

Short Communication

Control Failures Following Insecticide Applications in Commercial Agriculture: How Often Do They Occur? A Case Study of *Lygus hesperus* (Hemiptera: Miridae) Control in Cotton

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Abstract

Although surveys of pest populations documenting evolved insecticide resistance often suggest abundant potential for insecticide control failures, studies documenting the actual occurrence of such failures in commercial agriculture are rare. If farmers currently practice adaptive management, abandoning the use of insecticides once resistance emerges, actual control failures could be rare. Here I use data gathered by independent pest management consultants to describe a case study of the realized efficacy of commercial field applications of insecticides, examining the control of *Lygus hesperus* Knight on cotton. On average, insecticides reduced target pest populations to 19% of their preapplication densities. Short-term efficacy of insecticides was variable, but only one severe control failure was observed (1 of 50, 2%). The rarity of severe control failures observed in this study is in agreement with the few other studies conducted in commercial settings, but additional research is needed to assess the generality of this result. Although pesticides can cause longer-term problems, including target pest resurgences and secondary pest outbreaks, risk-averse attitudes among farmers coupled with relatively consistent short-term insecticide efficacy may be potent forces propelling farmers toward the use of insecticides.

Key words: control failure, insecticide efficacy, risk aversion, *Lygus hesperus*, cotton

Insecticides are widely used to control insect pest populations in agriculture, but may have negative consequences for human and environmental health (Hoppin and LePrevost 2017). Agroecologists and agricultural economists have repeatedly suggested that insecticides are often overused (Liu and Huang 2013, Lefebvre et al. 2015). One possible contributor to this putative overuse is the perception among farmers that insecticides allow them to reduce the risk of pest outbreaks that cause severe crop damage. Economic theory has shown that increased use of insecticides is favored if insecticides reduce financial risk (Tisdell et al. 2017), and empirical studies have shown that more risk-averse farmers use elevated amounts of insecticides relative to their more risk-tolerant neighbors (Liu and Huang 2013, Gong et al. 2016).

But how reliable are insecticides as a tool for suppressing pest populations in commercial agriculture? Insecticide applications

can fail to suppress target pest populations for two broad classes of reasons. First, procedural errors can cause control failures (reviewed by Nansen and Ridsdill-Smith 2013). For example, applications can fail because of the use of the wrong active ingredient, wrong rate, or wrong pH of the carrier solution. Mistakes can also be made in the mechanics of the application, for instance using insufficient spray volume, inappropriate nozzles, too-high driving speeds, or making applications under weather conditions that adversely affect spray penetration of the crop canopy and resulting coverage. Second, insecticide applications can fail because the target pest population has evolved resistance to the active ingredient being used. Resistance is an ever-expanding problem, now documented in a vast array of insect pest species (Gould et al. 2018). Surveys of pest populations that are tested using laboratory bioassays are widely used to project likely control failures under

field conditions (Dângelo et al. 2017, Guedes 2017). Although such studies may predict abundant potential for control failures, whether or not such potential is actually realized in commercial agriculture is less clear. Farmers who experience a control failure, or learn of such failures from others, may rapidly switch to alternate insecticides or different control methods altogether (i.e., ‘adaptive management’). Thus, it is possible that control failures are actually rare, despite widely documented resistance.

Perhaps surprisingly, the simple question of how often insecticide applications in commercial agriculture result in control failures has rarely been addressed and, to my knowledge, the literature on this subject has never been synthesized. Connected to this is the absence of a consensus definition for a control failure. Guedes (2017) suggested that insecticide applications that fail to suppress target populations below 80% of their initial densities can be used as an operational definition of a control failure. But the level of pest population suppression clearly varies continuously, so it is useful to characterize the full distribution of pest suppression levels attained. For the purposes of this article, I propose the following simple and intuitive categories of control outcome, based on the percentage of the target pest population remaining after the insecticide application: <20%, successful control; 20 to <50%, minor control failure; 50 to 100%, major control failure; and >100% severe control failure.

Traditional small-scale field plot insecticide efficacy trials performed by researchers do not always reflect the likelihood of control failures under commercial production conditions, because insecticide efficacy on a small spatial scale may not predict efficacy on the much larger spatial scales of commercial agriculture (Macfadyen et al. 2014). Furthermore, researchers may test active ingredients that farmers would not opt to use. The few published studies examining the efficacy of commercial applications of insecticides come primarily from the special cases of fumigations of stored products pests in postharvest settings (reviewed in Campbell et al. 2015) or the performance of transgenic crop plants (reviewed in Dively et al. 2021). Little work has been performed with conventionally-applied insecticides in open field commercial agriculture (e.g., Byers et al. 1992). Thus, a clear picture of the realized efficacy of most commercial insecticide applications remains elusive.

Further contributing to the paucity of relevant studies is the difficulty of obtaining the needed data, which include estimates of pest density just before and after an insecticide application and a quantification of associated sampling variances. Many farmers move very quickly from the detection of damaging pest populations to an insecticide application, leaving little time for a researcher to obtain a measurement of preapplication pest density (e.g., Rosenheim et al. 2004). Here, I avoid this difficulty by evaluating the realized efficacy of insecticides using data gathered by independent pest control consultants working in commercial agriculture, an ecoinformatics approach (Rosenheim and Gratton 2017). I focus on control of a major insect pest, the western tarnished plant bug *Lygus hesperus* Knight attacking cotton in California’s San Joaquin Valley (Rosenheim and Meisner 2013). All motile stages of *L. hesperus* feed on the above-ground portion of the plant. However, *L. hesperus* eggs are embedded in plant tissue with only the operculum exposed, and some *L. hesperus* nymphs may also feed under the bracts that subtend the developing cotton bolls; thus, these stages may be partially shielded from direct exposure to insecticide sprays. Formal surveys for pesticide resistance have not been performed in California, but resistance to organophosphate insecticides in populations of *L. hesperus* from Utah and Idaho has been well characterized (Zhu and Brindley 1990, Xu and Brindley 1993). Control failures of organophosphate, pyrethroid, and neonicotinoid insecticides targeting *L. hesperus* in

coastal California strawberries have also been observed in small-plot trials (Joseph and Bolda 2016).

Here I seek to characterize the distribution of control efficacies achieved by commercial insecticide applications, including six different active ingredients: acephate and oxamyl (organophosphates); beta-cyfluthrin, bifenthrin, and zeta-cypermethrin (pyrethroids); and a mixture of imidacloprid + beta-cyfluthrin (neonicotinoid plus pyrethroid).

Materials and Methods

I compiled data that were originally gathered by an independent pest management consulting firm working in cotton fields managed by three commercial farming operations in western Fresno County in the San Joaquin Valley, California from 1997 to 2006. Independent consultants are paid a flat per-acre fee for their services, and thus are free of potential conflicts of interest regarding recommendations for pesticide applications. Each of the records ($N = 50$) included (1) an estimate of *L. hesperus* density prior to the insecticide application; (2) a double-confirmation of the insecticide application, including the identity and amount of active ingredient applied, whether the application was made by ground or air, and its date; (3) the number of additional active ingredients included in the application (0, 1, or 2) to accommodate cases where *L. hesperus* was jointly targeted with other insects as part of a tank-mix; and (4) an estimate of *L. hesperus* density after the insecticide application and no more than 6 d after the preapplication density estimate. Per-acre insecticide application rates varied only moderately across treatments (rate ranges: acephate, 1 lb Orthene; oxamyl, 26–36 oz Vydate; beta-cyfluthrin, 1 oz (ground) or 3 oz (air) Baythroid; bifenthrin, 4–5 oz Capture; zeta-cypermethrin, 3–4 oz Mustang; imidacloprid + bifenthrin, 3.75 oz Leverage); I did not have sufficient replication to examine the consequences of rate variation within each insecticide or the use of different brands of surfactants. These six insecticides represented the full set of active ingredients used against *L. hesperus* by the consulting firm during the study period for which the requisite *L. hesperus* density estimates were available. I chose a maximum interval between density estimates of 6 d to reduce the influence of potential population changes stemming from reproduction or migration. Density estimates were made with an insect sweep net (diameter = 38.1 cm) swept through the upper canopy of the cotton plants fifty times to create a single sample; each preapplication and postapplication density estimate was based on an average of 14.0 ± 7.1 (range 3–33) and 10.1 ± 6.1 (range 2–30) of these sweep samples, respectively. Seven different field scouts performed the sweep samples. Whenever possible I used density estimates generated by the same individual field scout checking the field both before and after the insecticide application (sometimes more than one scout sampled a given field on the same day); this was possible for 28 out of the 50 records. Counts of *L. hesperus* nymphs and adults were recorded separately. Although nymphs are often sampled less efficiently than adults during commercial scouting operations (Rosenheim et al. 2004), nymphal counts are of particular interest, because they are likely to be almost completely unaffected by immigration after the insecticide application.

Statistical Analysis

Short-term efficacy of each insecticide application was measured by calculating the proportion of the preapplication population that remained postapplication; thus, 0.0 represents the highest level of control efficacy (no pests detected postapplication), 1.0 represents

no change in the pest population density, and values > 1.0 represent populations that increased despite the insecticide application. A linear mixed-effect model was fit using R package *lme4* (Bates et al. 2015) to evaluate a set of fixed-effect predictors of short-term efficacy, including (1) the active ingredient applied; (2) the number of additional active ingredients, targeting other insect pests, present in tank mixes; (3) the application method, air versus ground; (4) the number of days between the application and the postapplication estimate of pest density; and (5) year, with 1997, the earliest year in the data set, coded as 1 and each year thereafter incremented by one. Year was included in the model to look for any evidence of an underlying progression of resistance. Random effects were included for the identity of the field scouts who generated the density estimates before (*scout1*) or after (*scout2*) the insecticide application and for the identity of the commercial farming operation (*ranch*). Scout identity was included because significant differences among scouts in *L. hesperus* density estimates are common (unpublished data); no two individuals use a sweep net in precisely the same way. As emphasized by Larsen and Noack (2021), inclusion of *ranch* in statistical models of pesticide use is important to control for any differences in agronomic or pest management practices across farming operations that are not directly measured, but that might influence the response variable or predictors. The Kenward–Roger method for approximating degrees of freedom for fixed effects was implemented in package *pbrttest* (Halekoh and Højsgaard 2014), allowing me to generate approximate *P*-values for fixed effects using the *t*-distribution.

A nonparametric Wilcoxon signed rank test with continuity correction was used to test the hypothesis that mean short-term efficacy of insecticide applications differed between nymphal versus adult

L. hesperus; for this analysis, each treated field generated one paired set of observations (suppression of nymphs, suppression of adults).

Ninety-five percent confidence intervals for short-term insecticide efficacy estimates were calculated using nonparametric bootstrapping implemented in package *boot* (Ripley 2020), thereby avoiding the difficulties of computing variance estimates for a ratio of count-based variables. Ten thousand samples were taken with replacement, and the percentile method was used with the 2.5th and 97.5th percentiles of the empirical bootstrap distribution selected (Buonaccorsi and Liebhold 1988). Means are reported ± 1 SD throughout.

Results

Commercial insecticide applications were made in response to preapplication *L. hesperus* population densities that averaged 6.06 ± 4.48 total motiles per sweep sample (range 0.44–18.33), including 2.52 ± 3.22 nymphs (range 0.00–14.33) and 3.54 ± 2.56 adults (range 0.44–15.67). Mean postapplication densities were 0.76 ± 0.78 total motiles (range 0.00–2.88), including 0.27 ± 0.43 nymphs (range 0.00–0.63) and 0.50 ± 0.56 adults (range 0.00–2.11). The mean proportions of *L. hesperus* populations remaining postapplication were 0.19 ± 0.28 for all motiles (i.e., an 81% decrease), 0.21 ± 0.30 for adults (a 79% decrease), and 0.12 ± 0.19 for nymphs (an 88% decrease). Control efficacy was significantly greater for nymphal stages than for adults (nonparametric Wilcoxon signed rank test: $V = 618$, $N = 50$, $P = 0.038$).

Control efficacy did, however, vary substantially across applications (Fig. 1). Thirty-five of the 50 applications (70%) reduced the target population to $< 20\%$ of its initial density (successful control), 13 of the 50 applications (26%) reduced the target population to

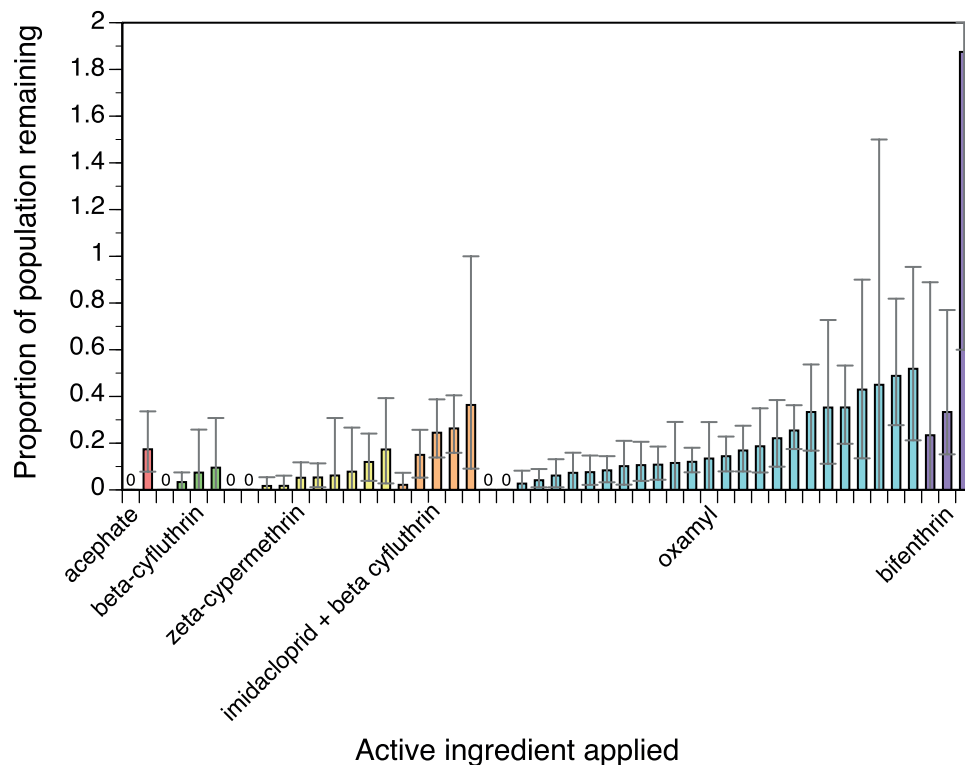


Fig. 1. Short-term efficacy of whole-field commercial insecticide applications targeting *Lygus hesperus* populations in cotton. Shown is the mean proportion of the preapplication *L. hesperus* population that remained postapplication, with bootstrapped 95% confidence intervals (CI). Observations are grouped and color-coded by active ingredient applied and ordered by decreasing efficacy across and within active ingredients. (The upper limit of the 95% CI for the final bifenthrin application is 7.50.)

between 20 and 50% of its initial density (minor control failure), 1 of the 50 applications (2%) reduced pest density to between 50 and 100% of its initial density (major control failure), and in a final case, the postapplication population density estimate was nearly twice as large as the preapplication density estimate (severe control failure).

The statistical model identified the active ingredient applied as the sole significant predictor of insecticide efficacy (Table 1), with bifenthrin identified as a less-effective material. The single severe control failure involved an application of bifenthrin; this was also the final application of bifenthrin in the field reports documented by my data set. Days between the insecticide application and the postapplication density estimate had no effect on observed short-term efficacy (Table 1), suggesting that recolonization of cotton fields postapplication by immigrating *L. hesperus* was not having a major effect on the apparent efficacy of the treatments.

Discussion

Short-term efficacy of commercial insecticide applications for control of *L. hesperus* in California cotton was highly variable. If we adopt the benchmark that effective insecticide applications should reduce pest populations to $\leq 20\%$ of their preapplication density, then control failures were quite common, observed in 15 of the 50 applications (30%). However, all but two of these control failures were minor (pest populations reduced to 20–50% of initial densities). I recorded only one major control failure (1 of 50, or 2%; *L. hesperus* population reduced to 51.8% of initial density) and one severe control failure (1 of 50, or 2%; *L. hesperus* population increased to 188% of initial density). Even an application of intermediate efficacy could be useful to ameliorate pest impacts, although clearly most farmers will wish for higher levels of pest suppression.

Despite the economic importance of *L. hesperus* as a pest of several important crops in California (strawberries, cotton, seed alfalfa,

and others), no population surveys assessing the possibility of resistance evolution have been conducted. Informal observations suggest that resistance to some insecticides is likely present in coastal areas of strawberry production (Joseph and Bolda 2016, <https://www2.ipm.ucanr.edu/agriculture/strawberry/Lygus-Bug/>). Thus, the causes for the variation in control efficacy observed in this study, including the cause of the severe control failure observed following an application of bifenthrin, are unknown, and it is possible that either application errors or resistance could be contributing.

Overall, despite a known history of resistance evolution by *L. hesperus* in other areas of the western United States, cotton growers who opted to use insecticides to control damaging *Lygus* populations had a moderately high likelihood of generating substantial short-term suppression. Thus, at least in this one case study, insecticides do appear to represent an attractive option for risk-averse farmers, as has been assumed in the agricultural economics literature (Liu and Huang 2013, Gong et al. 2016). I speculate that adaptive management of pests by farmers and consultants may contribute to the relative rarity of severe control failures: following one, or perhaps repeated severe failures, which should serve as a more reliable indicator of resistance, farmers may abandon the use of the failed active ingredient, at least when other effective options are available (Gould et al. 2018). In this study, the one insecticide, bifenthrin, that produced a severe failure did not appear subsequently in the data set, consistent with a decision by the consultant to cease the use of this compound for control of *L. hesperus*.

The distribution of short-term control efficacies observed for insecticide applications targeting *L. hesperus* is similar to those obtained for two other published studies of short-term insecticide efficacy in commercial agriculture. First, Campbell et al. (2015) studied fumigation treatments for control of *Tribolium* spp. in commercial grain storage facilities, showing that the postapplication population density was reduced, on average, to 22% of the preapplication density; severe control failures (densities after treatment > densities before treatment) were observed, but only infrequently (4 of 111 applications; 3.6%). Second, Byers et al. (1992) studied control of the pale western cutworm in grain crops by commercial permethrin applications, finding consistently strong control, with postapplication densities averaging 11.5% ($N = 4$ fields) of preapplication densities. If these results reflect the broader pattern of short-term insecticide efficacy in agricultural pest management, it will suggest that competing control methodologies may need to achieve similarly high levels of predictable short-term efficacy to be equally attractive options for immediate pest population suppression.

Importantly, insecticides may have much more mixed effects when the time frame of efficacy evaluation is extended; broad-spectrum materials may suppress populations of predators and parasitoids, leading to target-pest resurgences or secondary pest outbreaks (Hardin et al. 1995, Steinmann et al. 2011, Hill et al. 2017). For example, when insecticide applications targeting *L. hesperus* in cotton are made early in the growing season, before 1 July, farmers have been found to exhibit modestly elevated use of insecticides during the remainder of the season to control other pests, supporting the hypothesis of secondary pest outbreaks (Gross and Rosenheim 2011). Risk-averse attitudes among farmers coupled with relatively consistent short-term insecticide efficacy, may, however, be potent forces propelling farmers towards use of insecticides.

Table 1. Linear mixed-effect model of factors influencing the short-term efficacy of commercial insecticide applications targeting *Lygus hesperus* in cotton

Random effects	Variance			
Scout1	0.01297			
Scout2	0.00608			
Ranch	0.00041			
Residual	0.0469			
Fixed effects	Estimate	SE	t-value	P
(Intercept)	0.281	0.237	1.19	0.25
AI—beta-cyfluthrin	-0.018	0.211	-0.08	0.93
AI—bifenthrin	0.737	0.236	3.12	0.004
AI—imidacloprid+beta cyfluthrin	0.156	0.220	0.71	0.48
AI—oxamyl	0.183	0.195	0.94	0.36
AI—zeta cypermethrin	0.025	0.201	0.13	0.90
AdditionalActiveIngredients	0.052	0.048	1.09	0.29
GroundvsAir—ground	0.041	0.115	0.36	0.72
DaysPostApplication	-0.051	0.036	-1.44	0.16
Years	-0.017	0.017	-1.02	0.32

The model was fit with the following command: Efficacy < lmer(PopulationRemaining ~ ActiveIngredient + AdditionalActiveIngredients + GroundvsAir + DaysPostApplication + Years + (1|Scout1) + (1|Scout2) + (1|Ranch), data = EfficacyData). The reference level for the model was an aerial application of acephate. *P*-values calculated using Kenward–Roger approximated degrees of freedom.

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