae) larval injury and root compensation of 12 maize hybrids: an assessment of the economic injury index.* J Econ Entomol 91:723-740.

Gray, M.E., T.W. Sappington, N.J. Miller, J. Moeser, and M.O. Bohn. 2009. *Adaptation and invasiveness of western corn rootworm: intensifying research on a worsening pest.* Annual Rev Entomo. 54:303-321.


Gray, M.E. 2011. *Relevance of traditional integrated pest management (IPM) strategies for commercial corn producers in a transgenic agroecosystem: a bygone era?* J Agric Food Chem 59:5852-5858.

Greene, W.H. 2003. *Econometric Analysis*, 5th ed., Prentice Hall, Upper Saddle River, NJ.

Hurley, T.M., and P.D. Mitchell. 2014. *Value of Insect Pest Management to U.S. and Canadian Corn, Soybean and Canola Farmers.* AgInfomatics, Madison, WI. Online: http://aginfomatics.com/index.html.

Hurley, T.M., and P.D. Mitchell. 2017. *Use and Value of Insect Management Practices in U.S. Alfalfa, Corn, Cotton, and Soybean Production*. AgInfomatics, Madison, WI.

Insecticide Resistance Action Committee (IRAC). 2016. *IRAC Mode of Action Classification Scheme, Version 8.1. (April 2016).* Online: http://www.irac-online.org/documents/moa-classification/.

Jakka, S.R.K., R.B. Shrestha, and A.J. Gassman. 2016. *Broad-spectrum resistance to Bacillus thuringiensis toxins by western corn rootworm (Diabrotica virgifera virgifera).* Scientific Reports 6:27860 DOI: 10.1038/srep27860.

Krupke, C., N. Seiter, L. Beldsoe, A. Murphy, L.P. Liu, J. Oswalt, S. Smith, C. Race, and C. Short. 2009. *Corn and Soybean Insecticide Evaluations: 2009.* Department of Entomology, Purdue University, West Lafayette, IN. Online: https://extension.entm.purdue.edu/fieldcropsipm/pubs/INDfinal09.pdf.

Levine, E., and H. Oloumi-Sadeghi. 1991. M*anagement of diabroticite rootworms in corn.* Annu Rev Entomol 36: 229-255.

Levine, E., H. Oloumi-Sadeghi, and J.R. Fisher. 1992. *Discovery of multiyear diapause in Illinois and South Dakota northern corn rootworm (Coleoptera: Chrysomelidae) eggs and incidence of the prolonged diapause trait in Illinois.* J Econ Entomol 85:262-267.

Levine, E., J.L. Spencer, S.A. Isard, D.W. Onstad, and M.E. Gray. 2002. *Adaptation of the western corn rootworm to crop rotation: evolution of a new strain in response to a management practice.* Amer Entomolog 48:64-107.

Mason, C.E., M.E. Rice, D.D. Calvin, J.W. Van Duyn, W.B. Showers, W.D. Hutchison, J.F. Witkowski, R.A. Higgins, D.W. Onstad, and G.P. Dively. 1996. *European corn borer ecology and management.* North Central Regional Extension Publication 327. Iowa State University, Ames, IA.

Mitchell, P.D. 2014. *Methods and Assumptions for Estimating the Impact of Neonicotinoid Insecticides on Pest Management Practices and Costs for U.S. Corn, Soybean, Wheat, Cotton and Sorghum Farmers.* AgInfomatics, Madison, WI. Online: http://aginfomatics.com/index.html.

Mitchell, P.D. 2017. *Methods and Assumptions for Estimating the Impact of Pyrethroid Insecticides on Pest Management Practices and Costs for U.S. Crop Farmers.* AgInfomatics, Madison, WI.

Musick, G.J., and M.L. Fairchild. 1967. *Preliminary study on some of the factors affecting control of western corn rootworm larvae with soil insecticides.* J Econ Entomol 60:1522-1525.

Oleson, J.D., Y.L. Park, T.M. Nowatzki, and J.J. Tollefson. 2005. *Node-injury scale to evaluate root injury by corn rootworms (Coleoptera: Chrysomelidae).* J Econ Entomol 98:1-8.

Onstad, D.W., M. Joselyn, S. Isard, E. Levine, J. Spencer, L. Bledsoe, C.R. Edwards, C. Di Fonzo, and H. Wilson. 1999. *Modeling the spread of western corn rootworm (Coelop-*

*tera: Chrysomelidae) populations adapting to soybean-corn rotation.* Environ Entomol 28:188-194.

Rice, M. 2001. *Northern corn rootworms in corn and soybean fields.* Iowa State University Extension, Integrated Crop Management, Sept. 17, p. 182. Online: http://www.ipm.iastate.edu/ipm/icm/2001/9-17-2001/ncrw.html.

Spencer, J., B. Hibbard, J. Moeser and D. Onstad. 2009. *Behaviour and ecology of the western corn rootworm (Diabrotica virgifera virgifera LeConte).* Agric Forest Entomol 11:9-27.

Sutter, G.R., T.F. Branson, J.R. Fisher, N.C. Elliott, and J.J. Jackson. 1989. *Effect of insecticide treatments on root damage ratings of maize in controlled infestations of western corn rootworms (Coleoptera: Chrysomelidae).* J Econ Entomol 82:1792-1798.

Tinsley, N.A., R.E. Estes, and M.E. Gray. 2013. *Validation of a nested error component model to estimate damage caused by corn rootworm larvae.* J Appl Entomol 137:161-169.

Tinsley, N., P.D. Mitchell, R. Wright, L. Meinke, R. Estes, M. Gray. 2015. *Estimation of Efficacy Functions for Products Used to Manage Corn Rootworm Larval Injury.* J Appl Entomol doi: 10.1111/jen.12276.

Toepfer, S., M.M. Ellsbury, R. Eschen and U. Kuhlmann. 2007. *Spatial clustering of Diabrotica virgifera virgifera and Agriotes ustulatus in small-scale maize fields without topographic relief drift*. Entomologia Experimentalis et Applicata 124:61-75.

Unglesbee, E. 2016a. *Rootworm Alert: Rotation-Resistant Northern Corn Rootworm Suspected in Missouri.* DTN/Progressive Farmer August 5, 2016. Online: https://www.dtnpf.com/agriculture/web/ag/news/crops/article/2016/08/05/rotation-resistant-northern-corn

Unglesbee, E. 2016b. *When Pyramids Fall: Rootworm Resistance to Pyramided Bt Corn Confirmed.* DTN/Progressive Farmer August 10, 2016. Online: https://www.dtnpf.com/agriculture/web/ag/news/crops/article/2016/08/10/rootworm-resistance-pyramided-bt-2.

United States Department of Agriculture (USDA). 2017. *World Agricultural Supply and Demand Estimates Report (WASDE)*. WASDE 561, Jan. 12, 2017. USDA, Washington, DC. Online: https://www.usda.gov/oce/commodity/wasde/

United States Department of Agriculture — National Agricultural Statistics Service (USDA-NASS). *2017. Quick Stats.* Online database: https://quickstats.nass.usda.gov/.

United States Department of Agriculture — Economic Research Service (USDA-ERS). 2016. *Recent Trends in GE Adoption.* Online: https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us/recent-trends-in-ge-adoption.aspx

Wangila, D.S., A.J. Gassmann, J.L. Petzold-Maxwell, B.W. French, and L.J. Meinke. 2015. *Susceptibility of Nebraska western corn rootworm (Coleoptera: Chrysomelidae) populations to Bt corn events.* J Econ Entomol 108:742-751.

Wright, R. L. Meinke, and B. Siegfried. 1999. *Larval Western Corn Rootworm Insecticide Resistance in Nebraska.* Nebraska Cooperative Extension NF99-366, Lincoln, NE. Online: http://digitalcommons.unl.edu/extensionhist/1072.

# 3.0 Yield benefits and efficacy of pyrethroid insecticides for eleven major U.S. crops based on small-plot data

## 3.1 Executive summary

Small plot studies for the following 11 crops were assembled: alfalfa, citrus, cotton, potato, rice, sorghum, sugar beet, sunflower, sweet corn, tomato and wheat. Data from studies were included if they included yield or some measure of efficacy based on changes in pest abundance, crop damage or crop health for at least one treatment that included a pyrethroid insecticide and an untreated control. Most studies collected data for multiple insecticides, both pyrethroids and non-pyrethroids, as well as tank mixes, premixes or sequences of different insecticides, and these data were included as well. The final data included 335 site-years, generating a total of 2,971 observations for at least one measure of yield or efficacy relative to an untreated control, with data usually from multiple states and several years. However, the number of observations varied widely among the crops, from a high of 852 for alfalfa to a low of 15 for rice.

The meta-analysis used sample statistics to summarize the pest control efficacy data and yield benefits of pyrethroid insecticides and non-pyrethroids relative to the untreated control. Analysis for each crop focused on the advantages of pyrethroids and non-pyrethroids relative to the untreated control, expressed as the percentage change in yield, pest abundance, crop damage and/or crop health.

For these crops, pyrethroid insecticides substantially increase yields, reduce pest abundance/crop damage and improve crop health, which provides empirical support for the long-standing and widespread commercial use of pyrethroid insecticides in these and other crops. The benefits provided by pyrethroid insecticides were comparable to those provided by other commercially available insecticide classes, with the magnitude of the benefits tending to follow the same trends across crops. However, notable examples were identified in which pyrethroids out-performed other classes. Most noteworthy was pest abundance, in which the average efficacy of all pyrethroid treatments was generally larger than for non-pyrethroid treatments, except for Colorado potato beetles in potato, non-lepidopteran cotton pests and all pests in wheat. Other notable examples included yield increases for sweet corn, potato and sunflower and crop damages in cotton, potato, sugar beet, sunflower and tomato. Finally, the analysis found that benefits were often enhanced when insecticide treatments combined pyrethroids and non-pyrethroids, indicating the benefits from mixing or sequencing pyrethroids with other modes of action to increase yield and/or efficacy.

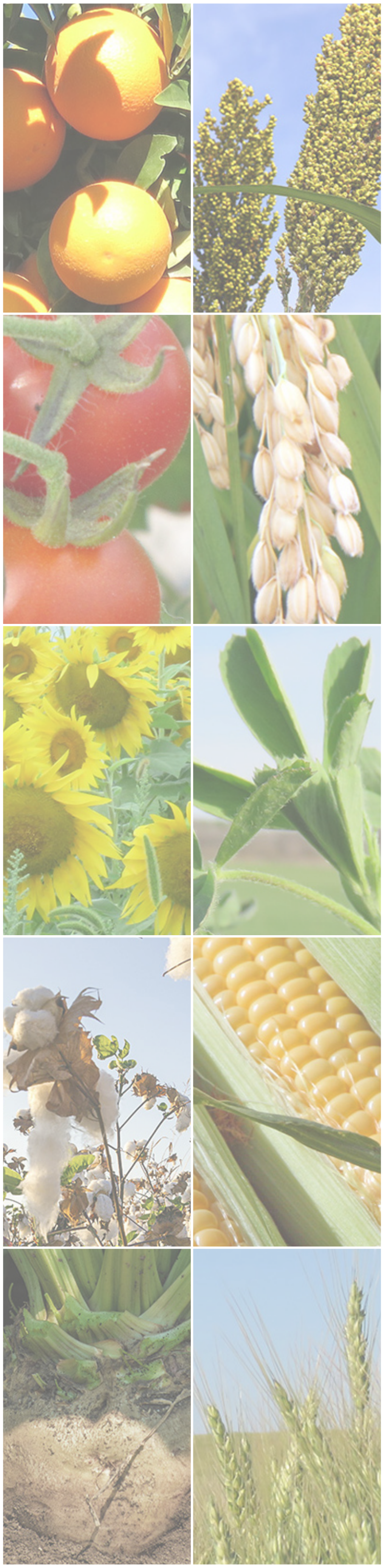
The largest average yield increases for pyrethroids compared to the untreated control were for sweet corn at 231%, 105% for alfalfa and 80% for potato, with more moderate yield increases of 55% for cotton and 36% for sugar beet, while the lowest yield increases were still 13.4% for sorghum, 12.5% for sunflower, 9.1% for wheat and 5.1% for rice. The average reductions of pest populations by pyrethroids compared to the untreated control ranged from 81% for sweet corn to 33.3% for aphids in potato, with the potato results the only average efficacy falling below 50%. The average pest control efficacies for pyrethroids generally exceeded all efficacies for non-pyrethroids except for Colorado potato beetles in potato, non-lepidopteran cotton pests and all pests in wheat, indicating that pyrethroid insecticides are particularly effective at reducing pest populations. The meta-analysis of Qureshi et al. (2014) for control of Asian citrus psyllid in Florida citrus showed the same result — pyrethroid insecticides provided the largest average population reduction and longest average duration of control.

The largest average reductions of crop damage by pyrethroids compared to the untreated control were 82% for potato and 80% for alfalfa, with reductions generally averaging around 60% to 65% for cotton, sweet corn, sugar beet and tomato, and the lowest reduction for rice, sunflower and wheat, generally around 30% to 35%. Little crop health data were available, but the largest average increase in crop health for pyrethroids compared to the untreated control was 34% for sorghum, with small increases for sunflower and sugar beet that exceeded the average increases for non-pyrethroids.

Important caveats apply to this analysis. First, this analysis did not develop a bioeconomic model of pest pressure, efficacy, yield impacts and economic benefits for any of these pest crop systems. The data were deemed insufficient to estimate parametric models of insecticide efficacy in terms of pest population reductions, decreases in crop injury measure or improvements in crop health, not were such measures linked to yield impacts. As a result, though sample statistics show that pyrethroids reduce pest impacts on crops and/or impact yields, these effects are never linked to explicit economic gains for farmers. Second, the resistance management benefits of pyrethroids are not accounted for in this analysis. Because pyrethroids are generally a lower cost class of insecticides, they are often a key part of insecticide rotations and mixes with more costly insecticide classes to help preserve insecticide efficacy in many of these pest crop systems.

## 3.2 Introduction

This section presents meta-analysis results for the yield and efficacy benefits of pyrethroid insecticides for 11 other major U.S. crops — alfalfa, citrus, cotton, potato, rice, sorghum, sugar beet, sunflower, sweet corn, tomato and wheat. These crops are economically important, both in terms of acres planted or harvested and in terms of total crop value. For example, in 2015, there were 54.6 million acres of wheat planted in the U.S., 17.8 million acres of alfalfa hay harvested, and 8.6 million acres of cotton and 8.5 million acres of sorghum planted (USDA NASS 2016a). Other crops such as rice, sunflower, sugar beet and potato had fewer planted acres, 2.6 million,1.9 million, 1.2 million, 1.1 million, respectively but substantially larger values per acre (USDA NASS 2016a). As a result, the total market value of production for these crops in 2015 was $3.9 billion for potato, $3.1 billion for rice, $1.4 billion for sugar beet and $500 million for sunflower (USDA-NASS 2016b). Fruit and vegetable crops also have substantial per acre values, so that the total market value of U.S. production in 2015 was $3.4 billion for citrus, $1.1 billion for tomato and $672 million for sweet corn (USDA-NASS 2016b). For comparison, the total market value of U.S. corn production was $49.0 billion in 2015 and $34.5 billion for soybean, while it was $10.2 billion for wheat,



$8.7 billion for alfalfa, $3.9 billion for cotton and $2.1 billion for sorghum (USDA-NASS 2016b).

The point of this information is to indicate the economic importance of these other 11 crops. Though corn and soybean dominate U.S. crop production in terms of acres and value, these other crops are also economically important in their own right. Furthermore, as with most crops, insect management is important, and as a result, pyrethroid insecticides play an important role in maintaining productivity, quality and value for these crops. Therefore, this meta-analysis of the yield and efficacy benefits of pyrethroid insecticides also includes these crops.

## 3.3 Materials and methods

The data for this meta-analysis are from four primary sources: 1) published in *Arthropod Management Tests*, 2) from registrant databases of small-plot field experiments conducted by faculty and academic staff at land grant universities, 3) published as miscellaneous reports from university researchers, often as part of Extension or outreach efforts, and 4) published literature from peer-reviewed journals. The first two data sources were chosen because they are relatively standardized databases that contain data collected from studies conducted under standardized field protocols and conducted by faculty and academic staff on university research stations or farms. The final two data sources were included because key studies were known, and it allowed expanding the data for crops with only a few studies in the first two databases. A few of the studies were in multiple sources because they were reported to the registrants who funded the university study but also reported by the researchers in AMT or other outlets, and/or were subsequently used as the basis for peer-reviewed journal articles. As a result, data are carefully examined to remove duplicates.

### 3.3.1 Yield and efficacy data

*Arthropod Management Tests* is an editor-reviewed publication of the Entomological Society of America (ESA) that reports the results from “preliminary and routine screening for management of arthropods” (http://www.entsoc.org/Pubs/Periodicals/AMT). ESA members can search and the access the reports online, though now many of the publications are open-access and searchable using Google or similar search engines. However, the data must be entered by hand from the publication tables into a database. Data were assembled for the following 11 crops: alfalfa, citrus, cotton, potato, rice, sorghum, sugar beet, sunflower, sweet corn, tomato and wheat. Data were available for these crops for studies conducted from 1986 to 2015 but not for all crops in all of these years. This analysis focused on pyrethroid insecticides, including bifenthrin, cyfluthrins, cyhalothrins, cypermethrins, deltamethrin, esfenvalerate, fenpropathrin, permethrin and tefluthrin, but collected data for other insecticides as well if the treatments were included in the same experiment.

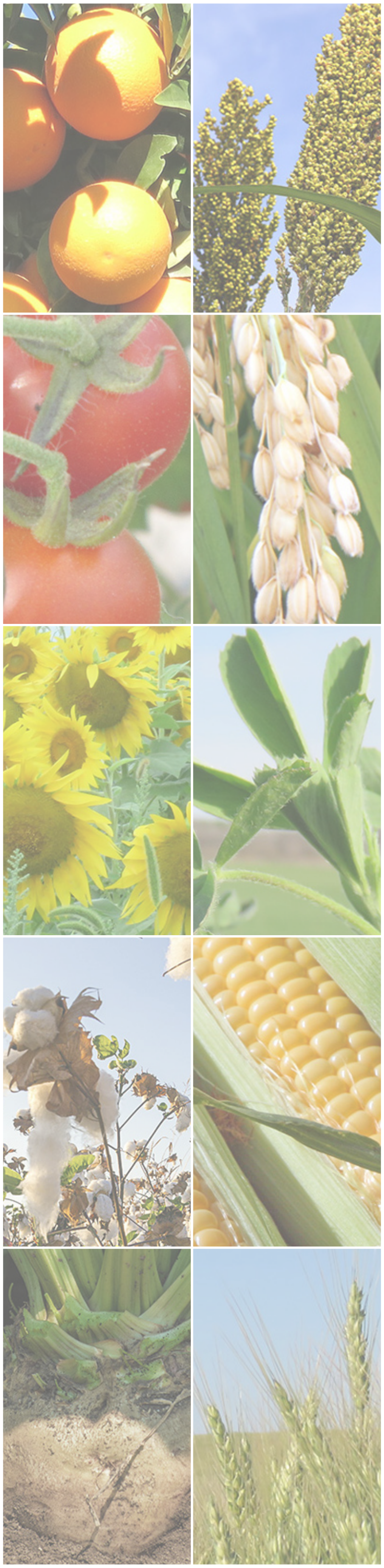
For inclusion in this analysis, an AMT study needed to report yield or some measure of pest abundance, crop damage or crop health for plots receiving a pyrethroid treatment and untreated control plots. Trade names used to describe insecticide treatments were checked using the Agrian online database (http://www.agrian.com/labelcenter/results.cfm) to ensure that an insecticide was the only difference between the treated and untreated control plots. Many studies also collected the same yield or efficacy data for insecticide treatments other than pyrethroids, and these data were included as well. Pertinent information entered for each study site-year included the measures of yield, pest control, pest abundance, crop damage and/or crop health for the treated and untreated plots. Additional identifying data from each of the studies was also recorded including:  author(s), title, year of the study, state, location, crop, pest target(s), insecticide active ingredient, insecticide rate and insecticide application technology (e.g., soil-applied, seed treatment, foliar applied).

Registrants fund research trials to be conducted by faculty and academic staff at land grant universities and maintain databases of results, and field trial data were assembled from these databases for these crops. Just as for the AMT data, to be included in this analysis, a study needed to report yield, pest abundance, crop damage or crop health for plots receiving insecticide treatments and untreated control plots. Again, identifying data from each of the studies were included, consisting of:  cooperating researcher(s), project identifier, year of the study, state, location, crop, pest target(s), insecticide active ingredient, insecticide rate and application technology.

In addition, information from published studies for these crops were gathered from the peer-reviewed literature and from various extension or other research reports from university researchers. Several studies were included from the peer-reviewed literature (e.g., Childers and Rogers 2005; Musser and Shelton 2003; Qureshi et al. 2014; Strausbaugh et al. 2012, 2014), as well as reports and conference papers from university researchers (e.g., Colwell et al. 2005; Groves et al. 2015; Hardke et al. 2005; Jarvi et al. 2006; Knodel et al. 2010, 2011; Stougaard and Bohannon 2012, 2013; Walsh and Johnson 2002). Duplicate studies were dropped based on the author, crop, year, available location information and by examining the reported data.

Table 3.1 summarizes the data used for this meta-analysis by crop and source. A single study may have multiple treatments at multiple sites for more than one year. As a result, the number of observations for analysis exceeds the number of site-years. Also, some studies collected only yield data or only pest abundance data, so the total number of observations does not mean that there are that many observations for each type of data (yield, pest abundance, crop damage and crop health). Based on Table 3.1, data from a total of 335 site-years were assembled for these 11 crops, generating 2,971 observations of at least one of these data types for an insecticide treatment and an untreated control from the same site-year.

Totals from Table 3.1 indicate that data were from 11 site years from publications in journals and 54 site-years from miscellaneous publications, plus 135 site-years from publications in AMT and 135 site-years from registrant funded studies at universities. An appendix of references includes the journal and miscellaneous publications but not those in AMT to reduce the space required. The registrant funded studies are not cited unless they were



published in other sources, in which case the other source is cited and the duplicate study in the database of registrant funded studies was deleted.

Totals from Table 3.1 also indicate that a little more than half of the observations are from AMT and other publications, while the remaining observations are from registrant databases, but this distinction varies greatly among the crops. For crops, such as alfalfa and sweet corn, registrant databases are the most important source, but no registrant data were available for citrus, potato, sorghum, tomato and little for sunflower — for these crops, the data are almost exclusively AMT and Extension publications. For sugar beet, the data are largely from the peer-reviewed literature. Finally, for crops, such as wheat, cotton and rice, the data are from a mix of publications and registrant databases. Note that for citrus, the recently published meta-analysis of Qureshi et al. (2014) is used here but supplemented by additional data not used for that study. Thus the citrus data summarized in Tables 3.1 and 3.2 is this supplemental data and does not include the data used by Qureshi et al. (2014).

Table 3.2 reports the number of states from which data were available for each crop to indicate the geographic distribution. Alfalfa data are from 20 states, as the crop is widely grown all over the U.S., while sweet corn data are from 16 states for a similar reason. Cotton data are from almost all the major producing states. Not surprisingly, data for citrus, rice, sugar beet and tomato are from only a few states, as large-scale commercial production for these crops is geographically limited. Table 3.2 also reports the number of different years for which data are available for each crop, plus the range these years are from. Data for most crops are from a relatively large number of years and from a wide range of years, though for most crops the data are from more recently years. Overall, Table 3.2 shows that the data for this meta-analysis are from a wide range of locations geographically and from a large number of years, indicating a broad coverage of the conditions under which these insecticides are used.

### 3.3.2 Yield and efficacy variables

For this meta-analysis, crop yield and three measures of insecticide efficacy — pest abundance, crop damage, and crop health — are the response variables of interest. More specifically, for each insecticide treatment at a site-year, data for one or more of these variables were collected. In order to aggregate these response variables across sites and years and across measures, the data for each treatment at a site-year were normalized by the untreated control, that is, converted to a percentage change relative to the untreated control. Expressing the yield benefit relative to the untreated control allows comparisons between sites and years by eliminating any direct effects of the environment or geographic location in that year. For crop yield and crop health, the insecticide treatment is expected to increase the measure, while for pest abundance and crop damage, the treatment is expected to decrease the measure. As a result, the normalized response variables are calculated slightly differently for each type of measure, as either a percentage increase yield and crop health and as a percentage decrease for pest abundance and crop damage.

**TABLE 3.1** Number of site-years and observations by source and by crop for meta-analysis data

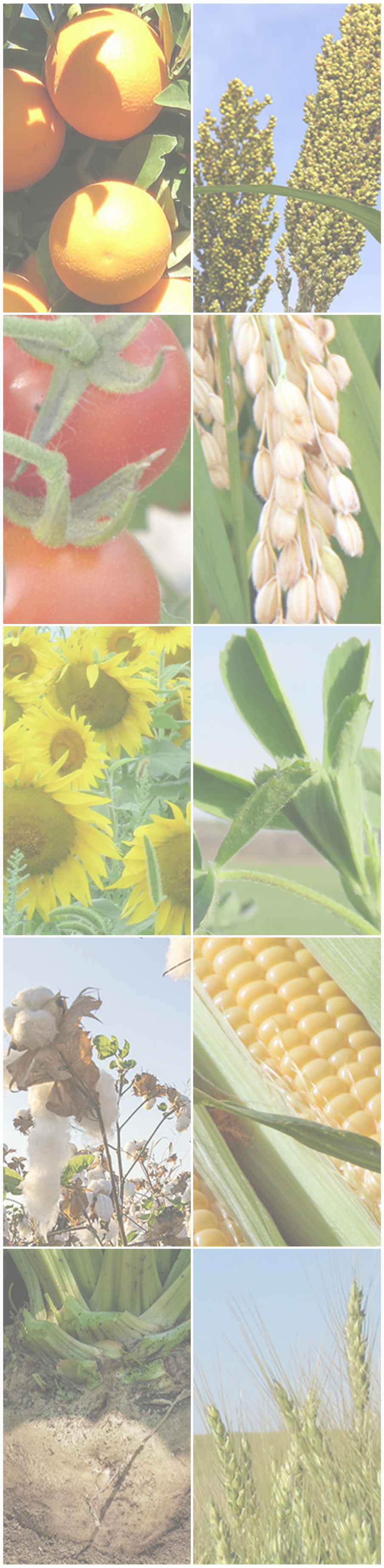
| Crop | Total | Arthropod Management Tests | Miscellaneous Publication | Peer-Reviewed Journal | Registrant Funded Study |
|---|---|---|---|---|---|
| **Site-Years** | | | | | |
| Alfalfa | 55 | 10 | 0 | 0 | 45 |
| Citrus* | 10 | 7 | 0 | 3 | 0 |
| Cotton | 85 | 51 | 9 | 0 | 25 |
| Potato | 47 | 25 | 22 | 0 | 0 |
| Rice | 5 | 0 | 3 | 0 | 2 |
| Sorghum | 9 | 4 | 5 | 0 | 0 |
| Sugar Beet | 18 | 2 | 0 | 6 | 10 |
| Sunflower | 17 | 8 | 6 | 0 | 3 |
| Sweet Corn | 33 | 5 | 0 | 2 | 26 |
| Tomato | 9 | 9 | 0 | 0 | 0 |
| Wheat | 47 | 14 | 9 | 0 | 24 |
| **Total** | **335** | **135** | **54** | **11** | **135** |
| **Observations** | | | | | |
| Alfalfa | 852 | 141 | 0 | 0 | 711 |
| Citrus* | 44 | 33 | 0 | 11 | 0 |
| Cotton | 405 | 146 | 68 | 0 | 191 |
| Potato | 675 | 214 | 461 | 0 | 0 |
| Rice | 15 | 0 | 8 | 0 | 7 |
| Sorghum | 71 | 25 | 46 | 0 | 0 |
| Sugar Beet | 132 | 14 | 0 | 87 | 31 |
| Sunflower | 88 | 16 | 60 | 0 | 12 |
| Sweet Corn | 295 | 6 | 0 | 36 | 253 |
| Tomato | 126 | 126 | 0 | 0 | 0 |
| Wheat | 268 | 66 | 33 | 0 | 169 |
| **Total** | **2,971** | **787** | **676** | **134** | **1,374** |

*Only includes studies and observations not cited by Qureshi et al. (2014).

The yield benefit of an insecticide treatment relative to no insecticide treatment is the percentage increase in yield, calculated for crop *i* for study site-year *j* and treatment *t* as:

$$\%YieldBenefit_{ijt} = \frac{Y_{ijt}^{TRT} - Y_{ijt}^{UTC}}{Y_{ijt}^{UTC}} \times 100 . \qquad (3.1)$$

Here *Y* denotes yield, the superscripts *TRT* and *UTC* respectively denoting the insecticide treated and untreated control. For example, if the measured



insecticide and untreated control yields were 105 and 100, respectively, then $\%YieldBenefit_{ijt}$ = ((105 — 100)/100) x 100 = 5%, implying that the yield for insecticide treatment *t* was 5% larger than the untreated control yield for crop *i* and site-year *j*. Note that this yield benefit is negative if the yield with the treatment is less than the yield with the untreated control. This yield benefit metric is also invariant to the units of measure, and so can be compared across studies and across crops.

The crop health benefit of an insecticide treatment relative to no insecticide treatment is the percentage increase in the crop health measure, calculated for crop *i* for study site-year *j* and treatment *t* as:

(3.2) $$\%CropHealthBenefit_{ijt} = \frac{H_{ijt}^{TRT} - H_{ijt}^{UTC}}{H_{ijt}^{UTC}} \times 100 \, .$$

Here *H* denotes crop health and again, the superscripts *TRT* and *UTC* respectively denote the insecticide treated and untreated control. Common examples of crop health measures are stand counts, crop height or crop biomass. Again, this crop health benefit is negative if the crop health with the treatment is less than the crop health measure with the untreated control. This crop health metric is also invariant to the units of measure, and so can be compared across studies and across crops and across measures. Finally, if more than one measure of crop health was collected for a site-year, the average of the percentage increases was used. For example, if insecticide treatment *t* at site year *j* and crop *i* increased the stand count by 5% and the crop height by 7%, then the final $\%CropHealthBenefit_{ijt}$ was ½(5% + 7%) = 6%.

The percentage decrease in pest abundance from using an insecticide treatment relative to no insecticide treatment is calculated for crop *i* for study site-year *j* and treatment *t* as:

**TABLE 3.2** Number of states, number of years, and range of years for meta-analysis data by crop

| Crop | Number of States | Number of Years | Year Range |
|---|---|---|---|
| Alfalfa | 20 | 11 | 1989-2013 |
| Citrus* | 1 | 6 | 2001-2014 |
| Cotton | 14 | 15 | 1997-2014 |
| Potato | 7 | 13 | 1998-2015 |
| Rice | 2 | 4 | 1995-2003 |
| Sorghum | 6 | 7 | 2003-2013 |
| Sugar Beet | 4 | 14 | 2000-2014 |
| Sunflower | 5 | 10 | 1989-2010 |
| Sweet Corn | 16 | 13 | 1986-2013 |
| Tomato | 4 | 7 | 2000-2014 |
| Wheat | 8 | 20 | 1987-2014 |

*Only includes studies and observations not cited by Qureshi et al. (2014).

(3.3) $$\%PestAbundanceDecrease_{ijt} = \frac{A_{ijt}^{UTC} - A_{ijt}^{TRT}}{A_{ijt}^{UTC}} \times 100 \,.$$

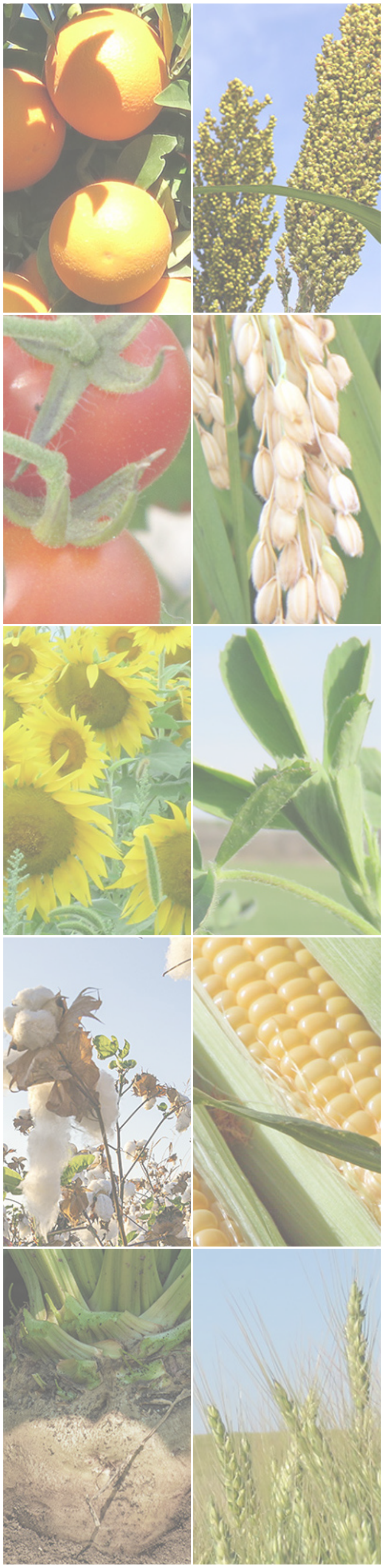
Here *A* denotes pest abundance and again, the superscripts *TRT* and *UTC* respectively denote the insecticide treated and untreated control. Just as for yield and crop health, the denominator is the measure for the untreated control so that the percentage change is relative to the untreated control, but the terms in the numerator are switched so that the percentage change is the net decrease. Common examples of pest abundance measures are the number of larvae per leaf or the number of adults per sweep net. Again, this decrease is negative if the pest abundance measure with the treatment is greater than the pest abundance measure with the untreated control. Also, this pest abundance decrease is invariant to the units of measure and so can be compared across studies and across crops and across measures.

In some cases, multiple measures of pest abundance were collected. If more than one measure of pest abundance was collected for a study, the average of the percentage decreases was used. For example, if insecticide treatment *t* at site year *j* and crop *i* decreased the pest abundance for one pest by 80% and by 90% for another pest, the final pest abundance decrease was 85%. This averaging was used for different life stages of the same pest species as well. For example, if an insecticide treatment decreased egg masses by 80% and larvae by 70%, then the average decrease for that pest species was 75%. In some cases, the same pest abundance measure was collected on multiple sample dates. If the study reported a cumulative measure, or a cumulative measure is commonly used for that pest, such as cumulative aphid days for soybean aphid in soybean (McCornack and Ragsdale 2006), then at the cumulative measure was used. Cumulative pest days for pest abundance collected on two sample dates is the average of the two abundance measures multiplied by the number of days between the sample dates, with these values are then added across consecutive sample dates (Hanafi et al. 1989). The percentage decrease in the cumulative measure was then calculated using equation (3.3) for that measure. If cumulative measures were not used, then the average pest abundance across the sample dates was used before calculating the percentage decrease using equation (3.3). Both methods give the same result if the number of days between sample periods is the same. However, the method using cumulative measures will give more weight to sample dates with longer periods of time between them, while the averaging method gives equal weight to all sample dates.

For crop damage, the percentage decrease from using an insecticide treatment relative to no insecticide treatment is calculated for crop *i* for study site-year *j* and treatment *t* as:

(3.4) $$\%CropDamageDecrease_{ijt} = \frac{D_{ijt}^{UTC} - D_{ijt}^{TRT}}{D_{ijt}^{UTC}} \times 100 \,.$$

Here *D* denotes crop damage and again, the superscripts *TRT* and *UTC* respectively denote the insecticide treated and untreated control. Again, the denominator is the measure for the untreated control so that the percentage change is relative to the untreated control, while the terms in the numerator are arranged so that the percentage change is the net decrease.



Common examples of crop damage measures are the length of larval tunnels in stalks, the number of holes in fruit or the percentage of damaged kernels. This damage decrease is negative if the damage measure for the treatment is greater than for the untreated control and again, this damage decrease is invariant to units and so can be compared across studies, crops and measures.

The meta-analysis calculates these four benefit measures using the available observations and then summarizes sample statistics for each crop in tables. These results are reported in Appendix A and are structured in a similar manner for each crop and benefit. The first column is the insecticide benefit, with four different categories for each benefit to indicate the insecticides used in the treatment. The Pyrethroid Only category is for any insecticide treatment containing only pyrethroid insecticides, though more than one pyrethroid insecticide can be part of the treatment, either as a tank mix, pre-mix or sequence. The Pyrethroid Mixed category is for any insecticide treatment containing a pyrethroid and at least one other insecticide from a different, non-pyrethroid, class based on the IRAC classification (IRAC 2016), again either as a tank mix, pre-mix or sequence. The Any Pyrethroid category combines the first two categories. Finally, the Non-Pyrethroid category is for any insecticide treatment containing only non-pyrethroid insecticides, and again, more than one insecticide can be part of the treatment as either a tank mix, pre-mix or sequence. For each of these categories, the reported sample statistics are the average, standard deviation, minimum and maximum for all the observations for that crop, as well as the number of observations.

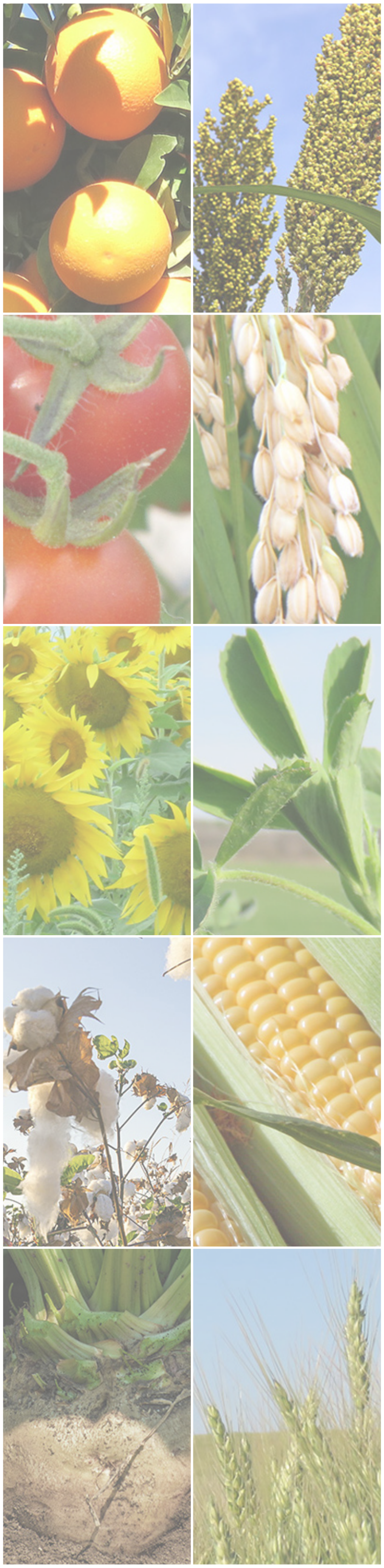
Field data can have some extreme observations for treatments due to small sample problems outside the control of the experiment, or if the denominator in a calculation becomes relatively small. As a result, a four-sigma rule is used to drop outliers, that is, any observation more than four standard deviations above or below the sample average is dropped. For example, the cotton data for the percentage decrease in the plant bug populations had an outlier that was dropped based on the four-sigma rule. The lowest observation for the non-pyrethroid category was a -100% reduction (i.e., the treated population was double the untreated control), with the next lowest reduction was -0.7% (Table A.3). Including this observation gives a sample average of 50.4%, but dropping it gives 53.1%, as reported in Table 3.4. Across all crops and categories, in general, only a few observations were dropped as a result of this rule — none for citrus, rice, sorghum, sugar beet and one for sunflower and tomato and four for alfalfa and cotton. Seven observations were dropped for sweet corn because the untreated control had a very small percentage of harvestable ears and so the increase in yield became very large for some observations. Also, nine observations were dropped for wheat because the untreated control had unusually small pest populations well below the treated plots, and so the percentage reduction became a very negative number. Finally, the 34 potato observations were dropped, most for the percentage reduction in potato leaf hopper populations and the reduction in defoliation by Colorado potato beetle. In these cases, the untreated control had unusually small pest populations or defoliation, well below the treated plots, and so the percentage reduction became a very negative number.

Qureshi et al. (2014) recently published a meta-analysis of the efficacy of insecticides to control Asian citrus psyllid in Florida. Their meta-analysis assembled data from multiple site years for more than 40 different insecticide active ingredients (including several pyrethroids) and summarized these data in multiple tables. More specifically, Qureshi et al. (2014) reported for each active ingredient the average duration of reduction in days, the average percentage reduction, and the number of site-years of data for adults (their Table 2) and nymphs (their Table 3). Rather than re-enter and re-analyze the data Qureshi et al. (2014) assembled, here we summarized the results from their Tables 2 and 3 for different groupings of the modes of action. Specifically, the active ingredients in Tables 2 and 3 of Qureshi et al. (2014) were grouped into 1) Any Pyrethroid for treatments containing a pyrethroid, either used alone or in a pre-mix, tank mix or sequence, 2) Any Neonicotinoid or Diamide for treatments containing a neonicotinoid or diamide insecticide (none contained a pyrethroid), 3) Any Other Synthetic for treatments containing insecticides with known or specific modes of action other than pyrethroid, neonicotinoid or diamide insecticides, and 4) Unknown/Non-Specific for other treatments categorized in this way based on the IRAC mode of action table (IRAC 2016). In addition, the All Synthetic category merged the groups 2 and 3, while the All Non-Pyrethroids category merged groups 2, 3, and 4, and the All Observations merges 1 through 4.

The average duration of reduction in days and the average percentage reduction was then calculated for each MOA grouping, separately for the adult and nymph results in Qureshi et al. (2014) Tables 2 and 3. However, the averaging for each grouping was weighted by the reported number of studies. For example, the Any Pyrethorid category reports averages for five active ingredients:  fenpropathrin, zeta-cypermethrin, lambda-cyhalothrin, beta-cyfluthrin, and zeta-cypermethirn + chlorpyrifos. Rather than using the simple average of results for these five active ingredients, which gives a weight of 1/5 for each reported average, the results here use a weighted-average based on the reported number of studies for each active ingredient. Specifically, the reported averages for fenpropathrin in their Table 2 are based on 8 studies, those for zeta-cypermethrin are based on 5 studies, while those for lambda-cyhalothrin and beta-cyfluthrin are based on 3 studies each, and the results for zeta-cypermethirn + chlorpyrifos are based on 1 study. In total there are 20 studies, so the averages for fenpropathrin receive a weight of 8/20, those for zeta-cypermethrin receive a weight of 5/20, etc. The averages for adults and nymphs are then averaged for each group, again weighting by the number of studies.

## 3.4 Results

Summary results are reported numerically in Tables 3.3 through 3.7, with the additional results reported in Appendix A Tables A.1 through A.11. Each table reports the average percentage increase or decrease in yield and each of the efficacy measures, as well as the number of observations. For each crop, results are reported in each table for four different categories of insecticide treatments: Pyrethroid Only for treatments using only pyrethroid insecticides, Pyrethroid and Non-Pyrethroid Mixed for any combination of pyrethroid and non-pyrethroid insecticides (as a tank mix, pre-mix or a sequence), Any Pyrethroid which combines these two categories, and



Non-Pyrethroid Only for treatments using only non-pyrethroid insecticides. For the yield data, Table 3.3 reports the average percentage yield increase for each of the crops. For the efficacy measures, Table 3.4 reports the average percentage decrease in pest abundance, Table 3.5 reports the average duration of reduction and average percentage reduction of Asian citrus psyllid in Florida citrus, Table 3.6 reports the average percentage decrease in crop damage, and Table 3.7 reports the average increase in crop health for each crop. Results are not reported for crops with no data to summarize (e.g., citrus and tomato in Table 3.3) and some crops have data for more than one measure summarized (e.g., cotton and potato in Table 3.4). Finally, Figures 3.1, 3.2 and 3.3 graphically report results for the Any Pyrethroid category from Tables 3.3, 3.5 and 3.6.

Table 3.3 shows that pyrethroid insecticides have substantially positive impacts on crop yields that compare favorably to alternative, non-pyrethroid insecticides. Among the Pyrethroid Only results, the largest yield increases are for sweet corn at 217%, 105% for alfalfa and 86% for potato, while more moderate yield increases are 50.5% for cotton and 20.5% for sorghum. Finally, since the sweet corn yield data are reported as the percentage of harvestable ears for each treatment, the yield benefit is also reported as the percentage point increase in harvestable ears across these treatments, which gives a few more observations since it does not remove those with a zero harvestable ears. Thus, the average benefit for any insecticide treatment containing a pyrethroid is a 41.8 percentage point increase in harvestable ears relative to the untreated control. Even the lowest yield increases are still substantial, 4.8% for sugar beet, 5.1% for rice, 6.9% for wheat and 7.9% for sunflower, though there are few observations for sugar beet and rice.

In Table 3.3, the yield increases when using a mixture of pyrethroid and non-pyrethroid insecticides show noticeably larger yield benefits than pyrethroids used alone, with only two exceptions. Potato with an insecticide a mixture still has a large 77.3% yield increase, while the sorghum yield increase of 1.64% is relatively low, but as a caveat, this value is only based on three observations. Once combined into the Any Pyrethroid category, results show yields benefits ranging from 5.1% for rice to well more than 200% for sweet corn.

The results for the Non-Pyrethroid Only treatments generally show that pyrethroid insecticides provide yield benefits comparable to other classes of insecticides. Also, the results for both the Any Pyrethroid and the Non-Pyrethroid Only categories generally show the same trends across crops, with relatively large yield benefits for crops such as alfalfa, sweet corn and potato, moderate benefits for crops such as cotton, sugar beet and sorghum, and relatively low, but still substantial benefits for wheat, sunflower and rice, though some of these results are based on very few observations. The most notable exception is for sugar beet, which shows a very large average yield benefit for the Non-Pyrethroid Only category, but this result is based on few observations. Finally, Figure 3.1 shows this same trend graphically, with relatively large yield benefits provided by pyrethroid insecticides for alfalfa and potato, moderate yield benefits for cotton, sweet corn and sugar beet, and relatively small, but still substantial benefits for sorghum, sunflower, wheat and rice.

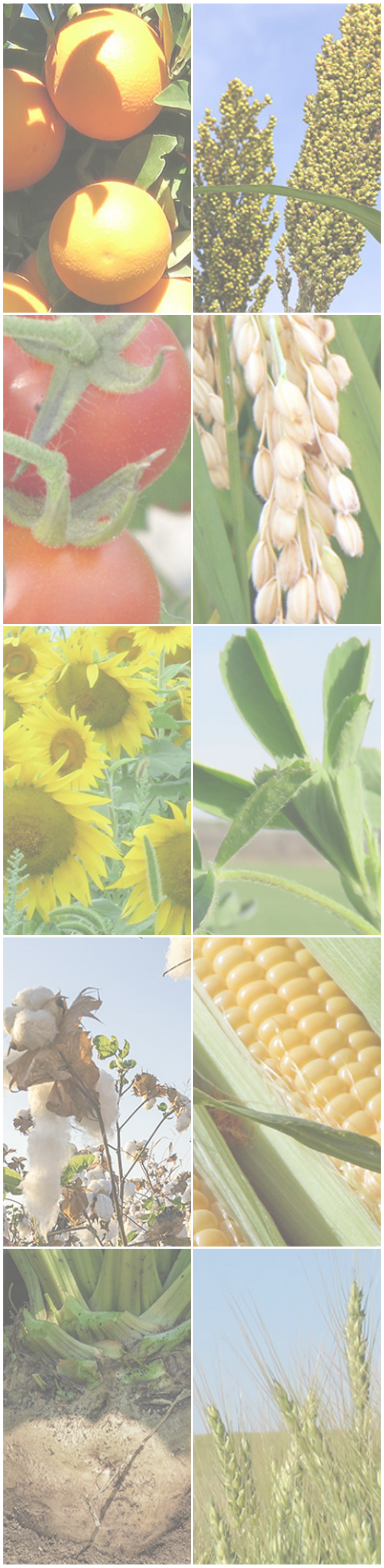
The results in Table 3.4 reveal the basis for these yield benefits — the substantial reductions in pest abundance measures when using pyrethroids and other insecticides. For pyrethroid insecticides used alone, the average reductions in pest populations range from 81.3% for all pests in sweet corn to a low of 35.5% for aphids in potato (the only case with less than 50% efficacy). All insecticides show low efficacy for controlling aphids in potato and high efficacy for controlling pests in sweet corn. For treatments using only non-pyrethroid insecticides, the average reduction in aphid populations in potato only reaches 22.5%, the lowest for that category; the highest efficacy is 68.3% for sweet corn. Combining pyrethroid and non-pyrethroid insecticides gives varied results for pest population control relative to using a pyrethroid alone. Comparing these two categories in Table 3.4, pest control increases for alfalfa, citrus, sorghum and sugar beet, remains about the same for tomato and lepidopteran and plant bugs in cotton, and decreases for sweet corn, wheat and all potato pests.

Comparing results for the Any Pyrethroid category to the Non-Pyrethroid Only category in Table 3.4 shows the generally better pest control provided by pyrethroids. The only exceptions are Colorado potato beetles in potato, non-lepidopteran cotton pests and wheat. The results also show that in general, the efficacy trends are similar across the crops and pests, with relatively higher efficacy for all insecticides in some crops (sweet corn, alfalfa, citrus, and sorghum), and relatively lower efficacies in other crops (all pests in potato). In Table 3.4, the largest difference between the two categories is for potato leafhopper control in potato, where the efficacy of pyrethroids is more than three-times the efficacy for non-pyrethroids, a result based on almost 125 observations for the Any Pyrethroid category and 239 observations for the Non-Pyrethroid Only category.

**TABLE 3.3** Average increase in yield by crop for treatments using only pyrethroid insecticides, a mixture of pyrethroid and non- pyrethroid insecticides, any pyrethroid insecticide, and non-pyrethroid insecticides, relative to untreated control for treatment

| | Pyrethroid Only | | Pyrethroid and Non-Pyrethroid Mixed | | Any Pyrethroid | | Non-Pyrethroid Only | |
|---|---|---|---|---|---|---|---|---|
| Crop | Ave. | Obs. | Ave. | Obs. | Ave. | Obs. | Ave. | Obs. |
| Alfalfa | 105% | 27 | | | 105% | 27 | 125% | 14 |
| Cotton | 50.5% | 97 | 71.1% | 26 | 54.9% | 123 | 75.0% | 63 |
| Potato | 85.7% | 11 | 67.2% | 5 | 79.9% | 16 | 62.3% | 74 |
| Rice | 5.05% | 4 | | | 5.05% | 4 | -2.03% | 2 |
| Sorghum | 20.5% | 5 | 1.64% | 3 | 13.4% | 8 | 32.7% | 8 |
| Sugar Beet | 4.82% | 9 | 43.0% | 40 | 35.9% | 49 | 309% | 7 |
| Sunflower | 7.90% | 35 | 27.0% | 11 | 12.5% | 46 | 1.38% | 27 |
| Sweet Corn | 217% | 115 | 632% | 4 | 231% | 119 | 126% | 71 |
| Sweet Corn* | 41.8% | 140 | 78.4% | 4 | 43.3% | 144 | 27.3% | 72 |
| Wheat | 6.86% | 51 | 25.1% | 7 | 9.06% | 58 | 12.7% | 24 |

*Additive percentage point increase in harvestable ears relative to untreated control treatments.



Overall the results in Table 3.4 demonstrate that pyrethroids are a particularly effective class of insecticides for reducing pest populations in these crops, with efficacies that generally equal or exceed efficacies for non-pyrethroid insecticides. They are broad spectrum insecticide class, which contributes to their wide use in these and other crops. Figure 3.2 graphically plots results for the Any Pyrethroid category, showing the generally smoothly declining trend from the high of 81% efficacy for pyrethroids for sweet corn pests to a low of 47% for Colorado potato beetle in potato, then a drop to 33% efficacy for aphids in potato, a pest for which pyrethroids are known to have a relatively low efficacy.

Table 3.5 reports the average efficacy results for foliar applied insecticides for controlling Asian citrus psyllid in Florida citrus based on the meta-analysis of Qureshi et al. (2014). For adults, the Any Pyrethroid category has longer duration (32.4 days) and a larger average percentage reduction (85.4%) for the adult population than all the other categories. Though the average duration is similar in magnitude to the Any Neonicotinoid or Diamide category, the average percentage reduction is noticeably larger than any other category. For nymphs, the average duration for the Any Pyrethroid category (23.0 days) is noticeably longer than for any other category — the next closest is 19.1 days for the Any Other Synthetic category, but the average percentage reduction is slightly less than for the Any Neonicotinoid or Diamide category. Note, that these differences in average duration may at least partially related to differences in the timing and/or method of insecticide applications, which were not necessarily standardized in the different studies, a point noted by Qureshi et al. (2014). Nevertheless, these results show that for Asian citrus psyllid in Florida citrus, pyrethroids are an effective "knock-down" insecticide class that also provides relatively long-lasting residual control.

Data for crop damage reductions and crop health improvements for insecticide treatments were sparser, and so Tables 3.6 and 3.7 and Figure 3.3 show results based on fewer observations and for noticeably fewer crops. Table 3.6 shows that pyrethroids provide the highest levels of crop damage reduction in potato, with an average of 82% reduction for the Any Pyrethroid category and even higher when used in combination with a non-pyrethroid. Alfalfa is a close second with an average reduction of 80% for the Any Pyrethroid category, though this result is based on few observations. In cotton, sugar beet and tomato, crop damage reductions generally average around 65%, though results for tomato are based on few observations. Finally, pyrethroids on average provide relatively low levels of crop damage reduction in wheat, sunflower and rice, generally around 30%. These same trends are visible graphically in Figure 3.3, with pyrethroids providing about an 80% damage reduction in potato and alfalfa, around 60-65% in sugar beet, cotton, tomato and sweet corn, and around a 30% reduction in rice, sunflower and wheat.

The crop health results summarized in Table 3.7 are primarily stand counts and are generally based on a few observations. Insecticide treatments show the largest average crop health improvements for sorghum, with average increases of around 33% for pyrethroid insecticides and about 28% for non-pyrethroid insecticides. Results for sugar beet are essentially equal

**FIGURE 3.1** Average increase in yield by crop for any insecticide treatment including a pyrethroid insecticide relative to the untreated control

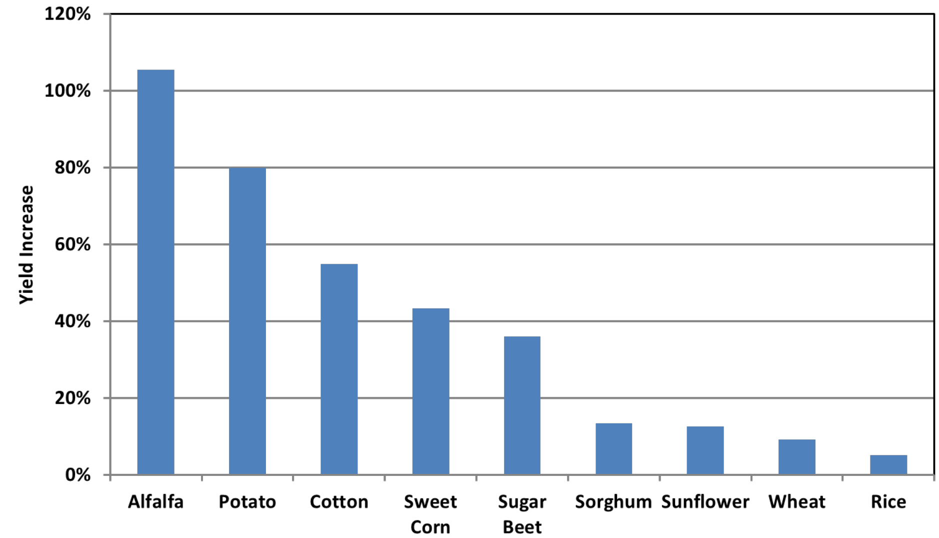



**FIGURE 3.2** Average decrease in pest abundance measures by crop for any insecticide treatment including a pyrethroid insecticide relative to the untreated control

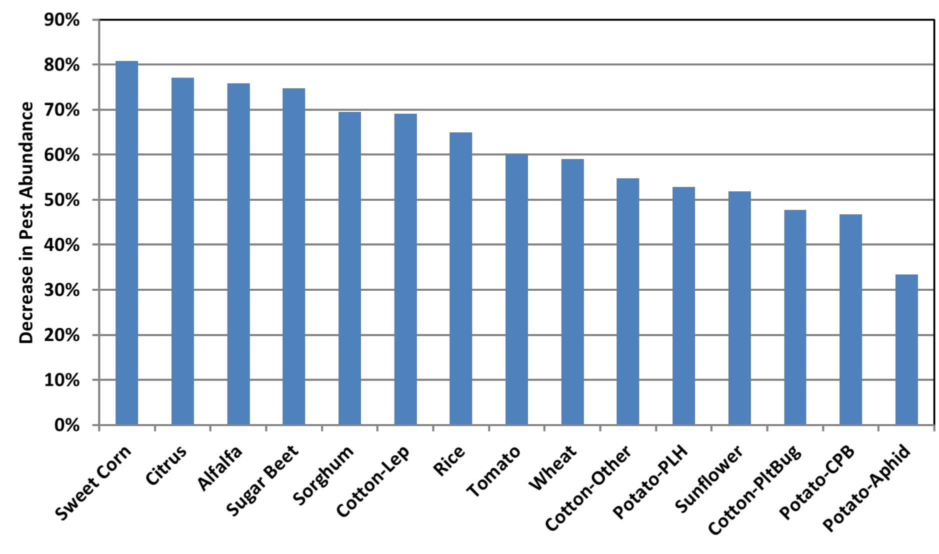
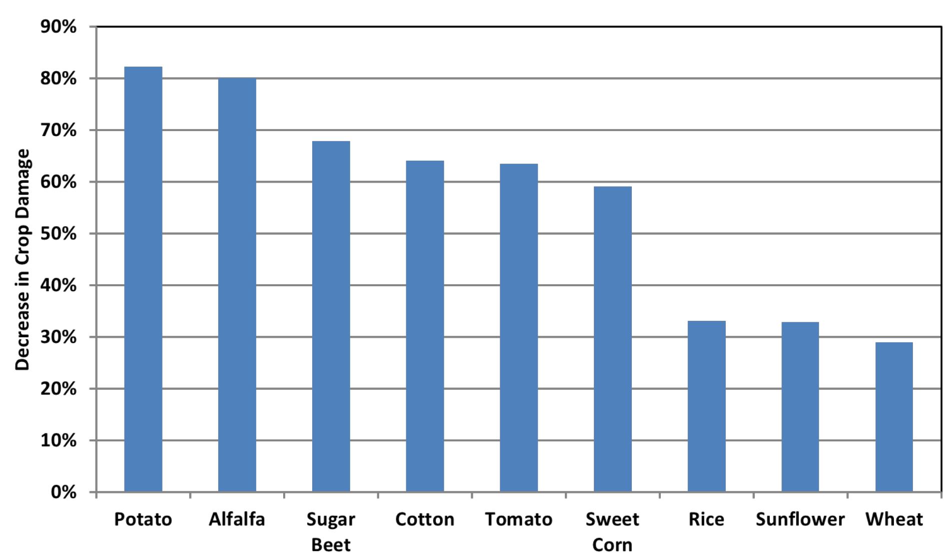
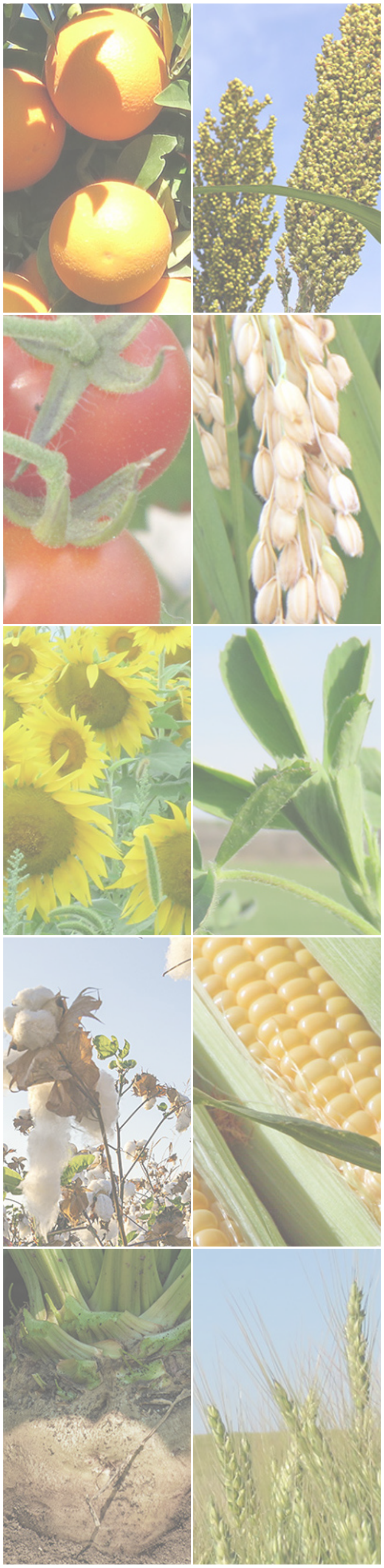



**FIGURE 3.3** Average decrease in crop damage measures by crop for any insecticide treatment including a pyrethroid insecticide relative to the untreated control





for pyrethroid and non-pyrethroid insecticide treatments at about a 1% average improvement. For sunflower, the crop with the most observations, results show an increase of about 4% for treatments using pyrethroid insecticides and well more than a 1% average reduction in crop health for those treatments using non-pyrethroid insecticides. For the few crops with data, these results show that pyrethroid insecticides are also effective at improving crop health, generally outperforming non-pyrethroid insecticides.

## 3.5 Conclusion

The results summarized here demonstrate the empirical foundation for the long-standing and widespread commercial use of pyrethroid insecticides in these and other crops. Across these crops, pyrethroid insecticides substantially increase yields, reduce pest abundance/crop damage and improve crop health. These results also show that these benefits provided by pyrethroid insecticides are comparable to those provided by other commercially available insecticide classes, with the magnitude of the benefits tending to follow the same trends across crops. However, notable examples exist in which benefits for the Any Pyrethroid category were larger than for

**TABLE 3.4** Average decrease in pest abundance by crop for treatments using only pyrethroid insecticides, a mixture of pyrethroid and non- pyrethroid insecticides, any pyrethroid insecticide and non-pyrethroid insecticides, relative to untreated control for treatment

| | | Pyrethroid Only | | Pyrethroid and Non-Pyrethroid Mixed | | Any Pyrethroid | | Non-Pyrethroid Only | |
|---|---|---|---|---|---|---|---|---|---|
| **Crop** | **Target Pest** | **Ave.** | **Obs.** | **Ave.** | **Obs.** | **Ave.** | **Obs.** | **Ave.** | **Obs.** |
| Alfalfa | All Species | 75.2% | 473 | 81.5% | 45 | 75.8% | 518 | 61.8% | 330 |
| Citrus* | All Species | 74.7% | 14 | 93.2% | 2 | 77.0% | 16 | 55.7% | 28 |
| Cotton | Lepidopteran | 69.5% | 78 | 67.6% | 29 | 69.0% | 107 | 54.9% | 74 |
| Cotton | Plant Bugs | 52.7% | 21 | 44.9% | 37 | 47.7% | 58 | 53.1% | 56 |
| Cotton | All Other Species | 52.3% | 17 | 63.1% | 5 | 54.8% | 22 | 65.4% | 70 |
| Potato | Colorado Potato Beetle | 54.7% | 38 | 42.6% | 72 | 46.8% | 110 | 55.0% | 350 |
| Potato | Potato Leaf Hopper | 60.2% | 38 | 49.5% | 87 | 52.7% | 125 | 17.3% | 239 |
| Potato | Aphids | 35.5% | 19 | 31.8% | 26 | 33.3% | 45 | 22.0% | 113 |
| Rice | All Species | 64.9% | 11 | | | 64.9% | 11 | 46.1% | 1 |
| Sorghum | All Species | 65.9% | 19 | 77.7% | 8 | 69.4% | 27 | 66.5% | 25 |
| Sugar Beet | All Species | 55.3% | 6 | 94.1% | 6 | 74.7% | 12 | 36.7% | 16 |
| Sunflower | All Species | 51.8% | 12 | | | 51.8% | 12 | -9.54% | 2 |
| Sweet Corn | All Species | 81.3% | 185 | 67.8% | 8 | 80.8% | 193 | 68.3% | 89 |
| Tomato | All Species | 61.2% | 2 | 59.8% | 7 | 60.1% | 9 | 54.2% | 83 |
| Wheat | All Species | 59.9% | 143 | 52.2% | 19 | 59.0% | 162 | 60.9% | 93 |

*Only includes studies and observations not cited by Qureshi et al. (2014).

**TABLE 3.5** Average duration and magnitude of Asian citrus psyllid reduction for adults and nymphs for different groupings of insecticide modes of action based on Tables 2 and 3 in Qureshi et al. (2014)

| | Asian Citrus Psyllid Adults | | | Asian Citrus Psyllid Nymphs | | | Weighted-Ave. | |
|---|---|---|---|---|---|---|---|---|
| IRAC Mode of Action | # of Studies | Ave. Dur. (days) | Ave. Red. (%) | # of Studies | Ave. Dur. (days) | Ave. Red. (%) | Ave. Dur. (days) | Ave. Red. (%) |
| Any Pyrethroid | 20 | 32.4 | 85.4% | 20 | 23.0 | 80.9% | 27.7 | 83.1% |
| Any Neonic. or Diamide | 34 | 31.9 | 77.8% | 32 | 16.3 | 82.3% | 24.3 | 80.0% |
| Any Other Synthetic | 151 | 29.4 | 68.3% | 152 | 19.1 | 76.5% | 24.2 | 72.4% |
| Unknown/ Non-Specific | 44 | 16.9 | 51.9% | 44 | 10.5 | 49.2% | 13.7 | 50.5% |
| All Synthetic* | 185 | 29.9 | 70.0% | 184 | 18.6 | 77.5% | 24.3 | 73.8% |
| All Non-Pyrethroids** | 229 | 27.4 | 66.6% | 228 | 17.0 | 72.1% | 22.2 | 69.3% |
| All Observations | 249 | 27.8 | 68.1% | 248 | 17.5 | 72.8% | 22.7 | 70.4% |

*Any Neonicotinoid or Diamide and All Other Synthetic combined
**Any Neonicotinoid or Diamide, All Other Synthetic, and Unknown/Non-Specific combined

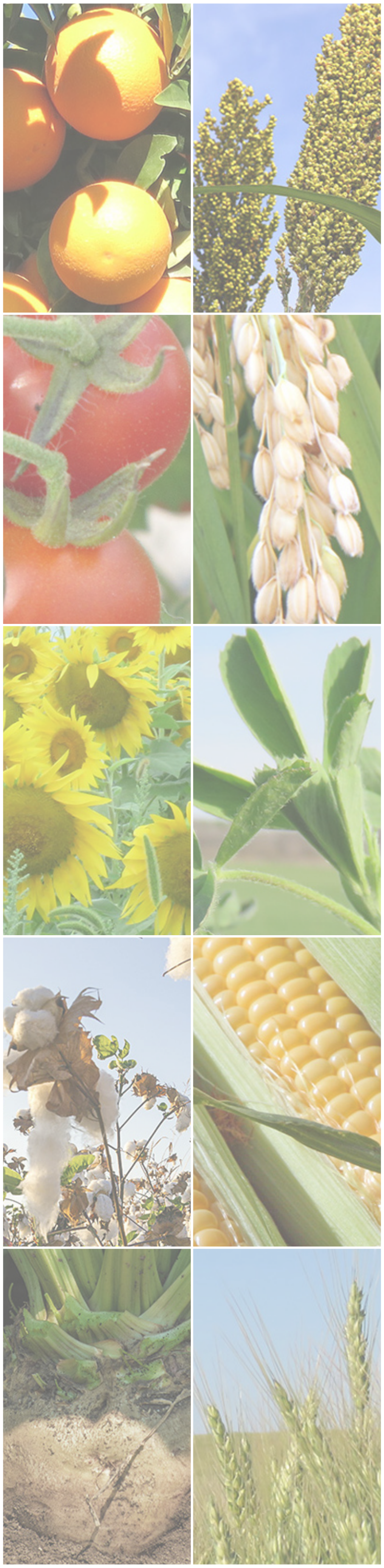
the Non-Pyrethroid category. Most noteworthy is pest abundance, in which the average efficacy of all pyrethroid treatments was generally larger than for non-pyrethroid treatments, except for Colorado potato beetles in potato, cotton pests other than lepidopterans and plant bugs, and all pests in wheat. In cases with at least 25 observations for both categories, other notable examples include yield increases for sweet corn, potato and sunflower and for crop damages in cotton and potato. Furthermore, in many cases, benefits are often larger when insecticide treatments combine pyrethroids and non-pyrethroids, indicating the benefits from mixing or sequencing pyrethroids with other modes of action, not only by increasing yield and efficacy in the short-term, but also in the long-term by improving resistance management.

## 3.6 References

Childers, C.C., and M.E. Rogers. 2005. *Chemical control and management approaches of the Asian citrus psyllid, Diaphorina citri Kuwayama (Homoptera: Psyllidae) in Florida citrus.* Proceedings of Florida State Horticultural Society 110:49-53.

Colwell, C.K., G.M. Lorenz III, Hardke, J.T., J. Greene, C. Capps, A. Chapell, G. Studebaker, and R. Edmund. 2005. *Efficacy of Selected Insecticides for Plant Bug Control in Arkansas, 2005.* Arkansas Agricultural Experiment Station Research Series 543, pp. 184-186. Online: http://arkansasagnews.uark.edu/543-33.pdf.

Groves, R., S. Chapman, L. Crumbaugh and E. Duerr. 2015. *Registered and experimental foliar insecticides to control Colorado potato beetle and potato leafhopper on potato (HAES).* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2015, Department of Entomology, University of Wisconsin, Madison, WI,



pp. 11-20. Online: http://labs.russell.wisc.edu/vegento/files/2016/01/2015_-Field-Research-Booklet.pdf.

Hanafi, A., E.B. Radcliffe, and D.W. Ragsdale. 1989. *Spread and control of potato leafroll virus in Minnesota*. Journal of Economic Entomology 82:1201-1206.

Hardke, J.T., G.M. Lorenz III, C.K. Colwell, and C. Shelton. 2005. *Efficacy of Selected Insecticides for Control of Heliothines in Conventional Non-Bt Cotton — 2004-2005*. Arkansas Agricultural Experiment Station Research Series 543, pp. 192-201. Online: http://arkansasagnews.uark.edu/543-35.pdf.

Insecticide Resistance Action Committee (IRAC). 2016. *IRAC Mode of Action Classification Scheme.* Brussels: CropLife International. Online: http://www.irac-online.org/documents/moa-classification/.

**TABLE 3.6** Average decrease in crop damage by crop for treatments using only pyrethroid insecticides, a mixture of pyrethroid and non- pyrethroid insecticides, any pyrethroid insecticide, and non-pyrethroid insecticides, relative to untreated control for treatment

| | Pyrethroid Only | | Pyrethroid and Non-Pyrethroid Mixed | | Any Pyrethroid | | Non-Pyrethroid Only | |
|---|---|---|---|---|---|---|---|---|
| **Crop** | **Ave.** | **Obs.** | **Ave.** | **Obs.** | **Ave.** | **Obs.** | **Ave.** | **Obs.** |
| Alfalfa | 80.0% | 5 | | | 80.0% | 5 | 85.9% | 4 |
| Cotton* | 61.7% | 65 | 70.1% | 25 | 64.1% | 90 | 55.9% | 60 |
| Potato | 71.7% | 37 | 87.1% | 79 | 82.2% | 116 | 72.7% | 235 |
| Rice | 33.0% | 4 | | | 33.0% | 4 | 75.0% | 2 |
| Sugar Beet | 16.8% | 4 | 71.2% | 61 | 67.8% | 65 | 39.7% | 9 |
| Sunflower | 36.5% | 32 | 3.82% | 4 | 32.8% | 36 | 14.6% | 14 |
| Sweet Corn | 59.1% | 4 | | | 59.1% | 4 | 77.3% | 1 |
| Tomato | 62.6% | 2 | 63.8% | 5 | 63.4% | 7 | 43.8% | 51 |
| Wheat | 29.7% | 32 | 22.1% | 4 | 28.9% | 36 | 35.6% | 18 |

*Lepidopteran pests only.

**TABLE 3.7** Average increase in crop health by crop for treatments using only pyrethroid insecticides, a mixture of pyrethroid and non- pyrethroid insecticides, any pyrethroid insecticide and non-pyrethroid insecticides, relative to untreated control for treatment

| | Pyrethroid Only | | Pyrethroid and Non-Pyrethroid Mixed | | Any Pyrethroid | | Non-Pyrethroid Only | |
|---|---|---|---|---|---|---|---|---|
| **Crop** | **Ave.** | **Obs.** | **Ave.** | **Obs.** | **Ave.** | **Obs.** | **Ave.** | **Obs.** |
| Sorghum | 33.3% | 4 | 35.0% | 1 | 33.6% | 5 | 27.5% | 14 |
| Sugar Beet | 2.25% | 5 | 0.36% | 8 | 1.09% | 13 | 0.99% | 7 |
| Sunflower | 4.40% | 27 | 2.78% | 4 | 4.19% | 31 | -1.43% | 14 |

Jarvi, K., T. Hunt, and R. Wright. 2006. *Seed treatments and alternatives for insect control in corn, soybeans, and sorghum.* Seed Quest, from University of Nebraska, Crop Watch, March 10, 2006. Online: https://www.seedquest.com/News/releases/2006/march/15168.htm.

Knodel, J.J., M. Ganehiarachchi, P.B. Beauzay and L.D. Charlet. 2010. *Bionomics and Integrated Control of the Sunflower Seed Maggot, (Neotephritis finalis) and the Sunflower Bud Moth (Suleima helianthana) in the Northern Plains Sunflower Production Region: 2009 Results*. National Sunflower Association Proceedings. Online http://www.sunflowernsa.com/uploads/research/380/Knodel_Bionomics_10.pdf.

Knodel, J.J., P.B. Beauzay, A. Chirumamilla, L.D. Charlet and T.A. Gross. 2011. *Pest management update on sunflower midge.* National Sunflower Association Proceedings. Online: http://www.sunflowernsa.com/uploads/research/588/knodel_midge_11.pdf.

McCornack, B.P., and D.W. Ragsdale. 2006. *Efficacy of thiamethoxam to suppress soybean aphid populations in Minnesota soybean.* Crop Management doi:10.1094/CM-2006-0915-01-RS.

Musser, F.R., and A.M. Shelton. 2003. *Bt Sweet Corn and Selective Insecticides: Impacts on Pests and Predators.* Journal of Economic Entomology 96:71-80.

Qureshi, J.A., B.C. Kostyk, and P.A. Stansly. 2014. *Insecticidal suppression of Asian citrus psyllid Diaphorina citri (Hemiptera: Liviidae) vector of huanglongbing pathogens*. PLoS ONE 9(12): e112331. doi:10.1371/journal.pone.0112331.

Stougaard, R., and B. Bohannon. 2013. *Orange Wheat Blossom Midge (OWBM) Response to Spring Wheat Varieties and Insecticides — 2013.* Montana State University Northwestern Agricultural Research Station, Kalispell, MT. Online: http://agresearch.montana.edu/nwarc/producerinfo/cereals/springwheat/springwheat-pdf/insect-management/owbm-resp-to-sw-and-insec-2013.pdf.

Stougaard, R., and B. Bohannon. 2012. *Orange Wheat Blossom Midge (OWBM) Response to Spring Wheat Varieties and Insecticides — 2012*. Montana State University Northwestern Agricultural Research Station, Kalispell, MT. Online: http://agresearch.montana.edu/nwarc/producerinfo/cereals/springwheat/springwheat-pdf/insect-management/owbm-resp-to-sw-and-insec-2012.pdf.

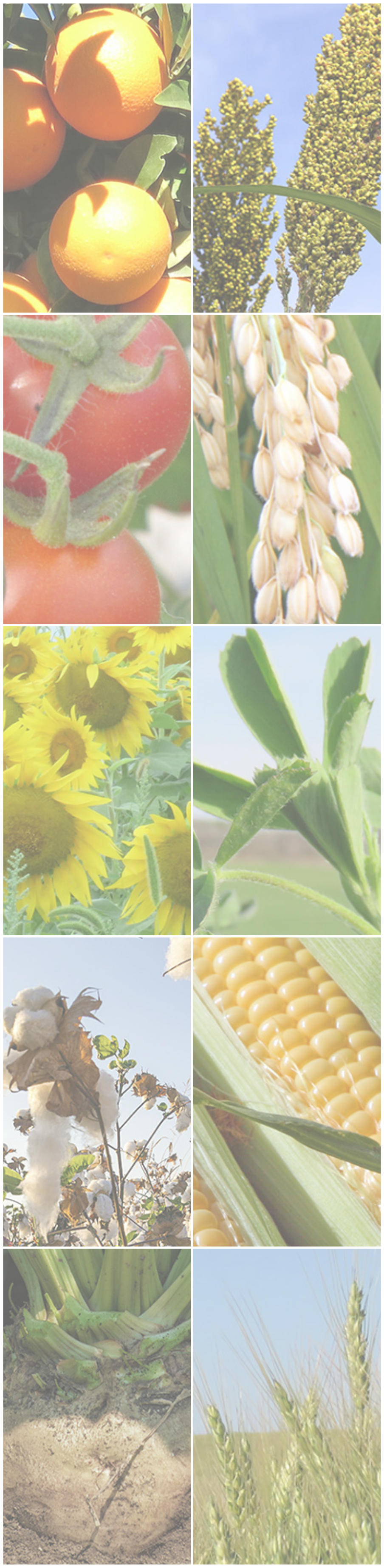
Strausbaugh, C.A., E.J. Wenninger and I.A. Eujayl. 2012. *Management of severe curly top in sugar beet with insecticides*. Plant Disease 96:1159-1164.

Strausbaugh, C.A., E.J. Wenninger and I.A. Eujayl. 2014. *Control of curly top in sugar beet with seed and foliar insecticides*. Plant Disease 98:1075-1080.

U.S. Department of Agriculture — National Agricultural Statistics Service (USDA-NASS). 2016a. *Crop Production: 2015 Summary*. Washington, DC: USDA-NASS. Online: http://www.usda.gov/nass/PUBS/TODAYRPT/cropan16.pdf.

U.S. Department of Agriculture — National Agricultural Statistics Service (USDA-NASS). 2016b. *Crop Values: 2015 Summary*. Washington, DC: USDA-NASS. Online: http://www.usda.gov/nass/PUBS/TODAYRPT/cpvl0216.pdf.

Walsh, K.D., and D.R. Johnson. 2002. *Rice Stink Bug Control with Selected Insecticides.* Arkansas Agricultural Experiment Station Research Series 504: B.R. Wells Rice Research Series 2002, pp. 207-210. Online: http://arkansasagnews.uark.edu/504-27.pdf.



## 3.7 Appendix A: Additional results for meta-analysis

Appendix A presents 11 tables that contain additional results for each crop for this meta-analysis. The main text focused primarily on the sample average for each measure and to some extent the number of observations, reporting both values in Tables 3.3, 3.4, 3.6, and 3.7. The tables in this appendix repeat these results and in addition, report other sample statistics, including the standard deviation, minimum and maximum. Depending on the available data, observations are separated into the same four types of measures as used in the main text: the percentage yield increase, pest abundance decrease, damage decrease and crop health increase relative to the untreated control. For each of these measures, depending on the available data, the observations are further separated into the same four categories as used in the main text: Pyrethroid Only, Pyrethroid Mixture for a pre-mix, tank mix or sequence of pyrethroid and non-pyrethroid insecticides, Any Pyrethroid for the combination of the first two and Non-Pyrethroid Only.

**TABLE A.1** Alfalfa sample statistics for the percentage yield increase, pest abundance decrease and crop damage decrease

| Measure | Average | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| **Yield: % Increase** | | | | | |
| Pyrethroid Only | 105% | 231% | -14.4% | 707% | 27 |
| Pyrethroid Mixture | -- | -- | -- | -- | -- |
| Any Pyrethroid | 105% | 231% | -14.4% | 707% | 27 |
| Non-Pyrethroid | 125% | 206% | -18.0% | 479% | 14 |
| **Pest Abundance: % Decrease** | | | | | |
| Pyrethroid Only | 75.2% | 22.6% | -5.28% | 100% | 473 |
| Pyrethroid Mixture | 81.5% | 15.9% | 40.9% | 100% | 45 |
| Any Pyrethroid | 75.8% | 22.1% | -5.28% | 100% | 518 |
| Non-Pyrethroid | 61.8% | 31.5% | -61.9% | 100% | 330 |
| **Crop Damage: % Decrease** | | | | | |
| Pyrethroid Only | 80.0% | 10.5% | 71.4% | 98.2% | 5 |
| Pyrethroid Mixture | -- | -- | -- | -- | -- |
| Any Pyrethroid | 80.0% | 10.5% | 71.4% | 98.2% | 5 |
| Non-Pyrethroid | 85.9% | 6.0% | 77.9% | 92.5% | 4 |

**TABLEA.2** Citrus sample statistics for the percentage of pest abundance decrease*

| Measure | Average | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| **Pest Abundance: % Decrease** | | | | | |
| Pyrethroid Only | 74.7% | 22.4% | 16.2% | 98.4% | 14 |
| Pyrethroid Mixture | 93.2% | 5.24% | 89.5% | 96.9% | 2 |
| Any Pyrethroid | 77.0% | 21.0% | 16.2% | 98.4% | 16 |
| Non-Pyrethroid | 55.7% | 32.0% | -8.31% | 99.9% | 28 |

*Only includes observations from studies not cited by Qureshi et al. (2014).

**TABLE A.3** Cotton sample statistics for the percentage yield increase, pest abundance decrease for lepidopteran pests, plant bugs and other cotton pests, and crop damage decrease from lepidopteran pests

| Measure | Average | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| **Yield: % Increase** | | | | | |
| Pyrethroid Only | 50.5% | 49.8% | -1.29% | 195% | 97 |
| Pyrethroid Mixture | 71.1% | 54.7% | 10.9% | 225% | 26 |
| Any Pyrethroid | 54.9% | 50.8% | -1.29% | 225% | 123 |
| Non-Pyrethroid | 75.0% | 57.7% | 8.45% | 227% | 63 |
| **Pest Abundance: % Decrease in Lepidopteran Pests** | | | | | |
| Pyrethroid Only | 69.5% | 21.2% | 0.00% | 100% | 78 |
| Pyrethroid Mixture | 67.6% | 25.0% | 11.9% | 100% | 29 |
| Any Pyrethroid | 69.0% | 22.3% | 0.00% | 100% | 107 |
| Non-Pyrethroid | 54.9% | 27.7% | -16.7% | 100% | 74 |
| **Crop Damage: % Decrease in Lepidopteran Damage** | | | | | |
| Pyrethroid Only | 61.7% | 13.5% | 32.7% | 87.4% | 65 |
| Pyrethroid Mixture | 70.1% | 15.3% | 25.9% | 89.8% | 25 |
| Any Pyrethroid | 64.1% | 14.0% | 25.9% | 89.8% | 90 |
| Non-Pyrethroid | 55.9% | 20.3% | 23.3% | 92.0% | 60 |
| **Pest Abundance: % Decrease in Plant Bugs** | | | | | |
| Pyrethroid Only | 52.7% | 51.7% | -142% | 94.0% | 21 |
| Pyrethroid Mixture | 44.9% | 62.2% | -200% | 100% | 37 |
| Any Pyrethroid | 47.7% | 58.6% | -200% | 100% | 58 |
| Non-Pyrethroid | 53.1% | 23.3% | -1.09% | 89.6% | 56 |
| **Pest Abundance: % Decrease in Other Insect Pests** | | | | | |
| Pyrethroid Only | 52.3% | 22.7% | 14.7% | 84.9% | 17 |
| Pyrethroid Mixture | 63.1% | 26.6% | 40.7% | 93.4% | 5 |
| Any Pyrethroid | 54.8% | 23.7% | 14.7% | 93.4% | 22 |
| Non-Pyrethroid | 65.4% | 25.3% | 7.30% | 101% | 70 |

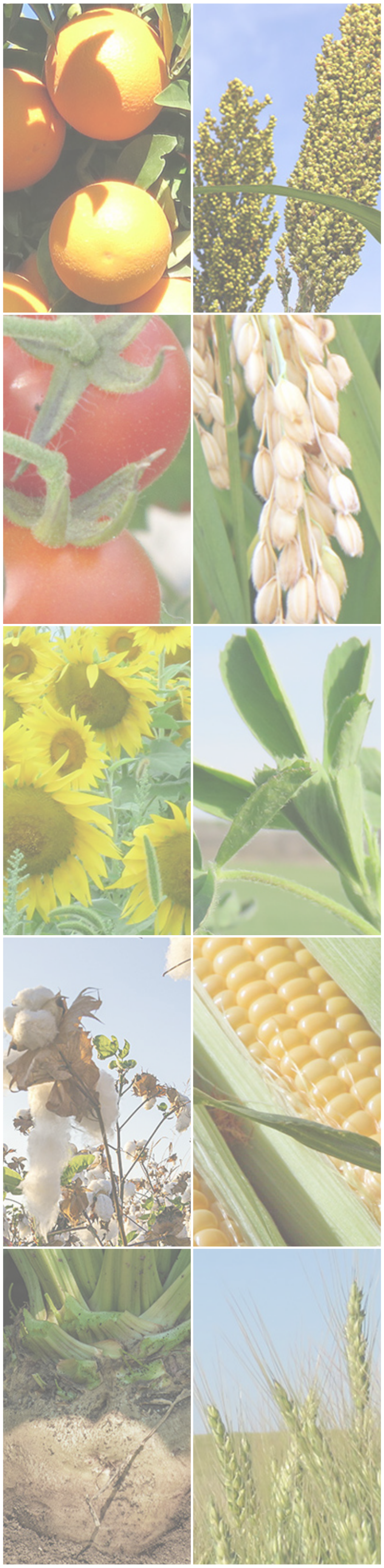


**TABLE A.4** Potato sample statistics for the percentage yield increase, pest abundance decrease for Colorado potato beetle, potato leaf hopper, and aphids and crop damage decrease

| Measure | Average | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| **Yield: % Increase** | | | | | |
| Pyrethroid Only | 85.7% | 54.3% | 26.9% | 161% | 11 |
| Pyrethroid Mixture | 67.2% | 36.8% | 26.7% | 107% | 5 |
| Any Pyrethroid | 79.9% | 49.5% | 26.7% | 161% | 16 |
| Non-Pyrethroid | 62.3% | 63.2% | -35.5% | 235% | 74 |
| **Pest Abundance: % Decrease in Colorado Potato Beetle** | | | | | |
| Pyrethroid Only | 54.7% | 31.8% | -8.14% | 97.4% | 38 |
| Pyrethroid Mixture | 42.6% | 44.2% | -91.5% | 97.2% | 72 |
| Any Pyrethroid | 46.8% | 40.3% | -91.5% | 97.4% | 110 |
| Non-Pyrethroid | 55.0% | 38.3% | -83.1% | 100% | 350 |
| **Pest Abundance: % Decrease in Potato Leaf Hopper** | | | | | |
| Pyrethroid Only | 60.2% | 50.3% | -98.8% | 100% | 38 |
| Pyrethroid Mixture | 49.5% | 53.1% | -86.5% | 100% | 87 |
| Any Pyrethroid | 52.7% | 52.3% | -98.8% | 100% | 125 |
| Non-Pyrethroid | 17.3% | 74.5% | -250% | 100% | 239 |
| **Pest Abundance: % Decrease in Aphids** | | | | | |
| Pyrethroid Only | 35.5% | 67.6% | -123% | 96.6% | 19 |
| Pyrethroid Mixture | 31.8% | 66.7% | -223% | 98.1% | 26 |
| Any Pyrethroid | 33.3% | 67.1% | -223% | 98.1% | 45 |
| Non-Pyrethroid | 22.0% | 71.2% | -200% | 100% | 113 |
| **Crop Damage: % Decrease** | | | | | |
| Pyrethroid Only | 71.7% | 24.8% | 12.5% | 98.3% | 37 |
| Pyrethroid Mixture | 87.1% | 15.6% | 33.3% | 100% | 79 |
| Any Pyrethroid | 82.2% | 19.0% | 12.5% | 100% | 116 |
| Non-Pyrethroid | 72.7% | 22.8% | -1.68% | 100% | 235 |

**TABLE A.5** Rice sample statistics for the percentage yield increase, pest abundance decrease and crop damage decrease

| Measure | Average | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| **Yield: % Increase** | | | | | |
| Pyrethroid Only | 5.05% | 2.64% | 1.44% | 7.52% | 4 |
| Pyrethroid Mixture | -- | -- | -- | -- | -- |
| Any Pyrethroid | 5.05% | 2.64% | 1.44% | 7.52% | 4 |
| Non-Pyrethroid | -2.03% | 6.02% | -6.29% | 2.22% | 2 |
| **Pest Abundance: % Decrease** | | | | | |
| Pyrethroid Only | 64.9% | 40.7% | -21.1% | 97.1% | 11 |
| Pyrethroid Mixture | -- | -- | -- | -- | -- |
| Any Pyrethroid | 64.9% | 40.7% | -21.1% | 97.1% | 11 |
| Non-Pyrethroid | 46.1% | --- | 46.1% | 46.1% | 1 |
| **Crop Damage: % Decrease** | | | | | |
| Pyrethroid Only | 33.0% | 23.4% | 0.00% | 53.1% | 4 |
| Pyrethroid Mixture | -- | -- | -- | -- | -- |
| Any Pyrethroid | 33.0% | 23.4% | 0.00% | 53.1% | 4 |
| Non-Pyrethroid | 75.0% | 35.4% | 50.0% | 100% | 2 |

**TABLE A.6** Sorghum sample statistics for the percentage yield increase, pest abundance decrease and crop health increase

| Measure | Average | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| **Yield: % Increase** | | | | | |
| Pyrethroid Only | 20.5% | 45.0% | -3.32% | 101% | 5 |
| Pyrethroid Mixture | 1.64% | 2.08% | 0.29% | 4.03% | 3 |
| Any Pyrethroid | 13.4% | 35.6% | -3.32% | 101% | 8 |
| Non-Pyrethroid | 32.7% | 33.4% | -3.58% | 77.4% | 8 |
| **Pest Abundance: % Decrease** | | | | | |
| Pyrethroid Only | 65.9% | 22.2% | 11.1% | 93.6% | 19 |
| Pyrethroid Mixture | 77.7% | 26.1% | 16.0% | 97.9% | 8 |
| Any Pyrethroid | 69.4% | 23.4% | 11.1% | 97.9% | 27 |
| Non-Pyrethroid | 66.5% | 24.5% | 20.9% | 100% | 25 |
| **Crop Health: % Increase** | | | | | |
| Pyrethroid Only | 33.3% | 11.2% | 23.3% | 45.6% | 4 |
| Pyrethroid Mixture | 35.0% | -- | 35.0% | 35.0% | 1 |
| Any Pyrethroid | 33.6% | 10.0% | 23.3% | 45.6% | 5 |
| Non-Pyrethroid | 27.5% | 8.17% | 9.71% | 40.8% | 14 |

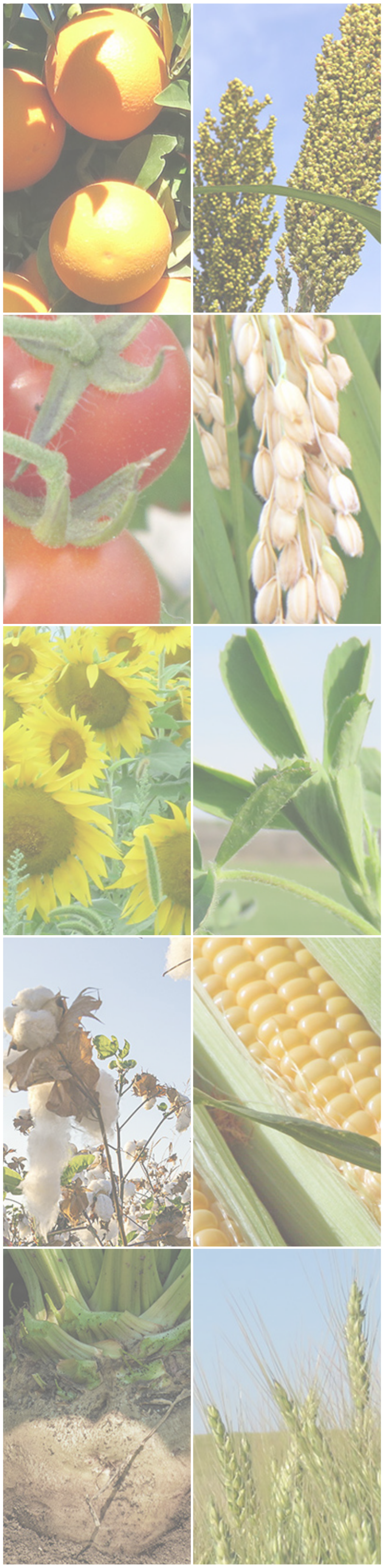


**TABLE A.7** Sugar beet sample statistics for the percentage yield increase, pest abundance decrease, crop damage decrease and crop health increase

| Measure | Average | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| **Yield: % Increase** | | | | | |
| Pyrethroid Only | 4.82% | 8.90% | -14.2% | 18.3% | 9 |
| Pyrethroid Mixture | 43.0% | 111% | 0.35% | 479% | 40 |
| Any Pyrethroid | 35.9% | 99.9% | -14.2% | 479% | 49 |
| Non-Pyrethroid | 309% | 173% | 5.90% | 493% | 7 |
| **Pest Abundance: % Decrease** | | | | | |
| Pyrethroid Only | 55.3% | 17.5% | 32.2% | 74.7% | 6 |
| Pyrethroid Mixture | 94.1% | 8.73% | 79.7% | 100% | 6 |
| Any Pyrethroid | 74.7% | 13.8% | 32.2% | 100% | 12 |
| Non-Pyrethroid | 36.7% | 73.1% | -163% | 100% | 16 |
| **Crop Damage: % Decrease** | | | | | |
| Pyrethroid Only | 16.8% | 14.9% | 2.86% | 37.9% | 4 |
| Pyrethroid Mixture | 71.2% | 28.4% | 8.11% | 100% | 61 |
| Any Pyrethroid | 67.8% | 27.8% | 2.86% | 100% | 65 |
| Non-Pyrethroid | 39.7% | 9.89% | 25.8% | 57.6% | 9 |
| **Crop Health: % Increase** | | | | | |
| Pyrethroid Only | 2.25% | 16.6% | -11.1% | 30.8% | 5 |
| Pyrethroid Mixture | 0.36% | 4.07% | -4.59% | 8.99% | 8 |
| Any Pyrethroid | 1.09% | 10.8% | -11.1% | 30.8% | 13 |
| Non-Pyrethroid | 0.99% | 7.82% | -16.3% | 7.14% | 7 |

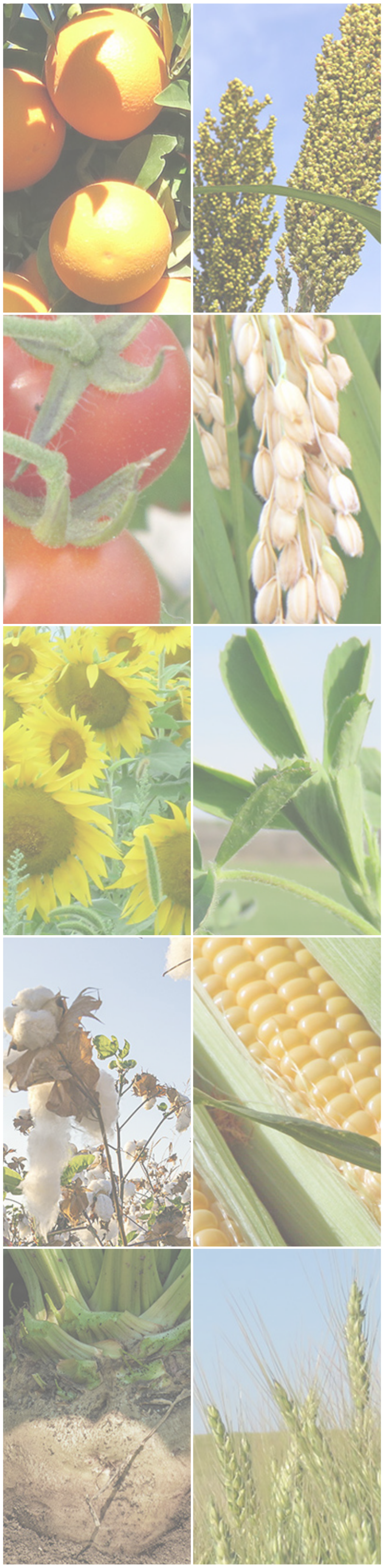
**TABLE A.8**: Sunflower sample statistics for the percentage yield increase, pest abundance decrease, crop damage decrease and crop health increase

| Measure | Average | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| **Yield: % Increase** | | | | | |
| Pyrethroid Only | 7.90% | 14.7% | -13.1% | 47.9% | 35 |
| Pyrethroid Mixture | 27.0% | 37.6% | -9.51% | 106% | 11 |
| Any Pyrethroid | 12.5% | 22.4% | -13.1% | 106% | 46 |
| Non-Pyrethroid | 1.38% | 13.0% | -22.7% | 38.5% | 27 |
| **Pest Abundance: % Decrease** | | | | | |
| Pyrethroid Only | 51.8% | 34.2% | 2.94% | 95.7% | 12 |
| Pyrethroid Mixture | -- | -- | -- | -- | -- |
| Any Pyrethroid | 51.8% | 34.2% | 2.94% | 95.7% | 12 |
| Non-Pyrethroid | -9.54% | 3.15% | -11.8% | -7.31% | 2 |

| | | | | | |
|---|---|---|---|---|---|
| **Crop Damage: % Decrease** | | | | | |
| Pyrethroid Only | 36.5% | 26.0% | -15.2% | 72.1% | 32 |
| Pyrethroid Mixture | 3.82% | 5.48% | -2.19% | 11.1% | 4 |
| Any Pyrethroid | 32.8% | 24.5% | -15.2% | 72.1% | 36 |
| Non-Pyrethroid | 14.6% | 26.6% | -33.3% | 59.8% | 14 |
| **Crop Health: % Increase** | | | | | |
| Pyrethroid Only | 4.40% | 8.75% | -3.68% | 37.0% | 27 |
| Pyrethroid Mixture | 2.78% | 1.78% | 1.31% | 4.90% | 4 |
| Any Pyrethroid | 4.19% | 8.19% | -3.68% | 37.0% | 31 |
| Non-Pyrethroid | -1.43% | 4.00% | -7.37% | 4.74% | 14 |

**TABLE A.9** Sweet Corn sample statistics for the percentage yield increase, the additive percentage point increase in yield, and the percentage pest abundance decrease and crop damage decrease

| Measure | Average | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| **Yield: % Increase** | | | | | |
| Pyrethroid Only | 217% | 261% | -90.0% | 1050% | 115 |
| Pyrethroid Mixture | 632% | 12% | 618% | 642% | 4 |
| Any Pyrethroid | 231% | 257% | -90.0% | 1050% | 119 |
| Non-Pyrethroid | 126% | 196% | -66.7% | 800% | 71 |
| **Yield: % Increase (Additive)** | | | | | |
| Pyrethroid Only | 41.8% | 26.5% | -27.0% | 94.0% | 185 |
| Pyrethroid Mixture | 78.4% | 1.45% | 76.6% | 79.7% | 8 |



| | | | | | |
|---|---|---|---|---|---|
| Any Pyrethroid | 43.3% | 25.9% | -27.0% | 94.0% | 193 |
| Non-Pyrethroid | 27.3% | 21.0% | -20.0% | 86.3% | 89 |
| **Pest Abundance: % Decrease** | | | | | |
| Pyrethroid Only | 81.3% | 17.6% | 16.3% | 100% | 185 |
| Pyrethroid Mixture | 67.8% | 31.2% | 29.1% | 98.3% | 8 |
| Any Pyrethroid | 80.8% | 18.4% | 16.3% | 100% | 193 |
| Non-Pyrethroid | 68.3% | 25.9% | -19.5% | 100% | 89 |
| **Crop Damage: % Decrease** | | | | | |
| Pyrethroid Only | 59.1% | 19.3% | 31.8% | 72.7% | 4 |
| Pyrethroid Mixture | -- | -- | -- | -- | -- |
| Any Pyrethroid | 59.1% | 19.3% | 31.8% | 72.7% | 4 |
| Non-Pyrethroid | 77.3% | -- | 77.3% | 77.3% | 1 |

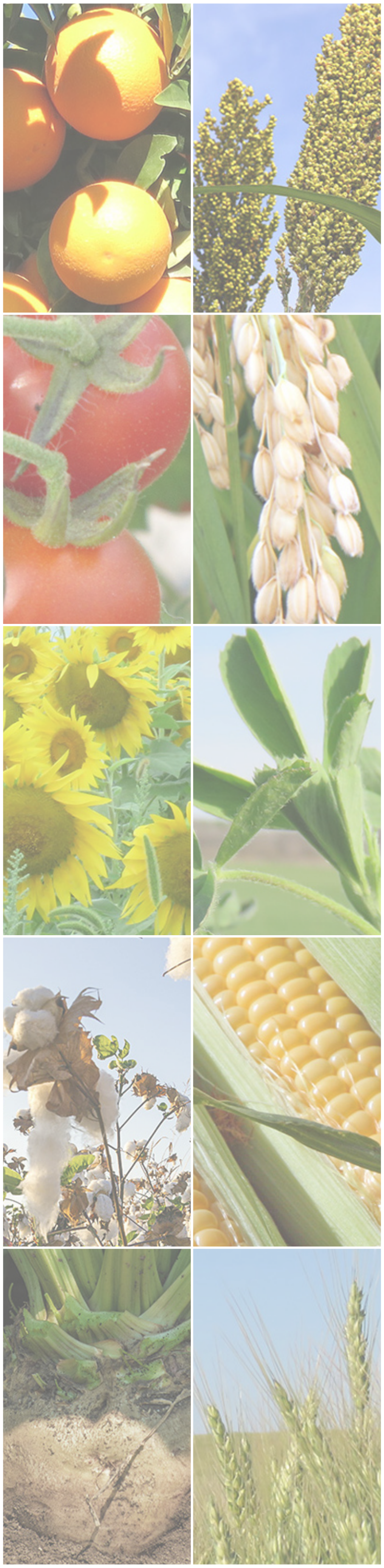
**TABLE A.10** Tomato sample statistics for the percentage decrease in pest abundance and crop damage

| Measure | Average | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| **Pest Abundance: % Decrease** | | | | | |
| Pyrethroid Only | 61.2% | 8.54% | 55.1% | 67.2% | 2 |
| Pyrethroid Mixture | 59.8% | 55.7% | -59.5% | 100% | 7 |
| Any Pyrethroid | 60.1% | 49.3% | -59.5% | 100% | 9 |
| Non-Pyrethroid | 54.2% | 42.9% | -94.4% | 100% | 83 |
| **Crop Damage: % Decrease** | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Pyrethroid Only | 62.6% | 6.00% | 58.4% | 66.8% | 2 |
| Pyrethroid Mixture | 63.8% | 16.9% | 47.3% | 86.6% | 5 |
| Any Pyrethroid | 63.4% | 14.7% | 47.3% | 86.6% | 7 |
| Non-Pyrethroid | 43.8% | 25.7% | -8.58% | 94.5% | 51 |

**TABLE A.11** Wheat sample statistics for the percentage yield increase, pest abundance decrease and crop damage decrease

| Measure | Average | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| **Yield: % Increase** | | | | | |
| Pyrethroid Only | 6.86% | 15.8% | -28.3% | 67.0% | 51 |
| Pyrethroid Mixture | 25.1% | 20.7% | 1.35% | 48.7% | 7 |
| Any Pyrethroid | 9.06% | 16.4% | -28.3% | 67.0% | 58 |
| Non-Pyrethroid | 12.7% | 21.9% | -14.0% | 100% | 24 |
| **Pest Abundance: % Decrease** | | | | | |
| Pyrethroid Only | 59.9% | 31.7% | -40.0% | 100% | 143 |
| Pyrethroid Mixture | 52.2% | 24.2% | -11.1% | 100% | 19 |
| Any Pyrethroid | 59.0% | 30.9% | -40.0% | 100% | 162 |
| Non-Pyrethroid | 60.9% | 25.4% | -30.2% | 91.3% | 93 |
| **Crop Damage: % Decrease** | | | | | |
| Pyrethroid Only | 29.7% | 39.4% | -110% | 100% | 32 |
| Pyrethroid Mixture | 22.1% | 23.6% | 0.00% | 53.3% | 4 |



| | | | | | |
|---|---|---|---|---|---|
| Any Pyrethroid | 28.9% | 38.0% | -110% | 100% | 36 |
| Non-Pyrethroid | 35.6% | 37.0% | -35.7% | 100% | 18 |

## 3.8 Appendix B: References by crop

This section contains the references by crop for the data used for the meta-analysis, other than those from *Arthropod Management Tests*.

### 3.81 Citrus

Arevalo, H., and P.A. Stansly. 2009. *Control of the Asian citrus psyllid, Diaphorina citri Kuwayama, with ground and aerial application of selected insecticides.* Proceedings of Florida State Horticultural Society 122:186-188.

Childers, C.C., and M.E. Rogers. 2005. *Chemical control and management approaches of the Asian citrus psyllid, Diaphorina citri Kuwayama (Homoptera: Psyllidae) in Florida citrus.* Proceedings of Florida State Horticultural Society 110:49-53.

Qureshi, J.A., B.C. Kostyk, and P.A. Stansly. 2014. I*nsecticidal suppression of Asian citrus psyllid Diaphorina citri (Hemiptera: Liviidae) vector of huanglongbing pathogens*. PLoS ONE 9(12): e112331. doi:10.1371/journal.pone.0112331.

Qureshi, J.A., and P.A. Stansly. 2009. *Insecticidal control of Asian citrus psyllid Diaphorina citri (Hemiptera: Psyllidae)*. Proceedings of Florida State Horticultural Society 122:172-175.

### 3.82 Cotton

Colwell, C.K., G.M. Lorenz III, J. Fortner, N. Tailon, and B. VanKanel. 2010. *Thrips Control Using Selected Insecticides in Arkansas Cotton, 2010*. Arkansas Agricultural Experiment Station Research Series 589, pp. 138-142. Online: http://arkansasagnews.uark.edu/589-24.pdf.

Colwell, C.K., G.M. Lorenz III, J. Fortner, N. Tailon, B. VanKanel and A. Vangilder. 2010. *Control of Spider Mites in Arkansas Cotton.* Arkansas Agricultural Experiment Station Research Series 589, pp. 155-157. Online: http://arkansasagnews.uark.edu/589-27.pdf.

Colwell, C.K., G.M. Lorenz III, Hardke, J.T., J. Greene, C. Capps, A. Chapell, G. Studebaker, and R. Edmund. 2005. *Efficacy of Selected Insecticides for Plant Bug Control in Arkansas, 2005.* Arkansas Agricultural Experiment Station Research Series 543, pp. 184-186. Online: http://arkansasagnews.uark.edu/543-33.pdf.

Greene, J.K, and C. Capps. 2001. *Efficacy of Emerging and Existing Insecticides for Control of Aphids and Whiteflies in Southeast Arkansas Cotton.* Arkansas Agricultural Experiment Station Research Series 497, pp. 189-192. Online: http://arkansasagnews.uark.edu/497-32.pdf.

Hardke, J.T., G.M. Lorenz III, C.K. Colwell, and C. Shelton. 2005. *Efficacy of Selected Insecticides for Control of Heliothines in Conventional Non-Bt Cotton, 2004-2005.* Arkansas Agricultural Experiment Station Research Series 543, pp. 192-201. Online: http://arkansasagnews.uark.edu/543-35.pdf.

### 3.8.3 Potato

Groves, R., S. Chapman and S. Schramm. 2010. *Drip irrigation insecticide treatments to control Colorado potato beetle in Wisconsin potatoes.* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2010, Department of Entomology, University of Wisconsin, Madison, WI, pp. 7-8. Online: http://labs.russell.wisc.edu/vegento/files/2012/05/2010-Groves-Research-Booklet_Final.pdf.

Groves, R., S. Chapman and S. Schramm. 2010. *Registered and experimental foliar insecticides to control Colorado potato beetle and potato leafhopper in potato.* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2010, Department of Entomology, University of Wisconsin, Madison, WI, pp. 9-10. Online: http://labs.russell.wisc.edu/vegento/files/2012/05/2010-Groves-Research-Booklet_Final.pdf.

Groves, R., S. Chapman and S. Schramm. 2010. *Foliar insecticide treatments for the control of potato leafhopper in Wisconsin potato production*. Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2010, Department of Entomology, University of Wisconsin, Madison, WI, pp. 11-12. Online: http://labs.russell.wisc.edu/vegento/files/2012/05/2010-Groves-Research-Booklet_Final.pdf.

Groves, R., S. Chapman and S. Schramm. 2010. *Foliar insecticide treatments to limit the spread of Potato virus Y in Wisconsin seed potato production*. Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2010, Department of Entomology, University of Wisconsin, Madison, WI, pp. 13-14. Online: http://labs.russell.wisc.edu/vegento/files/2012/05/2010-Groves-Research-Booklet_Final.pdf.

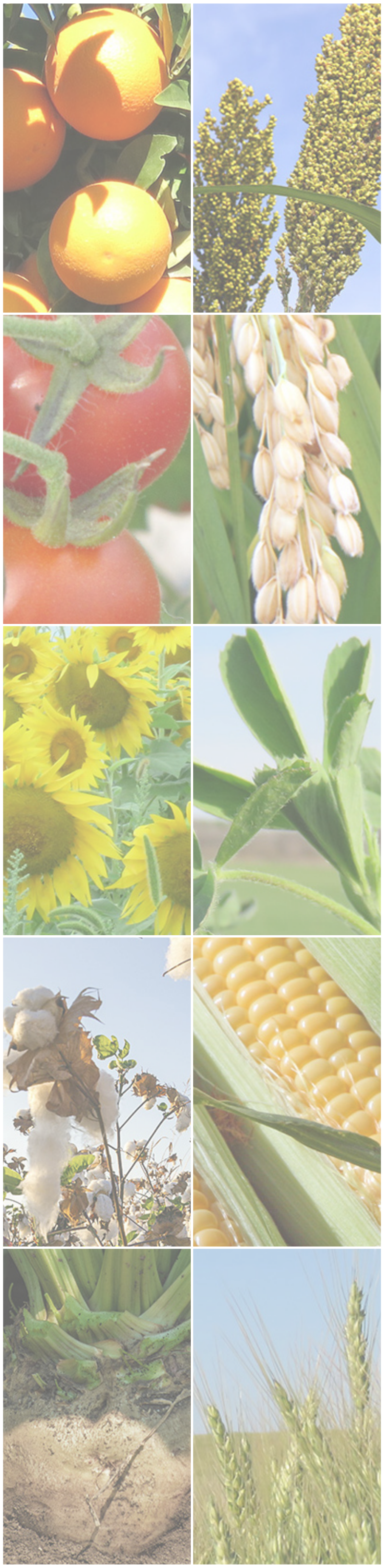
Groves, R., S. Chapman and S. Schramm. 2010. *Muck potato research.* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2010, Department of Entomology, University of Wisconsin, Madison, WI, pp. 15-16. Online: http://labs.russell.wisc.edu/vegento/files/2012/05/2010-Groves-Research-Booklet_Final.pdf.

Groves, R., S. Chapman and S. Schramm. 2010. *Evaluation of systemic insecticides for the control of the Colorado potato beetle, potato leafhopper, and aphids in potato.* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2010, Department of Entomology, University of Wisconsin, Madison, WI, pp. 17-18. Online: http://labs.russell.wisc.edu/vegento/files/2012/05/2010-Groves-Research-Booklet_Final.pdf.

Groves, R., S. Chapman, A. Huseth, D. Lowenstein and C. Groves. 2011. *Registered and experimental foliar insecticides to control Colorado potato beetle and potato leafhopper in potato.* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2011, Department of Entomology, University of Wisconsin, Madison, WI, pp. 8-9. Online: http://labs.russell.wisc.edu/vegento/files/2012/05/2011-Groves-Summer-Field-Research-Booklet.docx.

Groves, R., S. Chapman, A. Huseth, D. Lowenstein and C. Groves. 2011. *Registered and experimental foliar insecticides to control Colorado potato beetle in potato (AAES)*. Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2011, Department of Entomology, University of Wisconsin, Madison, WI, pp. 10-11. Online: http://labs.russell.wisc.edu/vegento/files/2012/05/2011-Groves-Summer-Field-Research-Booklet.docx.

Groves, R., S. Chapman, A. Huseth, D. Lowenstein and C. Groves. 2011. *Foliar insecticide treatments for the control of potato leafhopper in Wisconsin potato production*. Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2011, Department of Entomology, University of Wisconsin, Madison, WI, pp. 12-13. Online: http://labs.russell.wisc.edu/vegento/files/2012/05/2011-Groves-Summer-Field-Research-Booklet.docx.




Groves, R., S. Chapman, K. Frost, A. Huseth and C. Groves. 2012. *Registered and experimental foliar insecticides to control Colorado potato beetle and potato leafhopper in potato (HAES)*. Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2012, Department of Entomology, University of Wisconsin, Madison, WI, pp. 8-10. Online: http://labs.russell.wisc.edu/vegento/files/2013/01/2012-Wisconsin-Vegetable-Insect-Pest-Management-Research-Summer-Field-Trials.pdf.

Groves, R., S. Chapman, K. Frost, A. Huseth and C. Groves. 2012. *Foliar insecticide treatments for the control of potato leafhopper in Wisconsin potato production*. Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2012, Department of Entomology, University of Wisconsin, Madison, WI, pp. 11-12. Online: http://labs.russell.wisc.edu/vegento/files/2013/01/2012-Wisconsin-Vegetable-Insect-Pest-Management-Research-Summer-Field-Trials.pdf.

Groves, R., S. Chapman, K. Frost, A. Huseth and C. Groves. 2012. *Registered and experimental foliar insecticides to control Colorado potato beetle and potato leafhopper in potato (HAES)*. Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2012, Department of Entomology, University of Wisconsin, Madison, WI, pp. 8-10. Online: http://labs.russell.wisc.edu/vegento/files/2013/01/2012-Wisconsin-Vegetable-Insect-Pest-Management-Research-Summer-Field-Trials.pdf.

Groves, R., S. Chapman, K. Frost, A. Huseth and L. Crumbaugh. 2013. *Foliar insecticide treatments for the control of potato leafhopper in Wisconsin potato production.* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2013, Department of Entomology, University of Wisconsin, Madison, WI, pp. 15-16. Online: http://labs.russell.wisc.edu/vegento/files/2012/05/2013-Field-Research-Booklet.pdf.

Groves, R., S. Chapman, K. Frost, A. Huseth and L. Crumbaugh. 2013. *Registered and experimental foliar insecticides to control Colorado potato beetle and potato leafhopper on potato (HAES).* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2013, Department of Entomology, University of Wisconsin, Madison, WI, pp. 12-14. Online: http://labs.russell.wisc.edu/vegento/files/2012/05/2013-Field-Research-Booklet.pdf.

Groves, R., S. Chapman, K. Frost, L. Crumbaugh and E. Duerr. 2014. *Registered and experimental foliar insecticides to control Colorado potato beetle and potato leafhopper on potato (HAES).* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2014, Department of Entomology, University of Wisconsin, Madison, WI, pp. 11-13. Online: http://labs.russell.wisc.edu/vegento/files/2015/04/2014FieldResearchBooklet.pdf.

Groves, R., S. Chapman, K. Frost, L. Crumbaugh and E. Duerr. 2014. *Foliar insecticide treatments for the control of potato leafhopper in Wisconsin potato production.* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2014, Department of Entomology, University of Wisconsin, Madison, WI, pp. 14-15. Online: http://labs.russell.wisc.edu/vegento/files/2015/04/2014FieldResearchBooklet.pdf.

Groves, R., S. Chapman, L. Crumbaugh and E. Duerr. 2015. *Registered and experimental foliar insecticides to control Colorado potato beetle and potato leafhopper on potato (HAES).* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2015, Department of Entomology, University of Wisconsin, Madison, WI, pp. 11-20. Online: http://labs.russell.wisc.edu/vegento/files/2016/01/2015_-Field-Research-Booklet.pdf.

Groves, R., S. Chapman, L. Crumbaugh and E. Duerr. 2015. *Foliar insecticide treatments for the control of potato leafhopper in Wisconsin potato production.* Wisconsin Vegetable Insect Pest Management Research Summer Field Trials 2015, Department of Entomology, University of Wisconsin, Madison, WI, pp. 21-22. Online: http://labs.russell.wisc.edu/vegento/files/2016/01/2015_-Field-Research-Booklet.pdf.

Kuhar, T., and P. Blevins. 2011. *Wireworm control experiment in potatoes in Abingdon, VA in 2011*. Virginia Cooperative Extension, Blacksburg, VA. Online: http://pubs.ext.vt.edu/3110/3110-1596/3110-1596_pdf.pdf.

Lawson, V. 2010. *Potato insecticide evaluations.* Iowa State University Research and Demonstration Farms, Ames, IA. Online: http://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1223&context=farms_reports.

Lawson, V. 2013. *Potato insecticide evaluations. Iowa State University Research and Demonstration Farms*, Ames, IA. Online: http://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=3027&context=farms_reports.

Szendrei, Z., and A.M. Byrne. 2011. *Field evaluations of registered and experimental insecticides for managing Colorado potato beetle on potatoes*. Michigan Vegetable Insecticide Evaluation Studies 2011, Department of Entomology, Michigan State University, East Lansing, MI, pp. 10-11. Online: http://vegetable.ent.msu.edu/images/2011-insecticide-booklet.pdf.

## 3.8.4 Rice

Studebaker, G.E., D.R. Johnson and H. Robertson. 2003. *Rice Water Weevil Control in Drill-Seeded Rice.* Arkansas Agricultural Experiment Station Research Series 517: B.R. Wells Rice Research Series 2003, pp. 189-192. Online: http://arkansasagnews.uark.edu/517-25.pdf.

Walsh, K.D., and D.R. Johnson. 2002a. *Rice Stink Bug Control in Large-Plot Trials.* Arkansas Agricultural Experiment Station Research Series 504: B.R. Wells Rice Research Series 2002, pp. 211-214. Online: http://arkansasagnews.uark.edu/504-28.pdf.

Walsh, K.D., and D.R. Johnson. 2002b. *Rice Stink Bug Control with Selected Insecticides.* Arkansas Agricultural Experiment Station Research Series 504: B.R. Wells Rice Research Series 2002, pp. 207-210. Online: http://arkansasagnews.uark.edu/504-27.pdf.

## 3.8.5 Sorghum

Jarvi, K., T. Hunt, and R. Wright. 2006. *Seed treatments and alternatives for insect control in corn, soybeans, and sorghum.* Seed Quest, from University of Nebraska, Crop Watch, March 10, 2006. Online: https://www.seedquest.com/News/releases/2006/march/15168.htm.

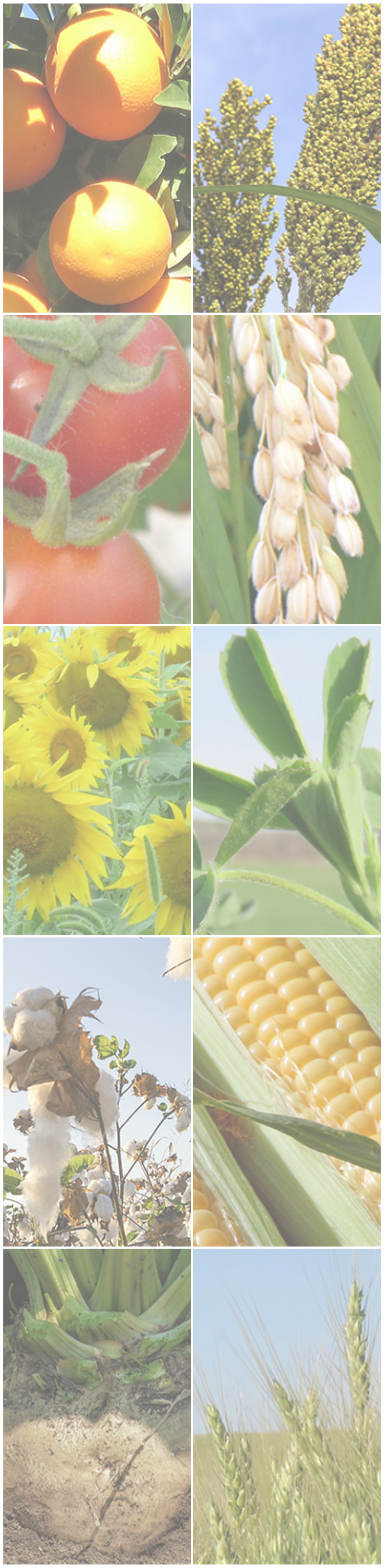
Parker, R.D. and J.R. Stapper. 2011. *Headworm and rice stink bug control on sorghum heads with selected insecticides*. AgriLife Extension, Texas A&M University, College Station, TX. Online: http://nueces.agrilife.org/files/2011/08/Mayo-Farm-using-Declare-etc-FINAL.pdf.

Whitworth, J., and H. Davis. 2014. *Sorghum insect management.* Kansa State University Agronomy Extension, Manhattan, KS. Online: http://www.agronomy.k-state.edu/extension/documents/sorghum-schools/2014-sorghum-school/Whitworth-Davis-Sorghum-2014%20.pdf.

## 3.8.6 Sugar beet

Strausbaugh, C.A., I.A. Eujayl and P. Foote. 2010. *Seed treatments for the control of insects and diseases in sugar beet*. J. Sugar Beet Res. 47:105-125.

Strausbaugh, C.A., E.J. Wenninger and I.A. Eujayl. 2012. *Management of severe curly top in sugar beet with insecticides.* Plant Disease 96:1159-1164.



Strausbaugh, C.A., E.J. Wenninger and I.A. Eujayl. 2014. *Control of curly top in sugar beet with seed and foliar insecticides.* Plant Disease 98:1075-1080.

### 3.8.7 Sunflower

Knodel, J.J., P.B. Beauzay, A. Chirumamilla, L.D. Charlet and T.A. Gross. 2011. *Pest management update on sunflower midge.* National Sunflower Association Proceedings. Online: http://www.sunflowernsa.com/uploads/research/588/knodel_midge_11.pdf.

Knodel, J.J., L.D. Charlet, P.B. Beauzay and T.A. Gross. 2009. *Review of Sunflower insect problems in North Dakota in 2008.* National Sunflower Association Proceedings. Online: http://www.sunflowernsa.com/uploads/research/363/Knodel_PestReview_09.pdf.

Knodel, J.J., M. Ganehiarachchi, P.B. Beauzay and L.D. Charlet. 2010. Bionomics and I*ntegrated Control of the Sunflower Seed Maggot, (Neotephritis finalis) and the Sunflower Bud Moth (Suleima helianthana) in the Northern Plains Sunflower Production Region: 2009 Results.* National Sunflower Association Proceedings. Online http://www.sunflowernsa.com/uploads/research/380/Knodel_Bionomics_10.pdf.

### 3.8.8 Sweet corn

Musser, F.R., and A.M. Shelton. 2003. *Bt Sweet Corn and Selective Insecticides: Impacts on Pests and Predators.* Journal of Economic Entomology 96:71-80.

### 3.8.9 Wheat

Anonymous. 2010. *Orange wheat blossom midge insecticide trials.* Montana State University Northwestern Agricultural Research Station, Kalispell, MT. Online: http://agresearch.montana.edu/nwarc/producerinfo/cereals/springwheat/springwheat-pdf/insect-management/insec-trl-owbm-2010.pdf.

Anonymous. 2014. *Effect of spring wheat resistance and insecticide application timing on the control of Orange Wheat Blossom Midge*. Montana State University Northwestern Agricultural Research Station, Kalispell, MT. Online: http://agresearch.montana.edu/nwarc/producerinfo/cereals/springwheat/springwheat-pdf/insect-management/resistance-timing-2014.pdf.

Anonymous. 2014. *Insecticide application timing for Orange Wheat Blossom Midge control.* Montana State University Northwestern Agricultural Research Station, Kalispell, MT. Online: http://agresearch.montana.edu/nwarc/producerinfo/cereals/springwheat/springwheat-pdf/insect-management/insec-timing-2014.pdf.

Dillon, M.A. 2001. *Evaluating new Syngenta seed treatment fungicide and insecticide products on spring wheat*. Colorado State University, San Luis Valley Research Center, Center, CO Online: http://www.colostate.edu/Depts/SLVRC/CROPWATER/2001reports/2001Syngentaseedtrt.pdf.

Stougaard, R., and B. Bohannon. 2012. *Orange Wheat Blossom Midge (OWBM) Response to Spring Wheat Varieties and Insecticides, 2012*. Montana State University Northwestern Agricultural Research Station, Kalispell, MT. Online: http://agresearch.montana.edu/nwarc/producerinfo/cereals/springwheat/springwheat-pdf/insect-management/owbm-resp-to-sw-and-insec-2012.pdf.

Stougaard, R., and B. Bohannon. 2013. *Orange Wheat Blossom Midge (OWBM) Response to Spring Wheat Varieties and Insecticides, 2013.* Montana State University Northwestern Agricultural Research Station, Kalispell, MT. Online: http://agresearch.montana.edu/nwarc/producerinfo/cereals/springwheat/springwheat-pdf/insect-management/owbm-resp-to-sw-and-insec-2013.pdf.

Stougaard, R., and Q. Xue. 2008. *Evaluation of Soil Insecticides for OWBM Control.* Montana State University Northwestern Agricultural Research Station, Kalispell, MT. Online: http://agresearch.montana.edu/nwarc/producerinfo/cereals/springwheat/springwheat-pdf/insect-management/eval-soil-insec-owbm-cntrl-2008.pdf.

Winslow, M. and A. Herbert. 2011. *Efficacy of spring-applied foliar insecticide treatments for Hessian fly (Mayetiola destructor) control in winter wheat for the Tidewater region of North Carolina.* Alabama Cooperative Extension Service. Online: http://www.aces.edu/agriculture/insects-diseases-weeds-pests/HessianFly/documents/MATTWINSLOWfoliardata.pdf.