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Spatial Externalities of Pest Control Decisions in the California Citrus Industry

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Predaceous and parasitic insects provide control of important citrus pests. However, many pesticides are toxic to these beneficials. Using California citrus grower survey data, this article tests whether landscape-level use of pesticides affects the presence of and reliance on *Aphytis melinus*, an important beneficial insect. Results show that landscape-level pesticide use decreases the presence of *A. melinus* and increases reliance on insecticides. Pesticide use on non-citrus crops has a significant negative effect on the presence of *Aphytis melinus*, suggesting a cross-crop spatial externality. Our findings illustrate that regulations designed to address cross-crop effects on beneficial insects can increase social welfare.

Key words: *Aphytis melinus*, beneficial insects, California red scale, citrus, integrated pest management, pesticide, spatial externalities

Introduction

Growers who practice integrated pest management (IPM) use a combination of biological control by natural enemies (predators or parasitoids), pesticide applications limited to cases where pest population thresholds are exceeded, and selective pesticides when necessary and available (University of California Integrated Pest Management, 2010). Many growers, however, still rely on broad-spectrum pesticides, such as organophosphates and carbamates. Most broad-spectrum pesticides are toxic not just to the targeted pests, but also to natural enemies. Natural enemies move freely between fields, so broad-spectrum pesticide use may reduce natural enemy populations throughout the regional landscape, causing a negative externality for growers who use biological control. Pests also move freely between fields, so pesticide use may reduce regional pest populations, causing a positive externality. This article empirically tests for positive and negative externalities of pesticide use in the California citrus industry.

Aphytis melinus, a parasitic wasp, provides control of California red scale (CRS), an economically important citrus pest (University of California Cooperative Extension, 2003). CRS damages citrus fruit, leaves, twigs, and branches by sucking on plant tissue; infested fruit receive a lower price (Grafton-Cardwell et al., 2008). *A. melinus* lays its eggs under the scale. When the egg hatches, the larva eats the scale. Commercial insectaries produce the wasp, and some citrus growers purchase and release it as part of an IPM program (Grafton-Cardwell et al., 2008). Some citrus growers in California use pesticides that are toxic to the wasp. These pesticides are used to treat CRS as well as other citrus pests (Grafton-Cardwell, 2010; University of California Integrated

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Pest Management, 2008). Some growers of non-citrus crops use pesticides that are toxic to the wasp, and *A. melinus* itself provides some control of various non-citrus crop pests (University of California Integrated Pest Management, 2003a). Non-citrus growers, do not, however, rely on or augment populations of *A. melinus* (Mullen et al., 2005).

Management of CRS is a useful case for testing for the presence of externalities across pest management decisions because of the timing of growers' decisions and actions. Most growers who apply pesticides do so relatively early in the citrus season (May and June) and most base their application decisions on population counts late in the previous season and previous harvest scale damage (University of California Integrated Pest Management, 2008).[1] This seasonality makes the previous season's landscape-level pesticide use the relevant explanatory variable when modeling a grower's current pest control decisions. From an econometric perspective, this relationship is advantageous because the previous season's landscape-level pesticide use is exogenous to current decisions, even under the hypothesis of spatial externalities.

Neighboring growers may create two types of externalities for an individual citrus grower. First, consider citrus grower *i*; all of his neighbors apply pesticides to control CRS in season one. Scale pressure on grower *i*'s field is likely to be lower at the end of season one than it would be in the absence of control by his neighbors, making it less likely that he will treat in season two based on his observations in season one. In other words, his neighbors' season-one pesticide applications create a positive externality for him that will be reflected in his season-two pest control decisions. Now consider grower *j*; all of his neighbors apply pesticides that are toxic to *A. melinus* in season one, lowering the wasp's landscape-level population and reducing the pest control the wasp provides grower *j*. This reduction will lead to a higher late-season scale population on grower *j*'s citrus than would occur in the absence of his neighbors' pesticide use. As a result, grower *j* may apply a pesticide in season two when he would not have done so otherwise. All pesticides toxic to *A. melinus* generate this negative externality, in contrast to the positive externality experienced by grower *i*, which is created only by pesticides toxic to CRS.

Previous work regarding the externalities of pesticide use includes theoretical models in which pesticide use generates off-farm environmental externalities (Reichelderfer and Bender, 1979), kills predators of a secondary pest (Harper and Zilberman, 1989), or kills predators of a primary pest (Zhang, 2007). All of these papers conclude that cases exist where a shift away from or a reduction in chemical control can be socially optimal, but none test their conclusions empirically. Goodhue, Klonsky, and Mohapatra (2010), Klemick and Lichtenberg (2008), and Hubbell and Carlson (1998) model determinants of pesticide decisions empirically, but do not examine the effects of pesticide use on nearby growers' pest management decisions.

This article contributes to the literature by testing for externalities generated by growers' pest control decisions that could affect other growers' decisions. Specifically, we test three hypotheses related to growers' reliance on *A. melinus* to control CRS. First, we test the hypothesis that citrus orchards in areas with higher landscape-level use of pesticides toxic to *A. melinus* are less likely to have detectable wasp populations than orchards in areas with less use. This would occur if the range of *A. melinus* were larger than an individual orchard, so that the use of pesticides on one orchard will affect other orchards included in the same population range. Anecdotal evidence of growers benefitting from *A. melinus* releases made by their neighbors suggests that this is the case. Second, we test the hypothesis that, given the level of pest pressure, growers in areas with higher landscape-level of use of pesticides that are toxic to *A. melinus* are more likely to apply pesticides to treat CRS than growers in other areas. This spatial correlation could be due to shared information sources, a tendency for growers to use control methods that others in the area use (peer effects), and/or less natural control by *A. melinus*, necessitating chemical control. Finally, we test the hypothesis that, for a given level of pest pressure, growers in areas with higher landscape-level use of pesticides that are toxic to *A. melinus* will use chemical controls that are less IPM compatible. Such behavior would,

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[1] This differs from pests where growers make decisions only based on the current season's pest population. Disentangling the effects of neighboring growers' pest management decisions in this case would be exceedingly difficult.

Table 1. Hypothesized Externalities of Landscape-level Pesticide Use and Their Hypothesized Effects on Outcome Variables

	Sign of Externality			Sign of Effect of Externality		
Pesticides Toxic to:	**Probability of *A. melinus* Presence**	**Probability of Pesticide Application**	**IPM Compatibility**	**Probability of *A. melinus* Presence**	**Probability of Pesticide Application**	**IPM Compatibility**
A. melinus	-	-	-	-	+	-
A. melinus and Red Scale	-	+/-	+/-	-	-/+	-/+
Red Scale	None	+	+	None	-	+

again, occur due to shared information sources, peer effects, and/or less control by *A. melinus*. The last step in our analysis allows us to differentiate between the third explanation and the first two.

We find evidence to support all three hypotheses, and we find evidence that pesticide use on non-citrus crops may generate a negative externality borne by citrus growers who wish to use *A. melinus* for pest control. To the best of our knowledge, our findings are the first of their kind, and they are useful for policymakers and pesticide registrants. Current use regulations and label requirements focus on direct effects on certain crops or direct effects on the target pest(s), such as the speed of resistance development. Our findings illustrate that policies designed to address cross-crop contemporary effects and effects on both the pest and beneficial insects can increase social welfare. A pesticide tax is one policy option. We calculate the unit tax that would internalize the negative externality inflicted on citrus growers due to the loss of *A. melinus*. The magnitude of the externality varies by region, so the optimal tax varies substantially as well, with a maximum regional rate of approximately $33 per pound of chlorpyrifos.

Models and Hypotheses

There are four steps in the pesticide use decision-making process. First, the grower must assess whether or not the pest is present. Second, if the pest is present, the grower will assess whether or not a natural enemy is present and if so, how much control it is providing. Third, the grower will decide whether or not to apply a pesticide, given all chemical and non-chemical control options. Finally, if the grower decides to apply a pesticide, he will decide which one(s). This article estimates the determinants of steps two, three, and four in the decision-making process.

Hypothesized Spatial Externalities

Potential for spatial externalities exists at each step in the decision-making process. Table 1 outlines these hypothesized externalities and the effects of these externalities on the outcome variables that we model. The probability that *A. melinus* is present will be a function of climate, field characteristics, and the use of pesticides that are toxic to *A. melinus* within the local population's range. These pesticides may or may not be used for CRS control. The landscape-level use of these pesticides may generate a negative externality by lowering the landscape-level wasp population and decreasing the probability that it is present.

The probability of a pesticide application will be a function of the pest population size, the control provided by *A. melinus*, economic factors that influence the marginal net benefit of control, and grower characteristics that influence the grower's pest control preferences. At this step, the potential exists for both positive and negative externalities to occur. Landscape-level use of pesticides that are used to control CRS can suppress its landscape-level population, lessening the need for chemical control, thus generating a positive externality. However, landscape-level use of pesticides that are toxic to *A. melinus* may lessen the amount of control provided by the beneficial insect, increasing the need for a pesticide application to provide CRS control, thus generating a negative externality. Pesticides that are both toxic to *A. melinus* and used for CRS control could generate a net positive or negative externality.

Finally, the choice of pest control method will depend on the pest population, the number of pest species that require control, the amount of control provided by *A. melinus*, economic factors that influence the marginal net benefit of different controls, and grower characteristics that influence pest control preferences. Landscape-level pesticide use for CRS control can suppress its population, which may generate a positive externality by allowing the grower to rely only on *A. melinus* or on more selective pesticides. Using pesticides that are toxic to *A. melinus* may generate a negative externality by reducing the control provided by *A. melinus*, causing the grower to shift towards broad-spectrum pesticides for CRS control, since the beneficial insect population has already been reduced. Pesticides that are both toxic to *A. melinus* and used for CRS control may have conflicting effects on the grower's decision.

Empirical Models

We are interested in the effects of nearby growers' actions on a grower's decision at each step. To determine whether or not we need to correct for spatial correlation across respondents, we use Moran's I and Geary's C to test for spatial autocorrelation in each of the outcome variables of interest. In all cases we cannot reject the null hypothesis of independence (results can be found in the appendix in table A1). Consequently, we use indices of tract-level pesticide use to account for landscape-level pesticide use. While a lack of spatial correlation prevents us from estimating spatial autoregressive and/or spatial error models, assuming spatial independence of the respondents' decisions allows us to identify the effects on their decisions of landscape-level pesticide use occurring on all citrus and non-citrus acreage, regardless of whether or not a respondent manages it.

We estimate three models. First, we estimate a probit model using the Heckman selection two-step procedure to estimate the probability of the known naturally occurring presence of the wasp in grower i's citrus orchards, taking into account landscape-level pesticide use.[2] Let y_i^* be the true wasp population, and Y be the level at which the population is detectable. We observe:

$$y_i = \begin{cases} 1 & \text{if} \quad y_i^* > Y \\ 0 & \text{if} \quad y_i^* \leq Y \end{cases} \tag{1}$$

We assume that the latent population of *A. melinus* on grower i's citrus can be represented as:

$$y_i^* = \alpha + \sum_{j=c,nc} lAM_{ij}\gamma^{AM_j} + \sum_{j=c,nc} lRSAM_{ij}\gamma^{RSAM_j} + \boldsymbol{dd}_i'\delta + \boldsymbol{f}_i'\theta + R_i\beta + \varepsilon_i. \tag{2}$$

lAM_{ij} and $lRSAM_{ij}$ are pairs of indices of landscape-level use of pesticides toxic to *A. melinus* but not used for CRS control and pesticides that are toxic to *A. melinus* and used for CRS control, respectively. We consider pesticide use on both citrus and non-citrus fields. $\boldsymbol{dd}_i$ is a 4×1 vector of generations and generations squared for *A. melinus* and CRS. $\boldsymbol{f}_i$ is a vector of farm characteristics, and R_i is a dummy variable that equals 1 if the respondent produces in the coastal region, the region most well-suited for *A. melinus*.[3] Farm characteristics include acres of citrus and total acres, whether or not the grower has organic production, whether or not the grower utilizes cover crops, and whether or not the grower has a majority of citrus acreage in lemon and/or grapefruit. CRS grows more quickly on lemon and grapefruit, so these crops will potentially have more CRS for *A. melinus* to parasitize (Grafton-Cardwell and Stewart-Leslie, 1998).

Negative coefficients on the landscape-level pesticide use indices will indicate that landscape-level use of pesticides toxic to *A. melinus* reduces the likelihood that *A. melinus* is naturally occurring

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[2] We focus on the naturally occurring presence of *A. melinus* during the growing season because including recent releases does not allow us to analyze the effects of previous pesticide use.

[3] There are four main citrus growing regions: San Joaquin Valley, Coastal-Intermediate, Interior, and Desert Regions (University of California Cooperative Extension, 2003). There is also a relatively small northern region.

on grower i's field, suggesting that negative externalities exist. We hypothesize that increasing generations of either the scale or the wasp will have a positive effect on the probably that *A. melinus* is present. The probability of its presence may vary based on the grower's region due to differences in climate not reflected in the generations variables.

Only about 58% of survey respondents with CRS present know whether or not *A. melinus* is present, so we control for sample selection bias using the Heckman two-step estimation procedure. We observe y_i if $K_i^* \geq \overline{K}$, where K_i^* is a latent measure of grower i's knowledge of *A. melinus*, and $\overline{K}$ is the minimum amount of knowledge required to be able to determine whether or not *A. melinus* is present. We model this latent knowledge as:

$$K_i^* = \mu + \boldsymbol{f}_i'\phi + \boldsymbol{R}'\omega + \boldsymbol{g}_i'\eta + v_i, \tag{3}$$

where $\boldsymbol{g}_i$ is a vector of grower characteristics, including whether or not the grower has a college degree and the grower's years of experience. We test for the independence of equations (2) and (3) using a likelihood ratio test.

Next, for the decision of whether or not to apply a pesticide, we observe:

$$Apply_i = \begin{cases} 1 & \text{if} \quad a_i^* > 0 \\ 0 & \text{if} \quad a_i^* \leq 0 \end{cases} \tag{4}$$

where

$$a_i^* = U(Apply_i = 1) - U(Apply_i = 0). \tag{5}$$

$U(Apply_i = 1)$ is grower i's utility from applying at least one pesticide to control CRS, and $U(Apply_i = 0$ is the utility from not applying any pesticides. Utility is a function of expected profits under the two alternatives and may include disutility from pesticide use due to potential health and environmental effects. We model the difference in utility as:

$$\begin{aligned} a_i^* = \alpha &+ \sum_{j=c,nc} lAM_{ij}\gamma^{AM_j} + \sum_{j=c,nc} lRSAM_{ij}\gamma^{RSAM_j} + \sum_{j=c,nc} lRS_{ij}\gamma^{RS_j} + \boldsymbol{dd}_i'\delta + \\ &\boldsymbol{f}_i'\theta + \boldsymbol{p}_i'\mu + \boldsymbol{g}_i'\eta + \boldsymbol{C}_i'\beta + e_i, \end{aligned} \tag{6}$$

where lRS_{ij} is the index of landscape-level use of pesticides that are used to control CRS but are non-toxic to *A. melinus*, $\boldsymbol{p}_i$ and $\boldsymbol{g}_i$ are vectors of production and grower characteristics, respectively, $\boldsymbol{C}_i$ is a vector of county dummy variables, and all other variables are as previously defined.[4] The production vector includes expected value per acre, since growers with a higher expected value will be more likely to implement control, and production outlets, because different outlets treat damaged fruit differently. The grower characteristics vector controls for education, experience, gender, and ethnicity. Women and minorities may have different attitudes towards and perceptions of risk and environmental quality (Cabrera and Leckie, 2009; Finucane et al., 2000; Konisky, Milyo, and Richardson, 2008; Slovic, 1999). The county dummy variables will control for any climatic and environmental factors that may influence CRS and *A. melinus* populations that are not controlled for with the generation variables, $\boldsymbol{dd}_i$.

We estimate equation (9) as a probit model. Negative coefficients on lAM_{ij} would indicate that the use of pesticides toxic to *A. melinus* lowers wasp populations and necessitates chemical control. Positive coefficients on lRS_{ij} would indicate that the use of pesticides that are used to control CRS but that are not toxic to *A. melinus* positively affect respondent i by reducing the likelihood that (s)he applies a chemical control. The coefficient on $lRSAM_{ij}$ could be positive or negative depending on which externality is greater in absolute terms. Increased generations of CRS, corresponding to

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[4] Only a Coastal Region dummy variable was included in the model for *A. melinus* presence in order to obtain model convergence.

increased pest pressure, are hypothesized to increase the probability of a chemical application, while increased generations of *A. melinus* are hypothesized to decrease it.

Finally, if grower *i* decides to apply a pesticide, (s)he will choose the level of IPM compatibility.[5] Grower *i*'s optimal choice of IPM compatibility, c_i^*, can be written as:

$$\begin{aligned} c_i^* = \alpha + \sum_{j=c,nc} lAM_{ij}\gamma^{AM_j} + \sum_{j=c,nc} lRSAM_{ij}\gamma^{RSAM_j} + \sum_{j=c,nc} lRS_{ij}\gamma^{RS_j} + \\ \boldsymbol{dd}_i'\delta + CPP_i\phi + \boldsymbol{f}_i'\theta + \boldsymbol{p}_i'\mu + \boldsymbol{g}_i'\eta + \boldsymbol{C}_i'\beta + e_i, \end{aligned} \tag{7}$$

where CPP_i, combined pest pressure, denotes how many of four major citrus pests grower *i* reported as present in the 2009 growing season. Increasing CPP_i is expected to decrease IPM compatibility since broad-spectrum pesticides are capable of killing multiple pests while the more compatible options are species-specific. Instead of observing c_i^*, we observe c_i, the choice of pesticide that has the closest IPM compatibility of all available pesticides. This implies:

$$c_i = \begin{cases} 1 & \text{if} \quad c_i^* \le \tau_1 \\ 2 & \text{if} \quad \tau_1 < c_i^* \le \tau_2 \\ 3 & \text{if} \quad \tau_2 < c_i^* \le \tau_3 \\ & \vdots \\ M & \text{if} \quad \tau_{M-1} \le c_i^* \end{cases} \tag{8}$$

where M is the number of pest control options available, ranked such that pest control option 1 is the least compatible with an IPM program and pest control option M is the most compatible, and τ_m and τ_{m-1} represent the latent levels of compatibility that separate pesticide m from $m-1$ and $m+1$. About 73% of growers with CRS present choose to utilize any form of control. Because the choice of utilizing any control likely occurs simultaneously with the decision of what to apply, we use a two-step selection model where the first step estimates whether or not any control (chemical and/or biological) is utilized, and the second step estimates the parameters in equation (10) and τ_m using an ordered probit model, controlling for selection. We model the selection as:

$$AnyControl_i = \begin{cases} 1 & \text{if} \quad ac_i^* > 0 \\ 0 & \text{if} \quad ac_i^* \le 0 \end{cases} \tag{9}$$

where

$$ac_i^* = U(AnyControl_i = 1) - U(AnyControl_i = 0). \tag{10}$$

We model the difference in utility as:

$$\begin{aligned} ac_i^* = \alpha + \sum_{j=c,nc} lAM_{ij}\gamma^{AM_j} + \sum_{j=c,nc} lRSAM_{ij}\gamma^{RSAM_j} + \sum_{j=c,nc} lRS_{ij}\gamma^{RS_j} + \\ \boldsymbol{dd}_i'\delta + \boldsymbol{f}_i'\theta + \boldsymbol{p}_i'\mu + \boldsymbol{g}_i'\eta + e_i. \end{aligned} \tag{11}$$

If using pesticides that are toxic to *A. melinus* lowers population levels and reduces grower *i*'s ability to rely on *A. melinus* for CRS control, we will see negative marginal effects for these indices with respect to the choice of reliance on *A. melinus*, the most compatible control option. If growers simply use methods similar to their neighbors, we should see positive marginal effects from tract-level use

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[5] Ideally, this analysis would include multinomial logit estimation of grower *i*'s choice of pest control bundle. Our sample size combined with the number of variables required does not yield enough degrees of freedom to estimate such a model.

of pesticides included in $RSAM_{ij}$ on grower *i*'s use of pesticides included in $RSAM_{ij}$ and similarly, we should see positive marginal effects from tract-level use of pesticides included in RS_{ij} on grower *i*'s use of pesticides included in RS_{ij}.

Statistically significant coefficients on the landscape-level pesticide use indices in equations (2), (6), and (7) would suggest that respondents bear externalities generated by nearby growers. Although *A. melinus* is less mobile than some insects, it is a generalist parasitoid and parasitizes a wide range of scales found on citrus and non-citrus crops (Bernal and Luck, 2007; University of California Integrated Pest Management, 2003a). We predict that the limited movement of the wasp will limit the spatial scale of the negative externality generated by the use of pesticides that are toxic to the wasp, while the generalist nature of the wasp implies that it will spend time on both citrus and non-citrus fields, so that the use of pesticides on either type of crop generates a negative externality.

The host range and movement patterns of CRS suggest that it will spend time on non-citrus fields, as *A. melinus* does. CRS is only an economic pest of citrus and olives, but it also lives on other trees, shrubs, and bushes such as acacia, boxwood, grapes, mulberry, palm, and roses (Dreistadt et al., 2008). While males are capable of flight, females are only able to crawl and depend on wind and the movement of birds, humans, and machinery for long distance movement (University of California Integrated Pest Management, 2008). Given these factors, there is the potential for pesticide use on citrus and non-citrus fields to create a positive externality. To test whether or not the effects of the use of these pesticides on citrus differs from the effects of the use of these pesticides on non-citrus, we test the hypothesis for equations (6) and (7) that:

$$\gamma^{AMc} = \gamma^{AMnc}, \gamma^{RSAMc} = \gamma^{RSAMnc}, \quad \text{and} \quad \gamma^{RSc} = \gamma^{RSnc}. \tag{12}$$

Additionally, to test whether the net effect of $RSAM_{ij}$ is similar in magnitude to the effect of AM_{ij} or RS_{ij}, $j = c, nc$, we test two restrictions for equations (6) and (7):

$$\gamma^{RSAM_j} = \gamma^{RS_j}, \quad j \in \{c, nc\}; \tag{13}$$

$$\gamma^{AM_j} = \gamma^{RSAM_j}, \quad j \in \{c, nc\}. \tag{14}$$

If equation (13) or (14) cannot be rejected, then the net effect of $\boldsymbol{RSAM}_{ij}$ is similar in magnitude to the positive effect of $\boldsymbol{RS}_{ij}$ or the negative effect of $\boldsymbol{AM}_{ij}$, respectively. All restrictions are tested using likelihood ratio tests.

Data

We use four datasets: survey data, Pesticide Use Reporting (PUR) data from the California Department of Pesticide Regulation (DPR), pest development and pesticide data from the University of California Integrated Pest Management Program (UC IPM), and crop value data from county agricultural commissioners' reports. Table 2 reports descriptive statistics.

A mail survey of California citrus growers regarding the 2009 pre-bloom to harvest season was conducted in spring 2010. Addresses were obtained from agricultural commissioner's offices in eighteen counties, representing 99.1% of California citrus acreage (U.S. Department of Agriculture, 2007). With a 12.3% response rate, the respondents represented about 11.6% of the acreage reported by the 2007 Census of Agriculture for the surveyed counties (U.S. Department of Agriculture, 2007).[6] Growers were asked about the presence or absence of CRS, the naturally occurring presence or absence of *A. melinus*, and whether or not any insecticides were applied to control the scale if it was present. Other relevant survey questions addressed cultural pest control practices, production outlets, and grower and farm characteristics, including acreages of citrus and other crops, ethnic

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[6] Comparisons of respondents with the USDA's 2007 Census of Agriculture and 2008 Citrus Acreage Report indicate that the respondents are representative of the state's citrus growers in terms of their acreage and crop composition (U.S. Department of Agriculture, 2007, 2008).

background, education, age, and experience. The samples are restricted to growers who reported that CRS was present. The number of respondents varies by model because the research question and relevant set of growers differ, and because some respondents did not answer every question. There are no statistically significant differences in the means for any of the summary statistics across the groups of respondents included in each model estimated.

We use 2008 PUR data to create measures of landscape-level pesticide use for each respondent. The PUR data include a township, range, and section on the Public Land Survey System's township grid. We converted respondents' addresses to latitudes and longitudes (geocoder.us), and then to townships (geocommunicator.gov). We then create a "tract" that is 18 by 18 miles for each respondent, containing the respondent's township and eight adjacent townships. Each tract is large enough that an individual respondent accounts for an insignificant portion of land area and pesticide use, yet small enough to be a reasonable approximation of the scale and wasp's ranges. Total pesticide use from the PUR data within each respondent's tract represents landscape-level pesticide use.

For our analysis, there are ten pesticides of interest: acetamiprid, cyfluthrin, and fenpropathrin, which are toxic to *A. melinus* but not used for CRS control (referred to collectively as *AM* pesticides); buprofezin, petroleum oil, pyriproxyfen, and spirotetramat, which are used for CRS control but are not toxic to *A. melinus* (*RS* pesticides); and carbaryl, chlorpyrifos, and methidathion, which are toxic to *A. melinus* and are used for CRS control (*RSAM* pesticides). For our analysis, the applications of these pesticides that occur during the 2008 calendar year are relevant. The calendar year approximates the growing season for the average citrus grower (California Citrus Quality Council, 2003). Additionally, the first CRS flight occurs in early March, and growers who make releases of *A. melinus* begin them in mid-February or early March. The residues from pesticides applied in January can still remain at levels toxic to insects several months later (Grafton-Cardwell et al., 2008). Both insects remain in the field throughout the season, allowing pesticides applied at any time during the season to affect CRS and/or *A. melinus*.

Weather drives pest populations, so areas with larger populations of a given pest tend to have more overall pest pressure. This creates strong correlation between the pesticide variables. Inclusion of all ten pesticides for citrus and non-citrus growers creates multicollinearity. Consequently, we construct a pair of landscape-level pesticide use indices for each category of pesticides. Each pair contains an index for citrus use and an index for non-citrus use.

Simple summing of pounds applied across active ingredients is not adequate because the attributes of one pound of a given active ingredient differ from the attributes of one pound of active ingredient of another pesticide. Instead, we construct z-scores for tract-level usage on citrus fields and on non-citrus fields. For respondent *i*, crop category *j*, and pesticide *k*:

$$z_{ijk} = \frac{pounds_{ijk} - \overline{pounds}_{jk}}{\sigma_{jk}}, \text{ j = citrus, non-citrus,} \tag{15}$$

where $pounds_{ijk}$ is the number of pounds of active ingredient k applied in grower i's tract on crop category j, $\overline{pounds}_{jk}$ is the pounds of k applied on j averaged over all respondents' tracts, and σ_{jk} is the standard deviation of the tract-level pounds of k applied on j.

To create each index, we sum the z-scores across the corresponding index pesticides for crop category j, resulting in the following three pairs of variables for respondent i:

$$AM_{ij} = \sum_{k=1}^{3} z_{ijk}, \quad RS_{ij} = \sum_{k=1}^{4} z_{ijk}, \quad \text{and} \quad RSAM_{ij} = \sum_{k=1}^{3} z_{ijk}, j = c, nc. \tag{16}$$

Finally, we correct the indices for skewness by taking the log of the index minus the skewness correction factor, resulting in the variables lAM_{ij}, $lRSAM_{ij}$, and lRS_{ij} in equations (2), (6), (7), and (11).

The UC IPM degree-day calculators are used to construct controls for pest pressure and natural *A. melinus* presence (University of California Integrated Pest Management, 2007). We consider degree-days from February 25 to October 26, the dates used by the University of California for CRS monitoring purposes. For each species, we calculate the number of degree-days in the range suitable for its population development and divide by the number of degree-days per generation to obtain the number of generations in the growing season (University of California Integrated Pest Management, 2003b; University of California Kearney Agricultural Center Citrus Entomology, 2012). We use degree-day data from the closest station for each survey respondent. Table 2 includes summary statistics for the generations variables, weighted by each station's frequency among respondents.[7]

Our next set of data regards CRS chemical control options. UC IPM ranks pest control methods by their compatibility with an IPM program. We create a variable of IPM compatibility that corresponds to the ranking for each control option, assigning a value of one to the least compatible option. For respondents who used multiple controls, we assign the lowest ranking. The insect growth regulators buprofezin and pyriproxyfen are assigned the same index. (Only two respondents applied buprofezin.) The organophosphates methidathion, carbaryl, and chlorpyrifos are assigned the same index. (No respondents applied carbaryl and only one applied methidathion.) Just under half of all growers who control for CRS rely on *A. melinus*, either through releases or naturally occurring populations.

Finally, we generate an exogenous expected value per citrus acre variable for all respondents. For each respondent we construct an expected revenue per citrus acre weighted by his crop composition based on county-level prices. (If a respondent reported acreage in a citrus crop for which no county value per acre was reported, we use the mean value for that crop across all reporting counties.) This variable is preferred to respondents' reported prices because the prices growers receive depend on fruit quality, which is a function of pest control decisions.

Results

Table 3 reports the estimated coefficients for equations (2) and (3). We reject the null hypothesis that the selection equation is independent from the presence model, so we control for sample selection. Increasing non-citrus tract-level use of pesticides that are toxic to *A. melinus* and used to treat CRS decreases the probability that grower *i* reports *A. melinus* present. Most citrus growers wait until May to apply these pesticides, while non-citrus growers use them throughout the winter and spring. This earlier use may stunt the growth of *A. melinus* populations more than applications made in May. The marginal effect, however, is quite small. A one z-score unit increase in $RSAM_{nc}$ decreases the probability that respondent i reports *A. melinus* present by only 0.05%. Table 4 shows the estimated coefficients for equation (6). Consistent with the previous results, $RSAM_{nc}$ has a statistically significant, positive effect on the probability that respondent *i* applies a pesticide to control CRS. The marginal effect here is larger than in table 3. A one z-score unit increase in $RSAM_{nc}$ increases the probability of applying a pesticide by 17.5%. The difference in marginal effects is consistent with anecdotal evidence regarding the effects of landscape-level pesticide use. It suggests that the use of these pesticides lowers *A. melinus* populations below levels at which they can provide effective control, but often does not eliminate them.

Citrus tract-level use of pesticides that are toxic to *A. melinus* and used to treat CRS also increases the probability that grower *i* applies a chemical control for CRS. A one z-score unit increase in $RSAM_c$ increases the probability of applying a pesticide by 30%, almost twice the

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[7] 42% of respondents are located in municipalities with a weather station. All respondents are located 30 miles or less from a station. While the use of somewhat distant stations may result in measurement error, the statistical significance of the variables in our results suggests that it is small. Large measurement error would bias the coefficients towards zero. Additionally, the use of imputed generations variables for respondents in municipalities without a weather station does not alter the results pertaining to the pesticide use variables, suggesting any bias is minimal.

Table 2. Summary Statistics by Model

	Probability of *A. melinus* Presence (N=130, 74)[a]		Probability of Pesticide Application (N=140)		IPM Compatibility (N=123, 90)[b]	
Variables	**Mean**	**St. Dev.**	**Mean**	**St. Dev.**	**Mean**	**St. Dev.**
Dependent Variables						
Knows Whether *A. melinus* is Present[c]	0.57	0.04				
Reports *A. melinus* Present[c]	0.57	0.06				
Applies Chemical Control for Red Scale			0.42	0.04		
Uses any control for Red Scale					0.73	0.04
IPM Compatibility Level						
5 *A. melinus* Only					0.49	0.05
4 Oil					0.06	0.02
3 Buprofezin or Pyriproxyfen (IGRs)					0.17	0.03
2 Spirotetramat					0.13	0.03
1 Chlorpyrifos, Carbaryl, or Methidathion (OPs)					0.16	0.03
Index of Tract-level Use of Pesticides Toxic to:						
A. melinus on Citrus	−0.90	2.68	−1.13	2.59	−1.15	2.68
A. melinus on Non-Citrus	−0.29	1.47	−0.27	1.15	−0.33	1.53
A. melinus and Red Scale on Citrus	0.45	1.27	0.38	1.22	0.41	1.25
A. melinus and Red Scale on Non-Citrus	0.31	1.11	0.35	1.11	0.51	1.13
Red Scale on Citrus			1.31	0.74	1.33	0.76
Red Scale on Non-Citrus			0.52	1.00	0.58	1.01
Red Scale Generations during Season	3.45	0.70	3.56	0.67	3.58	0.68
A. melinus Generations during Season	10.68	1.64	10.89	1.52	10.95	1.53
Combined Pest Pressure					3.03	0.92
Farm Characteristics						
Majority of Citrus Acres in:						
Oranges			0.66	0.04		
Lemons			0.14	0.03		
Grapefruits			0.06	0.02		
Mandarins			0.06	0.02		
Other			0.04	0.02		
Lemons and/or Grapefruits	0.18	0.05			0.21	0.41
Total Citrus Acres	135.24	234.01	167.22	556.65	199.43	640.34
Total Acres	211.20	657.36	319.47	1,134.12	388.45	1,312.30
Organic	0.09	0.03	0.08	0.02	0.07	0.03
Production Characteristics						
% of Output Sold to Packinghouse			80.55	37.76	86.64	31.52
% of Output Sold to Processor			2.91	15.51	1.44	10.35
% of Output Sold to Other			15.74	34.39	11.84	29.95
Reliance on Aphytis melinus			0.48	0.04		
Expected Value/Acre			6,329.95	2,806.36	6,475.73	2,822.45
Grower Characteristics						
College Degree			0.64	0.04	0.63	0.05
Experience			28.85	15.59	28.67	15.60
Female D.V.			0.14	0.03	0.15	0.04
White			0.89	0.03	0.90	0.03
Asian			0.06	0.02	0.04	0.02
Hispanic			0.04	0.02	0.03	0.02
Other			0.03	0.01	0.03	0.02

Notes: No statistics indicate that the variable is not included in the model.

[a] n = 130 for the selection equation. n = 74 for the presence equation.

[b] n = 123 for the selection equation. n = 90 for the presence equation.

[c] 57% of all respondents with red scale present (74 of 130) knew whether or not *A. melinus* was naturally occurring on their fields. Coincidentally, 57% of those with this knowledge (42 of 74) reported that *A. melinus* was naturally occurring.

Table 3. Presence of *Aphytis melinus* Probit Model with Heckman Selection, Marginal Effects Reported for Mean Values of the Independent Variables

	Presence of *A. melinus*				Selection Model			
Variables/Statistics	**Coeff.**	**Robust Std. Error**	**Marginal Effect (%)**	**Robust Std. Error**	**Coeff.**	**Robust Std. Error**	**Marginal Effect (%)**	**Robust Std. Error**
lAM_c	−0.11	(0.26)	−0.02	(0.05)				
AM_c^a			−0.01					
lRSAMc	0.78	(0.63)	0.12	(0.16)				
RSAM_c^a			0.04					
lAM_{nc}	−0.08	(0.14)	−0.01	(0.02)				
AM_{nc}^a			−0.01					
lRSAM_{nc}	−0.86**	(0.39)	−0.14	(0.16)				
RSAM_{nc}^a			−0.05					
CRS Generations	−41.93*	(25.40)	−6.68	(9.02)				
CRS Generations^2	5.41	(3.30)	0.86	(1.17)				
AM Generations	17.33	(12.85)	2.76	(3.90)				
AM Generations^2	−0.69	(0.55)	−0.11	(0.16)				
Majority Lemons and/or Grapefruit	0.85**	(0.40)	0.14	(0.16)				
Total Citrus Acres/100	−0.93	(1.07)	−0.15	(0.14)	0.43*	(0.24)	14.26*	(7.78)
(Total Citrus Acres/100)^2	0.20	(0.15)	0.03**	(0.02)	−0.03	(0.02)	−0.89*	(0.53)
Total Acres/100	1.35	(1.01)	0.21	(0.18)	−0.14	(0.14)	−4.65	(4.45)
(Total Acres/100)^2	−0.24*	(0.14)	−0.04	(0.02)	$1.9E-04$	$(2.1E-03)$	0.06	(0.07)
Organic	0.15	(0.46)	0.02	(0.08)	−0.06	(0.23)	−1.94	(7.52)
Cover Crop	1.11*	(0.61)	0.18	(0.23)				
Coastal Region	0.34	(0.82)	0.05	(0.15)	−31.12	(20.61)	−10.35	(6.72)
College Degree					92.07***	(18.13)	30.62***	(5.16)
Experience					−0.15	(2.50)	−0.05	(0.83)
Experience^2					0.01	(0.04)	$3.90E-05$	(0.01)
Constant	−27.3	(27.24)			−46.33	(29.03)		
Uncensored N	74				130			
Rho	−1.00	(0.00)						
Chi^2(1):	8.38***							

Notes: Single, double, and triple asterisks (*, **, ***) represent significance at the 10%, 5%, and 1% level.

[a] The model was estimated with the indices corrected for skewness. We calculate and report the marginal effects for the untransformed variables because the marginal effects for the transformed indices are not easily interpreted.

Table 4. Pesticide Application Probit Model with Marginal Effects Reported for Mean Values of the Independent Variables

	Unrestricted Model				Restricted Model[a]			
Variables/Statistics	Coeff.	Robust Std. Error	Marginal Effect (%)	Robust Std. Error	Coeff.	Robust Std. Error	Marginal Effect (%)	Robust Std. Error
lAM_c	−0.65**	(0.31)	−25.78**	(12.33)	−0.17	(0.15)	−6.47	(7.20)
AM_c^b			−22.94				−2.45	
lRSAM_c	2.27**	(0.82)	89.65**	(32.94)	1.10**	(0.35)	42.60	(29.90)
RSAM_c^b			30.12				7.46	
lRS_c	−1.57	(0.99)	−61.90	(39.55)	−0.42	(0.37)	−16.12	(17.30)
RS_c^b			−10.60				−1.79	
lAM_{nc}	−0.03	(0.26)	−1.33	(10.16)	−0.17	(0.15)	−6.47	(7.20)
AM_{nc}^b			−0.88				−2.45	
lRSAM_{nc}	1.21**	(0.54)	47.87**	(22.26)	1.10**	(0.35)	42.60	(29.90)
RSAM_{nc}^b			17.53				7.46	
lRS_{nc}	0.10	(0.45)	3.87	(17.66)	−0.42	(0.37)	−16.12	(17.30)
RS_{nc}^b			1.22				−1.79	
CRS Gen.	519.85**	(200.36)	20,539.22**	(8,349.98)	298.89	(395.60)	11,532.81	(17,627.55)
CRS Gen. ^{2}	−144.17**	(53.82)	−5,696.13**	(2,247.73)	−83.68	(111.73)	−3,228.97	(4,969.94)
CRS Gen. ^{3}	13.24**	(4.80)	522.96**	(200.94)	7.75	(10.37)	299.00	
AM Gen.	−451.19**	(171.62)	−17,826.40**	(7,167.18)	−252.51	(275.70)	−9,743.21	(12,847.41)
AM Gen. ^{2}	40.99**	(15.37)	1,619.54**	(642.40)	23.03	(25.16)	888.63	(1,172.63)
AM Gen. ^{3}	−1.24**	(0.46)	−48.96**	(19.14)	−0.70	(0.76)	−26.96	(35.48)
Total Citrus Acres/10,000	22.21	(14.58)	877.56	(573.60)	12.91	(13.31)	498.14	(590.4)
(Total Citrus Acres/10,000) ^{2}	−0.26	(0.48)	−10.11	(18.60)	−0.11	(0.41)	−4.24	(16.10)
Total Acres/10,000	−0.42	(8.43)	−16.58	(333.10)	4.61	(7.92)	178.03	(325.5)
(Total Acres/10,000) ^{2}	0.10	(0.14)	4.06	(5.40)	−0.01	(0.12)	−0.44	(4.60)
Organic	−0.09	(0.54)	−3.64	(21.07)	−0.26	(0.55)	−9.69	(21.78)

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Table 4. – continued from previous page

Variables/Statistics	Unrestricted Model				Restricted Model[a]			
	Coeff.	**Robust Std. Error**	**Marginal Effect (%)**	**Robust Std. Error**	**Coeff.**	**Robust Std. Error**	**Marginal Effect (%)**	**Robust Std. Error**
Percent of Output Sold to:								
Processor	-0.04^{**}	(0.01)	-1.56^{**}	(0.51)	-0.03^{**}	(0.01)	-1.15	(0.84)
Non- Processor/Packer	-0.01^{**}	(0.01)	-0.55^{**}	(0.25)	-0.01^{*}	(0.01)	-0.44	(0.35)
Uses Wasp	-1.73^{***}	(0.38)	-60.58^{***}	(10.80)	-1.59^{***}	(0.37)	-55.26^{*}	(32.40)
Value/1,000 Acres	-0.07	(0.02)	-2.80	(6.00)	-0.03	(0.14)	-1.02	(5.00)
College Degree	0.28	(0.38)	10.90	(14.88)	0.11	(0.37)	4.29	(14.58)
Experience	-0.04	(0.04)	-1.46	(1.63)	-0.02	(0.04)	-0.70	(1.54)
Experience^2	$6.4E-04$	$(6.1E-04)$	0.03	(0.02)	$3.7E-04$	$(5.6E-04)$	0.01	(0.02)
Female	-0.57	(0.50)	-21.21	(17.14)	-0.59	(0.48)	-20.97	(27.01)
Asian	-0.16	(0.91)	-6.07	(35.03)	0.25	(1.03)	10.00	(40.68)
Hispanic	-2.05^{**}	(0.98)	-45.65^{**}	(15.56)	-1.69^{*}	(0.95)	-39.20	(26,197.49)
Other Ethnicity	-1.18	(0.94)	-35.79	(2,634.43)	-0.91	(0.89)	-28.17	(47.33)
Constant	1032.83^{**}	(392.11)			567.69	(543.56)		
County Dummy Variables	*Yes*				*Yes*			
Crop Dummy Variables	*Yes*				*Yes*			
N	140				140			
pseudo R^2	0.48				0.46			
LR Test	$\gamma^{AMj} = \gamma^{RSAMj}$,	$j \in \{c,nc\}$	$\gamma^{RSAMj} = \gamma^{RSj}$,	$j \in \{c,nc\}$	$\gamma^{AMc} = \gamma^{AMnc}$,	$\gamma^{RSAMc} = \gamma^{RSAMnc}$,	$\gamma^{RSc} = \gamma^{RSnc}$	
Chi^2 (2)	10.99^{***}		6.67^{**}					
Chi^2 (3)					4.58			

Notes: Single, double, and triple asterisks (*,**,***) represent significance at the 10%, 5%, and 1% level. Robust standard errors reported in parentheses.

[a] The restricted model restricts the citrus and non-citrus tract-level coefficients to be the same.

[b] The model was estimated with the indices corrected for skewness. We calculate and report the marginal effects for the untransformed variables.

magnitude of the marginal effect of non-citrus tract-level use. This coefficient may include the effects of shared information sources or peer effects, leading to spatial correlation, or it could be that citrus pesticide use reduces *A. melinus* populations below levels at which is provides adequate control. If spatial correlation was the cause of this effect, we would expect the coefficient on lRS_c, citrus tract-level use of pesticides used to control CRS, to also be positive and significant, but it is not. It is negative and insignificant, suggesting that the coefficient on $RSAM_c$ is not simply due to spatial correlation.

The coefficient on AM_c is statistically significant and negative, contrary to expectations. The difference in sign is consistent with interactions between management decisions for two citrus pests. Acetamiprid is used to control citricola scale, an economically important citrus pest in the San Joaquin Valley (SJV). While it is less efficacious for CRS control than alternative pesticides, it is capable of suppressing CRS populations (Grafton-Cardwell et al., 2008; Rill, Grafton-Cardwell, and Morse, 2008). The coefficient on lAM_c may reflect this effect, suggesting a positive externality arising from citricola scale control that outweighs any direct negative externality due to the reduction in the wasp's population and associated CRS control.

As hypothesized, as the generations of CRS increase, the likelihood of a chemical application increases while as the generations of the wasp increase, it decreases. The statistical significance of the coefficients suggests that the model controls for pest pressure, so pesticide use coefficients do not just reflect spatial correlation in pest pressure.

Growers who reported using the wasp for CRS control are about 60% less likely to apply a pesticide than those who did not. This suggests that the wasp can substitute for chemical control if its population is sufficiently high. We examine the possibility that growers may make decisions regarding reliance on the wasp and pesticide applications simultaneously by estimating an instrumental variables model using dummy variables for educational attainment levels (variables which are insignificant determinants of the decision to use a chemical control, but are significant determinants of reliance on the wasp). We could not reject the null hypothesis of exogeneity (Appendix, table 2).

Testing restrictions (13) and (14) shows that grouping just by toxicity to *A. melinus* or toxicity to CRS would not represent the role of these characteristics in growers' decisions correctly. We were unable to reject restriction (12), which equates the effects of pesticide use on citrus and on non-citrus. Table 4 reports results when the effects of citrus and non-citrus tract-level use are constrained to be equal. The coefficient on $RSAM_{c+nc}$ is statistically significant at the 5% level. The marginal effect of a 1 z-score unit increase in $RSAM_{c+nc}$ on the probability of a pesticide application is 7.5%.

If the increase in the probability of applying a pesticide is due to shared information sources or peer effects, we expect to see this "culture of chemical control" represented in the level of IPM compatibility chosen. Growers located in areas with high usage of *RSAM* index pesticides should be more likely to choose these pesticides than growers in areas with less chemical control and less use of these pesticides. If we do not see this relationship, then the previous results are likely due to the effects of these pesticides on populations of *A. melinus*.

The estimation results support the latter explanation with respect to tract-level pesticide use on non-citrus crops. They provide some support for both explanations with respect to tract-level pesticide use on citrus (table 5). None of the non-citrus tract-level pesticide use coefficients are statistically significant, implying that the respondents are not simply using methods similar to their non-citrus neighbors. This is consistent with the explanation that the earlier results regarding the effects of $RSAM_{nc}$ on the presence of *A. melinus* and CRS treatment decisions are likely due to the effects of these pesticides on *A. melinus*.

The coefficient on $lRSAM_c$ is statistically significant and negative. A 1 z-score unit increase in $RSAM_c$ decreases the probability that the respondent relies on the wasp by 40.7% and increases the probability of applying an organophosphate (in *RSAM*) or spirotetramat (in *RS*) by 8.4% and 17.6%, respectively. Simple spatial correlation in pest management decisions would

Table 5. IPM Compatibility Level Ordered Probit Model and Marginal Effects

	Choice of Control Method						Selection Equation	
	Coeff.	Marginal Effects (%)					Coeff.	Marginal Effect (%)
Variables/Statistics		OPs	Spiro.	IGRs	Oil	*A.m.* Only		
lAM$_c^a$	0.52*	−4.27	−8.95	−7.23	−0.20	20.65*	0.04	$9.8E-04$
	(0.31)	(2.84)	(5.52)	(5.50)	(0.87)	(12.31)	(0.31)	$(9.0E-05)$
AM$_c^a$		−2.32	−4.87	−3.93	−0.11	11.23		$5.4E-04$
lRSAM$_c$	−2.02**	16.65**	34.85**	28.15	0.79	−80.44**	0.17	$4.5E-03$
	(0.88)	(7.32)	(17.17)	(18.51)	(3.38)	(35.29)	(0.75)	(0.03)
RSAM$_c^a$		8.43	17.64	14.25	0.40	−40.72		$2.28E-03$
lRS$_c$	0.96	−7.90	−16.54	−13.35	−0.38	38.17	−2.50**	−0.07
	(1.01)	(6.69)	(17.89)	(16.51)	(1.69)	(40.12)	(1.26)	(0.24)
RS$_c^a$		−1.80	−3.76	−3.04	−0.09	8.69		−0.02
lAM$_{nc}$	0.27	−2.24	−4.68	−3.78	−0.11	10.81	−0.31	−0.01
	(0.24)	(2.04)	(4.27)	(3.85)	(0.46)	(9.64)	(0.25)	(0.03)
AM$_{nc}^a$		−2.96	−6.19	−5.00	−0.14	14.28		−0.01
lRSAM$_{nc}$	−0.64	5.27	11.04	8.91	0.25	−25.47	2.32***	0.06
	(0.48)	(4.76)	(8.99)	(7.17)	(1.03)	(19.18)	(0.68)	(0.22)
RSAM$_{nc}^a$		2.08	4.36	3.52	0.10	−10.06		0.02
lRS$_{nc}$	−0.12	0.96	2.00	1.62	0.05	−4.62	0.27	0.01
	(0.63)	(4.93)	(10.77)	(9.02)	(0.34)	(24.96)	(0.36)	(0.03)
RS$_{nc}^a$		0.38	0.79	0.64	0.02	−1.83		$4.0E-03$
CRS Generations	60.60**	−498.19**	−1,042.90*	−842.28	−23.75	2,407.12*	−13.21	−0.35
	(30.56)	(244.48)	(569.20)	(602.09)	(102.21)	(1,220.93)	(25.08)	(1.48)
CRS Generations^2	−8.22**	67.58**	141.48*	114.26	3.22	−326.54**	1.97	0.05
	(3.93)	(32.18)	(74.39)	(78.76)	(13.81)	(157.01)	(3.37)	(0.22)
AM Generations	−31.70*	260.58*	545.48*	440.55	12.42	−1,259.03*	6.97	0.18
	(16.73)	(132.77)	(310.50)	(322.39)	(53.53)	(667.99)	(14.58)	(0.81)

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Table 5. – continued from previous page

	Choice of Control Method						Selection Equation	
	Coeff.	Marginal Effects (%)					Coeff.	Marginal Effect (%)
Variables/Statistics		OPs	Spiro.	IGRs	Oil	*A.m.* Only		
AM Generations^2	1.46^{**}	-12.03^{**}	-25.17^{*}	-20.33	-0.57	58.10^{*}	-0.35	-0.01
	(0.74)	(5.95)	(13.85)	(14.40)	(2.46)	(29.39)	(0.66)	(0.04)
Combined Pest Pressure	-0.30	2.48	5.20	4.20	0.12	-12.00		
	(0.19)	(2.09)	(3.67)	(2.88)	(0.48)	(7.63)		
Total Citrus Acres/100	0.35^{**}	-2.85	-5.96^{*}	-4.81^{*}	-0.14	13.75^{**}	1.69^{***}	0.04
	(0.17)	(2.08)	(3.17)	(2.82)	(0.55)	(6.65)	(0.38)	(0.16)
(Total Citrus Acres/100)^2	-0.01^{**}	0.09	0.19^{**}	0.15^{*}	$4.3E-03$	-0.43^{**}	-0.06^{***}	$-1.6E-03$
	$(4.4E-03)$	(0.06)	(0.09)	(0.08)	(0.02)	(0.17)	(0.02)	(0.01)
Total Acres/100	-0.35^{***}	2.86^{*}	5.98^{**}	4.83^{**}	0.14	-13.80^{***}	-0.68^{***}	-0.02
	(0.10)	(1.57)	(2.34)	(2.25)	(0.56)	(4.09)	(0.21)	(0.06)
(Total Acres/100)^2	$4.4E-03^{***}$	-0.04	-0.08^{**}	-0.06^{**}	$-1.7E-03$	0.18^{***}	0.03^{***}	$8.2E-04$
	$(1.5E-03)$	(0.02)	(0.03)	(0.03)	(0.01)	(0.06)	(0.01)	$(3.0E-03)$
Organic	2.73^{***}	-5.88^{*}	-17.17^{***}	-28.35^{***}	-9.82^{**}	61.22^{***}	-0.24	-0.01
	(0.79)	(2.99)	(5.27)	(6.35)	(4.45)	(6.74)	(0.55)	(0.05)
Percent of Output Sold to:								
Processor	0.01	-0.09	-0.19	-0.15	$-4.4E-03$	0.44	-0.01	$-3.1E-04$
	(0.02)	(0.12)	(0.27)	(0.24)	(0.02)	(0.63)	(0.01)	$(1.0E-03)$
Non-Processor/Packinghouse	0.01	-0.11	-0.22	-0.18	-0.01	0.51	-0.02^{***}	$-4.1E-04$
	(0.01)	(0.07)	(0.21)	(0.21)	(0.02)	(0.49)	(0.01)	$(2.0E-03)$
Value/1,000 Acres	-0.02	0.14	0.29	0.24	0.01	-0.67	-0.21	-0.01
	(0.08)	(0.68)	(1.39)	(1.12)	(0.04)	(3.22)	(0.16)	(0.02)
College Degree	0.24	-2.08	-4.13	-3.10	$-3.2E-03$	9.32	-0.10	$-2.6E-03$
	(0.38)	(3.80)	(6.99)	(4.54)	(0.42)	(14.81)	(0.50)	(0.01)

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Table 5. – continued from previous page

	Choice of Control Method						Selection Equation	
	Coeff.	**Marginal Effects (%)**					**Coeff.**	**Marginal Effect (%)**
Variables/Statistics		**OPs**	**Spiro.**	**IGRs**	**Oil**	***A.m.* Only**		
Experience	−0.02	0.14	0.29	0.24	0.01	−0.67	−0.01	$-2.6E-04$
	(0.04)	(0.34)	(0.64)	(0.51)	(0.03)	(1.49)	(0.04)	$(2.0E-03)$
Experience^2	$1.6E-04$	$-1.3E-03$	$-2.8E-03$	$-2.2E-03$	$-6.3E-05$	0.01	$1.6E-04$	$4.1E-06$
	$(5.7E-04)$	$(5.0E-03)$	(0.01)	(0.01)	$(3.1E-04)$	(0.02)	$(6.6E-04)$	$(3.2E-05)$
Female	1.14**	−5.03*	−13.85*	−18.22**	−4.04	41.14***	−0.48	−0.03
	(0.48)	(2.79)	(5.34)	(8.00)	(3.49)	(14.01)	(0.51)	(0.10)
Asian	−1.84**	46.09	17.86	−9.67	−7.92	−46.37***	−2.44**	−6.09
	(0.80)	(32.96)	(12.04)	(13.70)	(4.83)	(8.65)	(0.95)	(13.39)
Hispanic	0.08	−0.58	−1.27	−1.09	−0.06	3.01	−0.73	−0.08
	(0.99)	(7.12)	(16.31)	(14.90)	(1.11)	(39.42)	(0.79)	(0.32)
Other Ethnicity	1.05	−3.81*	−11.74**	−17.28*	−4.39	37.22**	−1.27	−0.45
	(0.65)	(2.24)	(4.95)	(10.17)	(4.40)	(17.42)	(1.11)	(1.85)
Inverse Mills Ratio	−1.73**	14.24**	29.82*	24.08	0.68	−68.82**		
	(0.78)	(6.77)	(14.92)	(15.95)	(2.88)	(31.02)		
County D.V.	*Yes*						*Yes*	
Crop D.V.	Majority Lemon or Grapefruit						D.V. for individual crops	
N	90						123	
pseudo R^2	0.32						0.4435	
LR Test	$\gamma^{AMj}=\gamma^{RSAMj}, \quad j\in\{c,nc\}$		$\gamma^{RSAMj}=\gamma^{RSj}, \quad j\in\{c,nc\}$		$\gamma^{AMc}=\gamma^{AMnc}$,	$\gamma^{RSAMc}=\gamma^{RSAMnc}$,	$\gamma^{RSc}=\gamma^{RSnc}$	
Chi^2 (2)	11.10***		5.93*					
Chi^2 (3)					8.19**			

Notes: Single, double, and triple asterisks (*, **, ***) represent significance at the 10%, 5%, and 1% level. Robust standard errors reported in parentheses.
[a] The model was estimated with the indices corrected for skewness. We calculate and report the marginal effects for the untransformed variables.

lead to a shift away from *A. melinus* towards *RSAM* pesticides. We observe a small shift towards *RSAM* pesticides, but a larger shift towards an *RS* pesticide. This suggests that landscape-level use of *RSAM* pesticides reduce control by *A. melinus*, necessitating a chemical application.

Pesticide Taxation and Regulation

Our findings have several important policy implications. First, the use of *RSAM* pesticides has negative consequences above the field level, suggesting some policy tool or tools should be applied to mitigate this externality. Richards et al. (2010) find that quantity-based regulation is the preferred policy tool for whitefly management in Arizona. A permit trading system could potentially work for beneficial insects that can easily be monitored. *A. melinus*, however, only reaches 2 mm in length, and growers tend to monitor evidence of parasitism instead of actual populations (Grafton-Cardwell et al., 2008). Consequently, a price-based system is likely the more feasible policy tool in this instance.

Currently, California levies a uniform mill tax on pesticides equal to 2.1 cents per dollar of sales (California Department of Pesticide Regulation, 2009). The current mill tax could be replaced or augmented by a tax that induces growers to internalize the externalities of their pesticide use. The ideal tax would account for all negative and positive externalities, including spatially and temporally dependent ones. Estimating such a tax is beyond the scope of our analysis. However, we can calculate a tax based on the negative externality of the use of *RSAM* pesticides. We focus on chlorpyrifos because it is commonly applied to both citrus and non-citrus, and the pounds per tract applied of chlorpyrifos are an order of magnitude greater than those for methidathion and carbaryl (California Department of Pesticide Regulation, 2010).

The per-acre cost of applying a chemical control for CRS is approximately $100 (Luck and Hoddle, 2010). We scale respondents' acreage with CRS reported present in each region to estimate total tract-level acreage with CRS present. We then calculate the expected total increase in chemical control costs that results from an additional pound of chlorpyrifos applied on citrus and non-citrus (table 6). This increase varies from $0.11/pound in the Coastal-Intermediate region for applications to non-citrus to $33.23/pound in the SJV for applications to citrus. SJV cost increases are large because the majority of citrus is grown in the SJV and CRS is most common in this region. Calculated on a state-wide basis, the tax would be $14.11/pound and $12.48/pound for citrus and non-citrus, respectively. Based on a price of $17.30/pound (Wright et al., 2009), the resulting effective ad valorem tax rate varies from 0.66% in the Coastal-Intermediate Region for non-citrus growers to 192.07% in SJV for citrus growers. Uniform statewide rates would be 81.59% for citrus growers and 72.13% for non-citrus growers. These calculations demonstrate a major problem with taxes based on this kind of spatial externality. A statewide tax greatly exceeds the value of marginal damages for three of the four growing regions. However, regionally differentiated rates would give SJV growers an incentive to purchase chlorpyrifos outside of the SJV to avoid the tax.

The existence of negative externalities has implications for the design of pesticide use regulations. Restrictions on the number of applications in a season and application rates and timing are often intended to reduce a specific negative externality: the rate of the development of resistance in the target pest species. The negative effects of pesticides applied to citrus and non-citrus crops on *A. melinus* populations and citrus growers' ability to use the wasp for CRS control suggest that policymakers should also consider this type of negative externality. In this specific case, social welfare could be improved, potentially, by restricting when pesticides with certain active ingredients could be applied in areas with substantial amounts of citrus production.

Table 6. Mean Respondent Acres with Red Scale per Tract, Estimated Acres with Red Scale per Tract, and the Ad Valorem Tax and Effective Tax Rate per Pound of Chlorpyrifos Applied on Citrus and Non-Citrus, by Region and Statewide

Region	Mean Respondent Acres with CRS/Tract	Mean Acres with CRS/Tract Scaled	Citrus		Non-Citrus	
			Tax per Pound	Ad Valorem Tax Rate	Tax per Pound	Ad Valorem Rate
Northern	30.86	266.01	$0.73	4.24%	$0.65	3.75%
Coastal-Intermediate	5.45	46.98	$0.13	0.75%	$0.11	0.66%
San Joaquin Valley	1,396.65	12,039.12	$33.23	192.07%	$28.38	169.80%
Interior	180.57	1,556.51	$4.30	24.83%	$3.80	21.95%
State	593.27	5,113.99	$14.11	81.59%	$12.48	72.13%

Conclusions

This analysis detected the presence of negative externalities caused by the use by growers of both citrus and non-citrus crops of pesticides that are toxic to *A. melinus*, a natural enemy of CRS. An alternative explanation is that growers rely on forms of pest control similar to those used by nearby growers, creating spatial correlation. The latter explanation is eliminated for the case of respondents and nearby non-citrus producers by the lack of any effect of non-citrus tract-level pesticide use on respondents' IPM compatibility choices. The empirical results provide support for the contemporaneous existence of both explanations for the case of respondents and nearby citrus users. To the best of our knowledge, this is the first article to identify this type of negative externality of pest management decisions.

With respect to farm size and crop composition, the respondents are fairly representative of California citrus growers. However, respondents may differ from the representative citrus grower in other ways that are impossible to test. Representativeness in terms of beneficial insect use is most important for our research questions. Growers who rely on beneficial insects may be overrepresented if the survey's content was more appealing to them than to other growers. If this is the case, our results may detect larger effects than exist for the representative citrus grower.

A pesticide tax is one logical method to reduce the negative externality of broad-spectrum pesticide use. However, spatial variation in the damages that result from such use create spatial variation in an optimal tax. Implementation of such a tax would be challenging because arbitrage opportunities would exist.

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Appendix: Calculating the Tax per Pound of Chlorpyrifos

Computing the appropriate tax per pound of active ingredient involves two basic steps: calculating the marginal effect per pound of active ingredient and calculating affected citrus acreage and the resulting negative externality, which equals the tax.

Calculate Marginal Effect per Pound of Chlorpyrifos (Active Ingredient)

In equation (15), we defined the z-score for each pesticide k as $z_{ijk} = \frac{pounds_{ijk} - \overline{pounds}_{jk}}{\sigma_{jk}}$. A one-pound increase in chlorpyrifos from the mean value of pounds per acre on non-citrus is:

$$\text{(A.A1)} \qquad \frac{6913.77 - 6912.77}{7199.60} = 0.000139 \quad \text{z - score units.}$$

A one-pound increase in chlorpyrifos from the mean value of pounds per acre on citrus is:

$$\text{(A.A2)} \qquad \frac{10556.30 - 10555.30}{10916.97} = 0.0000916 \quad \text{z - score units.}$$

The marginal effect of one pound of chlorpyrifos is:

$$\text{(A.A3)} \qquad \frac{\text{Marginal Effect}}{\text{z - score unit}} \times \frac{\text{z - score units}}{\text{pound}}.$$

For non-citrus, this is:

$$\text{(A.A4)} \qquad 0.1753 \times 0.0001389 = 0.0000244.$$

A one-pound increase in chlorpyrifos applied within a grower's tract on non-citrus acreage increases the probability that the grower applies a pesticide to control red scale by 0.00244%.

For citrus, the marginal effect of one pound of chlorpyrifos is:

$$\text{(A.A5)} \qquad 0.3012 \times 0.00009160 = 0.0000276.$$

A one-pound increase in chlorpyrifos applied within a grower's tract on citrus acreage increases the probability that the grower applies a pesticide to control red scale by 0.00276%.

The private per acre cost of red scale control is \$100 (Luck and Hoddle, 2010). The external cost per pound applied per acre of citrus affected is then \$100 x 0.0000276 = \$0.00276 when chlorpyrifos is applied on citrus, and the external cost per pound applied per acre of citrus affected is \$100 x 0.0000244 = \$0.00244 when chlorpyrifos is applied on non-citrus.

Calculate Measures of Affected Acreage and Compute Tax

The external cost above is the external cost per acre of citrus affected by chlorpyrifos application. To calculate the total acreage affected by an application, we sum the acres of citrus in each tract for which respondents reported having red scale present. This method assumes that the effects of an increase in use are distributed evenly through the tract, regardless of where the application occurs. This might be a strong assumption, but this is the level at which we have marginal effects. We then calculate the mean acres affected by growing region and for the state as a whole. The total effect per pound of an application is then the marginal effect per pound per acre times the number of acres affected. Since respondents represent 11.6% of citrus acres, we scale external effects by 8.62. The per-pound tax is the total damages per pound of chlorpyrifos applied.

Lorsban 4E, the most commonly used chlorpyrifos product, is formulated as four pounds chlorpyrifos per gallon or one pound per quart. At a price of \$8.65 per pint (Wright et al. 2009) for Lorsban 4E, the cost per pound of chlorpyrifos is \$17.30. We then use this price to calculate the effective ad valorem tax rate implied by the per pound tax.

Table A1. Moran's I and Geary's C Tests for Spatial Dependence for Outcome Variables

	I or C	Expected I or C	Standard Deviation	Z-Score
A. melinus Presence				
Moran's I	−0.014	−0.008	0.058	−0.105
Geary's C	1.018	1.000	0.060	0.298
Pesticide Application				
Moran's I	0.038	−0.008	0.056	0.829
Geary's C	0.955	1.000	0.056	−0.811
IPM Compatibility				
Moran's I	0.038	−0.011	0.070	0.702
Geary's C	0.960	1.000	0.072	−0.558

Table A2. Testing for Exogeneity of *UseWasp*. Instrumental Variables Probit for Probability of a Pesticide Application

	Pesticide Application	Instrumental Variables Equation (Uses Wasp)
	Coefficient	Coefficient
lAM_c	-0.59^{**}	$5.0E-03$
	(0.23)	(0.07)
lRSAM_c	2.19^{**}	−0.18
	(0.76)	(0.15)
lRS_c	-1.49^{*}	0.16
	(0.90)	(0.22)
lAM_{nc}	0.02	−0.02
	(0.23)	(0.06)
lRSAM_{nc}	0.78	0.14
	(0.76)	(0.11)
lRS_{nc}	$-3.9E-03$	0.08
	(0.39)	(0.12)
CRS Generations	446.23^{*}	−6.60
	(231.39)	(30.02)
CRS Generations^2	-125.55^{**}	3.03
	(61.26)	(7.76)
CRS Generations^3	11.65^{**}	−0.36
	(5.40)	(0.67)
AM Generations	-394.40^{**}	10.53
	(193.86)	(23.72)
AM Generations^2	36.17^{**}	−1.18
	(17.15)	(2.10)
AM Generations^3	-1.10^{**}	0.04
	(0.56)	(0.06)
Total Citrus Acres (100 acres)	0.11	0.05
	(0.20)	(0.04)
Total Citrus Acres^2	$-1.4E-03$	$-5.6E-04$
	($4.5E-03$)	($8.4E-04$)
Total Acres (100 acres)	0.03	−0.02

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Table A2. – continued from previous page

	Pesticide Application Coefficient	Instrumental Variables Equation (Uses Wasp) Coefficient
	(0.08)	(0.02)
Total Acres^2	$5.5E-04$	$2.3E-04$
	$(1.2E-03)$	$(2.5E-4)$
Organic	-0.27	0.13
	(0.53)	(0.16)
Percent of Output Sold to:		
Processor	-0.03	$-3.9E-03$
	(0.02)	$(3.2E-03)$
Non-Processor/Packer	-0.01^{*}	$7.3E-05$
	$(6.0E-04)$	$(1.2E-03)$
Uses Wasp	-0.04	
	(1.80)	
Value/Acre	$-5.2E-05$	$-4.4E-06$
	$(1.4E-04)$	$(3.1E-05)$
High School		-0.12
		(0.15)
Some College	-0.20^{**}	
		(0.10)
Some Graduate Education	0.15	
		(0.17)
Graduate Degree	-0.08	
		(0.11)
Experience	-0.06	0.02^{**}
	(0.04)	(0.01)
Experience^2	$9.1E-04$	$-2.8E-04^{**}$
	$(5.9E-04)$	$(1.4E-04)$
Female	-0.33	-0.08
	(0.59)	(0.11)
Asian	0.94	-0.78^{***}
	(1.26)	(0.17)
Hispanic	-1.72	-0.03
	(1.18)	(0.27)
Other Ethnicity	-0.79	-0.11
	(0.91)	(0.16)
Constant	905.85^{**}	-26.37
	(441.36)	(50.99)
County Dummy Variables	*Yes*	*Yes*
Crop Dummy Variables	*Yes*	*Yes*
N	140	140
Wald Test of Exogeneity		
Chi^2(1)	0.76	