The Environmental Impacts of Pesticide Use in Conventional and Organic Agriculture: Evidence from California

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Abstract

Organic farming is an icon of sustainable agriculture. Using the California Pesticide Use Report (PUR) database and a fixed effects model, I examine the environmental impacts of pesticide use in fields treated with conventional and organic pesticide programs. I find that pesticides used in organic production reduced the negative environmental impacts to surface water, groundwater, soil, air, and pollinators compared to pesticides used in conventional production. However, the difference in the environmental impacts of pesticide use between the two production systems has declined in multiple dimensions. The environmental benefit of adopting organic production systems may be less than is commonly perceived. Two additional regression results regard farm acreage and farming experience, and environmental impacts of pesticide programs. Farmers with more acreage are associated with the use of pesticides that have larger environmental impacts. More experienced farmers are associated with the use of pesticides that have more impact to surface water and groundwater, and less impact to soil, air, and pollinators. Pesticide use and environmental impacts in conventional agriculture remained stable in our study period regardless of changes in regulations and the use for active ingredients such as organophosphates, pyrethroid, and methyl bromide.

Key Words: organic agriculture, environmental impacts, fixed effect model, pesticide use

1 Introduction

The food system has faced concerns about its environmental impacts at least since Rachel Carson published *Silent Spring* (Carson, 1962). Today, concerns about its environmental impacts, especially from pesticide applications, continue to grow (Tang et al., 2018; Chen et al., 2018). In this context, organic agriculture is proposed as an alternative farming system as it prohibits the use of synthetic substances. (Reganold and Wachter, 2016, Muller et al., 2017). In Muller et al. (2017), simulation results support organic agriculture as an alternative production system capable of feeding the world population by 2050. The perception that organic agriculture is more environmentally friendly has facilitated its growth (Batte et al., 2007). According to the Organic Trade Association, U.S. organic food sales reached $39 billion in 2015 in real terms, up from $4 billion in 1997, the base year (OTA, 2016). The share of organic food sales to total food sales increased from less than 1% to 5% during the same time period.

In 2002, the National Organic Program (NOP) was launched. It established national standards for organic certification and took enforcement actions if there are violations of the standards. Organic growers must use numerous production practices that could reduce the negative environmental impacts relative to practices used solely in conventional production. However, the regulation of organic agriculture is process-based, not outcome-based, and does not monitor or enforce standards on environmental outcomes such as biodiversity and soil fertility (Seufert, Ramankutty, and Mayerhofer, 2017). Therefore, unintended consequences might emerge and organic agriculture could be less environmentally friendly than commonly perceived.

There is some evidence of this in the scientific literature. Organic agriculture has been reported to have higher nitrogen leaching and larger nitrous oxide emissions per unit of output (Tuomisto et al., 2012). Certain pesticide active ingredients (AIs) used in organic agriculture have been found to be more toxic than conventional AIs in laboratory environments and field experiments (Biondi et al., 2012; Bahlai et al., 2010). Racke (2007) reviewed the discovery and development of spinosad and observed that spinosad was approved based on its low mammalian toxicity. However, Biondi et al. (2012) found that spinosad is more harmful to natural predators than common pesticides used in conventional agriculture. As the case of spinosad demonstrates, pesticide use in organic agriculture could pose more environmental impact in one or more dimensions than conventional agriculture. Therefore more empirical evidence is needed to evaluate the environmental impact of organic farming practices and its determinants.

In this paper, I provide novel evidence regarding the impact of pesticide use in organic and conventional agriculture on different dimensions of environmental quality and quantify the difference between the environmental impacts of pesticide use in the two production systems in the context of California. In addition, I examine the relationships between farmers' pesticide use decisions and their farming experience and farm size.

California is the leading state for organic agriculture in the U.S., accounting for 12% of certified organic cropland and 51% of certified organic crop value nationally in 2016 (NASS, 2016). The number of certified operations and cropland acreage in California doubled between 2002 and 2016. State organic crop sales increased almost tenfold, in nominal term, during the same time period (Klonsky and Richter, 2005; Klonsky and Richter, 2011; Klonsky and Healy, 2013; Wei et al., 2020a).

This study uses field-level pesticide application records and a fixed effect model to analyze changes in the environmental impacts of pesticide use for both organic and conventional fields over 21 years. The database covers all registered agricultural pesticide applications in California and contains over 48 million pesticide application records for over 64,000 growers and 781,000 fields from 1995 to 2015. In total, more than 55,000 organic fields and 11,000 growers who operated organic fields are analyzed in this study.

The results show that the environmental impact of pesticide use is lower in organic fields across all dimensions of environment: surface water, groundwater, soil, air, and pollinators. The difference in the impact on air is the smallest because natural pesticides are not systematically different from synthetic pesticides in terms of volatile organic compound (VOC) emissions. Farm acreage is positively correlated with all environmental dimensions. The farmer's years of experience is positively correlated with impacts to surface water and groundwater, and negatively correlated with impacts to soil, air, and pollinators but the impacts are smaller than the effect of whether the field is organic or not by orders of magnitude. Environmental impacts and the difference between organic and conventional production vary by crop. Four major California crops, lettuce, strawberries, processing tomatoes, and wine grapes, are examined in detail.

The contribution of this paper is threefold. First, it links the environmental impacts of organic crop production directly to pesticide applications. To the best of my knowledge, no other studies have examined this relationship. Previous literature provided abundant evidence on the environmental impact of organic agriculture as a system but failed to quantify the impact of specific farming practices (Gomiero, Pimentel, and Paoletti, 2011; Hartmann et al., 2015; Pimentel et al., 2005; Tuomisto et al., 2012). Here, AIs and their contributions to environmental impacts are identified individually, which enhances our understanding of the differences in pesticide use between organic and conventional agriculture and how they vary across crops.

Second, this paper uses the Pesticide Use Risk Evaluation (PURE) model to assess the environmental impacts of pesticide use (Zhan and Zhang, 2012). Compared to the risk quotient approach, which is another common method in the literature (Nelson and Bullock, 2003; Kovach et al., 1992), the PURE model provides a more accurate measure of environmental impacts by incorporating additional environmental information, such as the distance from the pesticide application to the nearest surface water. The PURE model calculates risk scores for five environmental dimensions: surface water, groundwater, soil, air, and pollinators.

Third, by using the Pesticide Use Report (PUR) database, this study's findings are based on the population of pesticide application data. Prior works include meta-analyses that cover numerous field experiments (Pimentel et al., 2005) or commercial operations (Tuomisto et al., 2012), which examined on a narrow crop or geographic area over a limited period of time. California's agriculture is characterized by many crops and a diverse climate and soil conditions. The complete coverage of PUR database eliminates any sample selection issue and lays a solid foundation for identification.

The rest of the paper is organized as follows: section 2 introduces the PUR database and PURE model and presents summary statistics of historical pesticide use, section 3 provides the identification strategy to tackle grower heterogeneity, section 4 presents industry-level and crop-specific estimation results, and section 5 concludes.

2 Data and Descriptive Statistics

Pesticide Use Reports (PUR), a public database created and maintained by the California Department of Pesticide Regulation, is the largest and most complete database on pesticide and herbicide use in the world. Growers in California have reported information about every pesticide application since 1990. In this study, pesticide uses prior to 1995 are not evaluated due to data quality issues identified previously (Wilhoit, Zhang, and Ross, 2001; Wei et al., 2020b). More than 3 million applications are reported annually. Reports include information on time, location, grower id, crop, pesticide product, AIs, quantity of product applied, treated acreage and other information, for every agricultural pesticide application. A "field" is defined as a combination of *grower_id* and *site_location_id*, which is a value assigned to each parcel by its grower.

To obtain the USDA organic certification, growers must meet requirements on several aspects of production: pesticide use, fertilizer use, seed treatment, etc. The requirement on pesticide use is burdensome because pesticides approved in organic agriculture are expensive and have less efficacy. Pesticide and fertilizer AIs used in organic agriculture undergo a sunset review by the National Organic Standards Board (NOSB) every five years and the main criteria is whether the ingredient is synthetic or not. It is not reasonable for growers to use those pesticides solely but not apply for the organic certification. Therefore, growers who comply with the NOP's requirement on pesticide use can be viewed as an equivalent to certified organic growers. In Wei et al. (2020b), authors located individual organic fields using this approach. Namely, any field without a prohibited pesticide applied for the past three years is considered organic. The paper compared organic crop acreage from PUR to other data sources and showed that using pesticide use records alone is capable to capture organic crop production.

Environmental conditions for each field and toxicity values for each chemical are used to calculate the value of the PURE risk score developed by Zhan and Zhang (2012). The PURE risk score has been used in previous studies to assess environmental impacts of pesticide use (Lybbert, Magnan, and Gubler, 2016; Wang, Singhasemanon, and Goh, 2016; Fermaud et al., 2016). The PURE risk score evaluates environmental impacts of pesticide use in five dimensions: surface water, groundwater, soil, air, and pollinators. For each dimension, the PURE risk score is calculated on a per acre basis and it varies from 0 to 100, where 0 indicates trivial impact and 100 represents the maximum impact. Excluding air, the PURE risk score is the ratio of the predicted environmental concentration (PEC) to toxicity to the end organisms. The PEC estimates the effect of the pesticide application on the concentration level for chemicals in the environmental sample. The toxicity values cover both acute measures, such as LD50, and long-term measures, such as No Observed Effect Concentration and acceptable daily intake for humans. End organisms are fish, algae, and Daphnias for surface water, humans for groundwater, earthworms for soil, and honeybees for pollinators. The PURE risk score for air is calculated based on potential VOC emissions, which is a common measure of airborne pollutants emitted from agriculture production (CEPA, 2019). The emission of VOCs is defined as the percentage of mass loss of the pesticide sample when heated. Unlike toxicity, VOC emissions do not have a strong link to whether the AIs are synthetic or natural. For example, the herbicide Roundup®, which contains glyphosate, has zero VOC emissions because there is no evaporation or sublimation. Meanwhile, dusting sulfur products, which are widely used in organic agriculture, also have zero VOC emissions.

2.1 Pesticides Used in Conventional and Organic Agriculture

Conventional and organic growers adopt different pest management practices. As specified by the NOP, organic growers use pesticides only when biological, cultural, and mechanical/physical practices are insufficient. Chemical options remain essential for organic pest management programs. Currently over 7,500 pesticide products are allowed for use in organic crop and livestock production, processing, and handling. All AIs approved in organic agriculture are reviewed every five years to confirm that they continue to meet all requirements.

In figure 1, the acreage treated with different types of pesticides is shown on the left y-axis for both conventional and organic fields. Treated acreage is divided evenly among types for AIs that belong to multiple pesticide types, such as sulfur, which is both a fungicide and an insecticide. The average number of pesticide applications per acre, which is defined as the total treated acreage divided by the total planted acreage, is plotted against the right y-axis in both panels. This is a common measure of pesticide uses that controls for differences in application rate among pesticide products (Kniss, 2017).

Planted acreage remained stable for conventional agriculture over our study period, so changes in the number of applications per acre were due to changes in treated acreage. Organic planted acreage grew dramatically, but treated acreage increased even more. The number of applications per organic acre rose from 2 to 7. Figure 1 provides a highly aggregated view of pesticide use as different pesticide products with different AIs and application rates are used in conventional and organic fields.

Examining the figure, insecticide is the most used pesticide type, accounting for 36% and 44% of total treated acreage in conventional and organic agriculture respectively in 2015. Herbicide is the second most used type of pesticide in conventional fields. In contrast, organic growers' use of herbicides is limited. Fungicide is another major pesticide type, and sulfur is the most used fungicide AI in both conventional and organic fields. Sulfur is an important plant nutrient, fungi-

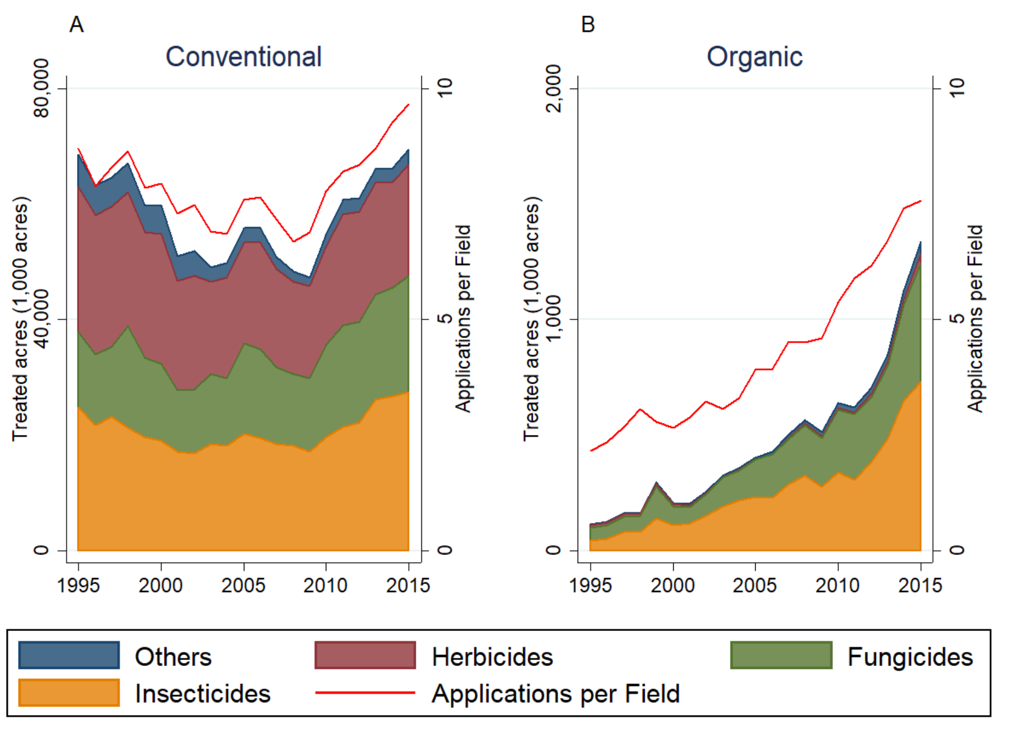

Figure 1: Acreage treated by major pesticide types and area treatment (A: conventional and B: organic): 1995 - 2015

cide, and acaricide in agriculture. The pesticide group "others" primarily includes plant growth regulators and pheromones.

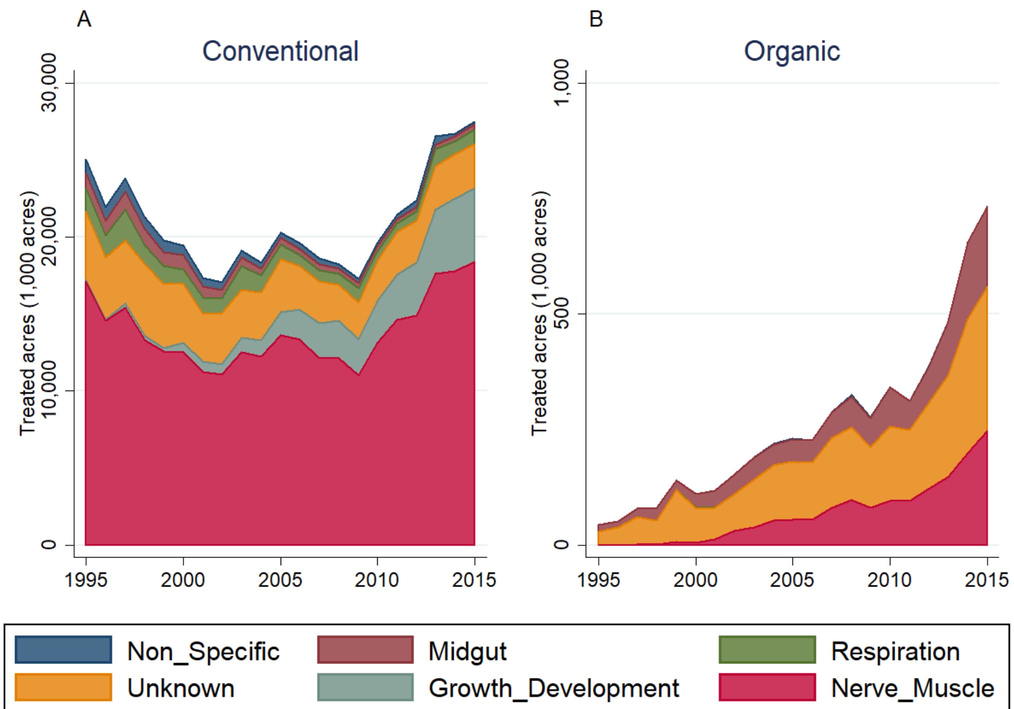

Figure 2: Acreage treated of insecticides by physiological targets (A: conventional and B: organic): 1995 - 2015

Disaggregating insecticide use provides more detailed insight into the nature of the difference between conventional and organic production. Figure 2 plots the insecticide-treated acreage by physiological functions affected (IRAC, 2020). Only three groups of insecticides are available to organic growers, while six are available to conventional growers. In conventional agriculture, 67% of treated acreage in 2015 was treated with insecticides that targeted nerve or muscle, which include organophosphates, pyrethroids, and neonicotinoids. For organic growers, two AIs, spinosad and pyrethrins, are available to target those physiological functions. The "unknown" category, which is mostly sulfur, accounted for a significant portion of treated acreage in organic agriculture. Insecticides that target the midgut, which includes *Bacillus thuringiensis* (Bt.) and several granulosis viruses, are widely applied in organic fields. Conventional growers rarely use them due to the high cost. In 2015, acreage treated with midgut targeted insecticides was 1% of total treated acreage in conventional agriculture and 24% in organic agriculture. A detailed discussion of insecticide and fungicide use by mode of action in conventional and organic production is in the appendix.

2.2 PURE Indices for Conventional and Organic Agriculture

Relatively few pesticide AIs are used in both conventional and organic agriculture. Insecticides and fungicides in the two pest management programs have different modes of action and pose different levels of environmental impact. Simply comparing treated acreage or the amount of pesticide products used does not identify the differences in environmental impacts. In this context, the PURE risk score serves as a consistent measure across farming systems.

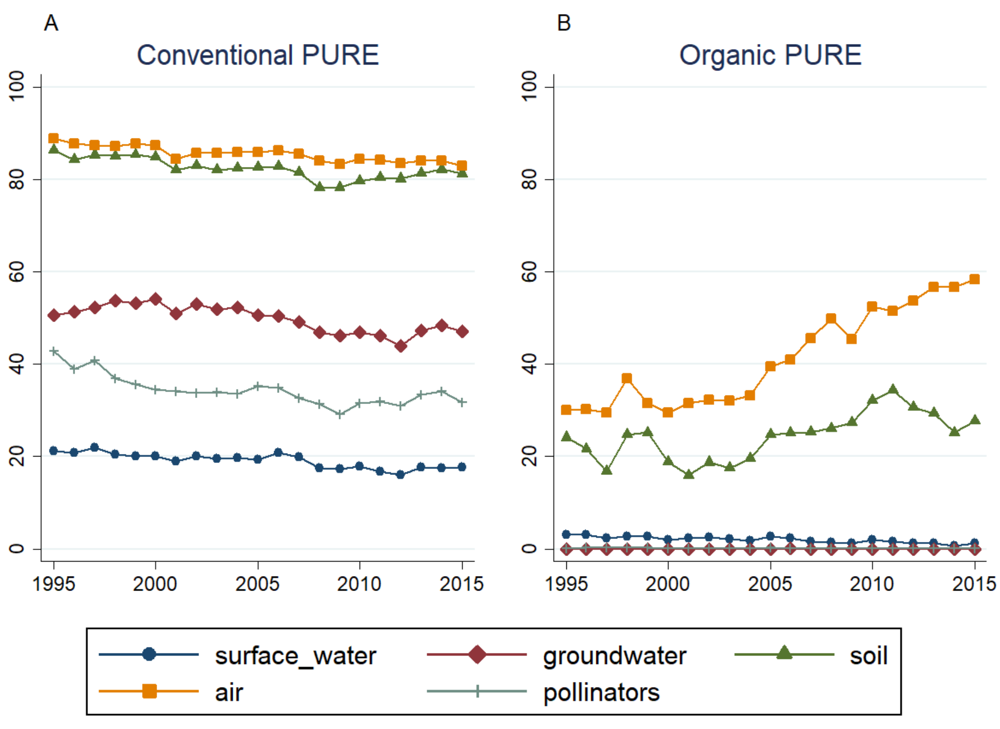

Figure 3: PURE risk score for conventional (A) and organic (B) fields

Figure 3 plots PURE risk scores for conventional and organic fields by year. Scores for air and soil are significantly higher than those for the other environmental dimensions in both farming systems, which means that pesticide use in general has greater impacts on air and soil quality than groundwater, pollinators, and surface water. Risk scores of conventional fields (figure 3A) are relatively stable from 1995 to 2015, with no obvious overall changes for air or soil, the top two environmental dimensions, despite the many changes that have occurred during this 20-year period in regulations and grower portfolios. While PURE risk scores decreased 16% for surface water, 26% for pollinators, and 7% for groundwater over the same time period, these three were much less impacted by pesticides in 1995, the beginning of the study period. Despite the numerous regulatory actions designed to reduce environmental impacts over this 20-year period, such as the methyl bromide phase-out, large-scale substitution of pyrethroids for organophosphates, and regulations to reduce VOC emissions from nonfumigant products, the overall environmental impacts of conventional pesticide use show only limited reductions when aggregated across all crops.

PURE risk scores for organic fields (figure 3B) are similar to conventional fields in that the air and soil have significantly higher scores than the others. However, the aggregate risk scores in all five dimensions are much lower in organic fields. Compared to conventional agriculture, organic agriculture has dramatically lower PURE risk scores for surface water (90%), groundwater (99%), air (51%), soil (70%), and pollinators (99%). The reduction for air varies greatly across major California crops. Large reductions in the PURE risk score for air are observed for table grapes (64%), wine grapes (63%), and processing tomatoes (63%), while others had relatively small ones such as leaf lettuce (19%) and almonds (28%). The reduction in the PURE risk score for soil varies across crops as well, ranging from leaf lettuce (86%) to carrots (33%). For surface water, groundwater, and pollinators, the differences between the PURE risk score in organic and conventional fields are similar across crops. A noticeable spike in PURE risk scores appeared in 1998 for organic agriculture caused by a single application of copper sulfate with an application rate of 150 lb/acre, which is ten times larger than the average application rate and clearly a data abnormality.

Each crop is susceptible to a different spectrum of pests, which are managed by a distinct pesticide portfolio as part of a broader pest management program. Comparing PURE risk scores for individual crops shows the benefit of pesticide use in organic agriculture varies significantly. Based on value, production region, and the acreage share of organic production, four crops are selected to illustrate this point: lettuce, strawberries, wine grapes, and processing tomatoes. Lettuce, strawberries, and wine grapes are the top three highest-valued organic crops in California, with organic sales values of $241, $231, and $114 million in 2016 respectively (NASS, 2016). Production of strawberries and lettuce is concentrated in the Central Coast region. Processing tomatoes are an important crop in the Central Valley. Wine grape production occurs in a number of regions across the state. Based on the PUR database, 40% of the state's total lettuce acreage was organic. Organic strawberries accounted for 12% of the state's total strawberry acreage. The organic acreage shares for wine grapes and processing tomatoes were below 5%.

Table 1: Field-Year Summary Statistics for Selected Crops

Production System	Variable	All crops	Lettuce	Strawberries	Wine Grapes	Processing Tomatoes
Conventional	Farm acreage (acre)	45:3$^+$	14:1$^+$	29:1$^+$	54:4$^+$	81:4$^+$
	Experience (year)	8:9$^+$	7:8$^+$	6:9$^+$	9:1	9:7$^+$
	PURE surface water	19:2$^+$	16:9$^+$	49:3$^+$	14:0$^+$	14:9$^+$
	PURE groundwater	47:2$^+$	44:8$^+$	32:0$^+$	51:5$^+$	55:4$^+$
	PURE soil	82:3$^+$	86:9$^+$	92:9$^+$	86:3$^+$	92:5$^+$
	PURE air	81:9$^+$	74:1$^+$	89:7$^+$	77:5$^+$	91:4$^+$
	PURE pollinators	36:7$^+$	59:2$^+$	57:2$^+$	19:4$^+$	34:9$^+$
	N	3,396,625	332,620	34,757	210,058	73,464
Organic	Farm acreage (acre)	18.4	8.9	16.1	30.4	68.9
	Experience (year)	7.2	5.6	5.4	10.1	8.1
	PURE surface water	1.9	0.1	0.0	0.9	0.5
	PURE groundwater	0.0	0.0	0.0	0.0	0.1
	PURE soil	21.6	9.8	5.1	25.7	24.6
	PURE air	48.8	45.3	71.9	35.4	36.3
	PURE pollinators	0.1	0.0	0.1	0.3	0.0
	N	114,952	17,851	1,888	7,741	1,998

Note: $^+$ Greater than organic mean at the 1% level.
Less than organic mean at the 1% level.

For my analysis, the unit of observation is a field-year, defined as a field with one or more pesticide applications in a given calendar year. In total, more than 3 million field-year observations are included in the PUR database from 1995 to 2015. Table 1 provides field-year summary statistics for key variables by crop. Overall, 3% of them applied only pesticides approved in organic agriculture. For all crops, conventional operations are significantly larger in size and have higher PURE risk scores. For all crops in general, lettuce, strawberries, and processing tomatoes, growers who operate conventional operations have significantly more farming experience, measured by years they are observed in the PUR. For wine grapes, conventional growers have less experience than organic growers. Conventional strawberries pose significantly more impact to surface water and less impact to groundwater, measured by the PURE indices, comparing to other conventional crops. Organic strawberries, on the other hand, had a higher PURE risk score for air and a lower PURE risk score for soil. Pesticides used in conventional wine grapes fields have less impact to pollinators.

3 Empirical Framework

To identify the effect of organic agriculture on pesticide uses and associated environmental impacts, I need to address the issues of selection bias at both the grower and the field levels. Compared to growers who utilize conventional practices, growers who choose to adopt organic farming practices may have different underlying characteristics, such as attitudes toward environmental issues, which can also affect their pesticide use decisions directly. If grower characteristics are time-invariant, an unbiased estimation could be achieved by including a grower fixed effect in the regression. There is also time-variant heterogeneity that is associated with individual growers, due to factors such as farm size and years of experience, that simultaneously influences the adoption of organic production and pesticide use decisions. The identification concern here is that growers with more farming experience or larger farms, including both conventional and organic acreage, are more likely to operate organic fields and use less pesticides (Bravo-Monroy, Potts, and Tzanopoulos, 2016, Genius, Pantzios, and Tzouvelekas, 2006). Therefore it is biased to compare environmental impacts of pesticide use for growers without considering these characters. For each grower, annual total acreage and years of farming experience serve as measures of time-variant heterogeneity. Acreage and farming experience may alter the environmental impact of growers' pesticide programs. As shown in table 1, there is a significant difference for these two variables between conventional and organic growers.

There could be field-level heterogeneity as well, such as pest or disease pressure, that undermines our identification strategy. Fields with less pest or disease pressure are more likely to be converted into organic production and fewer pesticides are needed. Including filed fixed effects in the estimation is one approach to address these issues. After controlling for these considerations, the effect of organic status on environmental impacts of pesticide use can be estimated by the following regression:

$$
\begin{aligned}
y_{it} = {}_0 + {}_1 Organic_{it} + {}_2 Organic_{it} \quad t + {}_3 t + {}_4 Acreage_{gt} + {}_5 Exp_{gt} \\
+ {}_g + {}_i + {}_t + {}_c + e_{it}
\end{aligned}
\tag{1}
$$

For field i in year t, grower g chooses to adopt either organic or conventional pest management practices, which is denoted by the binary variable $Organic_{it}$. The variable $Acreage_{gt}$ represents the total farm acreage, organic plus conventional, measured in 1,000 acres, for grower g who operated field i in year t. Exp_{gt} measures the years of farming experience for grower g, which is the number of years grower g was observed in PUR. The time value t ranges from 1 to 21, which matches year 1995 to 2015. The grower fixed effect ${}_g$ represents time-invariant grower heterogeneity. ${}_i$ is the field fixed effect, which covers the time-invariant field heterogeneity. The time fixed effect ${}_t$ captures year to year variations. Pest management practices vary across crops, which alter the environmental impact of pesticide uses. The crop fixed effect ${}_c$ captures such variation. The dependent variable y_{it} is the PURE risk score for one of the five environmental dimensions.

Pesticide use in conventional and organic agriculture varies across crops as shown previously. Therefore, equation 1 is estimated for a subset of crops, lettuce, strawberries, processing tomatoes, and wine grapes, to examine determinants of these differences. For lettuce, in particular, the environmental impacts from pesticide use do not have a linear time trend for the entire time period because pesticide portfolio for conventional growers changed dramatically. After 2005, organophosphorus insecticides are gradually replaced by pyrethroid and neonicotinoid insecticides, which are less toxic in general. To capture this trend more precisely, a dummy variable that splits the studying period in half is included to interact with the time trend in equation 1. The regression equation for lettuce is as follows:

$$\begin{aligned} y_{it} = {}_0 + {}_1 Organic_{it} + {}_2 Organic_{it} \quad 06\_15_t + {}_3 Organic_{it} \quad t + {}_4 t \\ + {}_5 Acreage_{gt} + {}_6 Exp_{gt} + {}_g + {}_i + {}_t + {}_c + e_{it} \end{aligned} \tag{2}$$

where 06_15_t is a dummy variable, which equals 1 for observations in years 2006 to 2015. The coefficient of $Organic_{it} \quad 06\_15_t$ captures the change of the difference between two systems in the second half the studying period. It is expected to be positive because conventional growers switched to less toxic pesticides, which reduce the difference between the environmental impacts of conventional and organic pesticide use.

In the fixed effect model, the identification of ${}_1$ requires the observation of a significant number of fields before and after the adoption of organic practices in our database. Although certified organic cropland was only 5% of total cropland in California (NASS, 2016), there are more than 53,000 fields using only pesticides approved for organic agriculture, which are operated by more than 10,000 growers, in the PUR database. The coefficient of interest, ${}_1$, is identified by comparing fields under conventional and organic management. The estimation of ${}_1$ using all observations does two comparisons simultaneously for the same grower-crop combination: (1) comparing fields converted from conventional to organic production to fields converted from organic to conventional production; (2) comparing organic fields to conventional fields that remained unchanged in our study period.

Adding field and grower fixed effects would introduce more noise than signal and amplify any potential measurement error. Comparing fields with similar attributes could serve as an alternative to address field heterogeneity. Therefore, I also propose to use a sub-sample containing only fields that transition between systems, that is fields where both conventional and organic practices were observed. The regression equation is as follows:

$$
\begin{aligned}
y_{it} = {}_0 + {}_1 Organic_{it} + {}_2 Organic_{it} \quad t + {}_3 t + {}_4 Acreage_{gt} + {}_5 Exp_{gt} \\
+ {}_g + {}_t + {}_c + e_{it}
\end{aligned} \tag{3}
$$

The hypothesis is that the intercept in equation 3 is smaller than that in equation 1 because fields that are continuously operated under the conventional method are not included and more pesticides are typically applied to them. However, fields that stay in organic production are also excluded, so the difference between two systems is not necessarily smaller in this sub-sample than the full sample estimation.

For the same reason, another sub-sample is estimated, for growers who operated both conventional and organic fields, as an alternative to including grower fixed effects. The estimated intercept for this sub-sample is expected to be smaller than that for the the full sample because growers who did not engage in organic production and their fields are excluded. The regression equation is as follows:

$$
\begin{aligned}
y_{it} = {}_0 + {}_1 Organic_{it} + {}_2 Organic_{it} \quad t + {}_3 t + {}_4 Acreage_{gt} + {}_5 Exp_{gt} \\
+ {}_i + {}_t + {}_c + e_{it}
\end{aligned} \tag{4}
$$

The evolution of the organic industry is another interesting direction to explore. In particular, does organic agriculture become less environmentally friendly when more profit-driven growers enter, as suggested in Läpple and Van Rensburg (2011)? This question is answered by including the interaction term $Organic_{it} \quad t$. The hypothesis is that the coefficient is positive because more profit-driven growers, with less concern for the environment, entered over time and chose pesticide portfolios with greater environmental impacts.

4 Results

The results from the full sample and sub-sample fixed effect model are reported first, followed by the results for four selected crops.

4.1 Results for Full Sample and Sub-Sample Estimation

The results from the full sample estimation are reported in table 2. For all five PURE dimensions, pesticides used in organic agriculture reduced environmental impact. The reduction, captures by the variable $Organic$, is significant at the 1% level for five environmental dimensions. The intercept measures the PURE risk score for an average-size conventional field, operated by a grower who does not have any farming experience previously or operate any organic fields currently. Relative to the intercept, organic practices reduced environmental impacts for surface water by 86%, for groundwater by 93%, for soil by 60%, for air by 53%, and for pollinators by 76% on a per acre basis holding other variables fixed. The relatively small impact on air is linked to the facts that natural AIs do not have less VOC emissions in general. Regulations regarding high VOC-emitting pesticide AIs also contribute to this result partially because they do no affect two systems evenly. In 2015, the sale and use of 48 pesticide products are restricted due to their VOC emissions, which accounted for 5% of treated acreage in conventional agriculture and 1 % of treated acreage in organic agriculture. Although reductions in PURE risk score values do not translate directly into dollar values or health outcomes, results from table 2 suggest that pesticide use in organic fields substantially reduced environmental impacts.

The coefficient for *Organic* *t* represents the change of the difference between two farming systems over time and is positive for all environmental dimensions, which supports the hypothesis that the environmental impacts associated with pesticide use in organic agriculture have grown over time. Air has the largest coefficient among five environmental dimensions, which is consistent with previous figures that environmental impacts increased the most for air at the aggregate level. The variable t is the common time trend for all conventional fields and t is negative for surface water and groundwater, which means the environmental impacts from pesticide use decreased in conventional agriculture on those dimensions. The environmental impact on soil and air increased. The combination of variables t and *Organic* *t* shows the time trend for organic fields alone, which is upward sloping for groundwater, soil, air, and pollinators, and downward sloping for surface water.

Table 2: The effect of organic pesticide use on PURE index values: full sample estimation

Variable	Surface water	Groundwater	Soil	Air	Pollinators
Organic	-15.04***	-36.06***	-53.59***	-42.51***	-29.60***
	(0.25)	(0.31)	(0.45)	(0.43)	(0.27)
Organic *t*	0.37***	0.81***	1.07***	1.37***	0.65***
	(0.02)	(0.02)	(0.03)	(0.03)	(0.02)
t	-0.62***	-0.53***	0.12**	0.12**	-0.07
	(0.03)	(0.05)	(0.04)	(0.04)	(0.04)
Acreage	0.10***	0.41***	0.18***	0.15***	0.09***
	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)
Exp	0.19***	0.16**	-0.28***	-0.44***	-0.28***
	(0.03)	(0.05)	(0.04)	(0.04)	(0.04)
$_0$	17.51***	38.84***	89.19***	79.92***	38.74***
	(1.51)	(1.38)	(1.48)	(1.44)	(1.26)
N	3,195,150	3,195,150	3,195,150	3,195,150	3,195,150
R^2	0.59	0.48	0.57	0.47	0.52

Robust standard errors are reported in parentheses. ***p<0.01; **p<0.05; *p<0.1. Grower, field, year, and crop fixed effects are included in all models.

Two variables *Acreage* and *Exp*, capture time-variant grower heterogeneity. Although the variable *Organic* dominates the overall effect, coefficients for both *Acreage* and *Exp* influence the environmental impact associated with crop production. Results in table 2 indicate that, for the same grower-crop combination, as farm acreage grows, growers choose pesticide application programs that pose more impact for the five PURE environmental dimensions. Meanwhile, more farming experience significantly reduce the environmental impacts on soil, air, and pollinators. The PURE risk scores for surface water and groundwater are positively correlated with experience. This is partially due to the fact that experienced farmers use less organophosphorus insecticides per acre, which are more toxic to earthworms and honeybees than alternative AIs.

Table 3: The effect of organic pesticide use on PURE index values: sub-sample estimation

Fixed effect	Variable	Surface water	Groundwater	Soil	Air	Pollinators
No field fixed effect	*Organic*	-16.94***	-37.77***	-55.51***	-42.77***	-32.05***
		(0.27)	(0.34)	(0.47)	(0.46)	(0.29)
	Organic *t*	0.50***	0.84***	1.16***	1.47***	0.73***
		(0.02)	(0.03)	(0.04)	(0.03)	(0.02)
	t	-0.60***	-0.62***	0.18	-0.20	0.31***
		(0.08)	(0.11)	(0.12)	(0.11)	(0.08)
	Acreage	-0.24***	-0.05	0.15	0.27***	-0.04
		(0.07)	(0.09)	(0.08)	(0.08)	(0.08)
	Exp	0.05	0.15	-0.26*	-0.23*	-0.63***
		(0.08)	(0.11)	(0.13)	(0.11)	(0.09)
	$_0$	10.33***	29.94***	73.27***	78.34***	27.55***
		(2.01)	(1.83)	(2.25)	(2.15)	(1.63)
	N	194,763	194,763	194,763	194,763	194,763
	R^2	0.40	0.38	0.50	0.41	0.45
No grower fixed effect	*Organic*	-15.25***	-36.49***	-54.40***	-43.96***	-30.48***
		(0.27)	(0.34)	(0.49)	(0.47)	(0.29)
	Organic *t*	0.39***	0.83***	1.14***	1.51***	0.72***
		(0.02)	(0.02)	(0.04)	(0.03)	(0.02)
	t	-0.91***	-0.67***	0.30**	0.23*	0.29***
		(0.07)	(0.10)	(0.10)	(0.09)	(0.08)
	Acreage	0.07***	0.41***	0.18***	0.12***	0.14***
		(0.02)	(0.03)	(0.02)	(0.02)	(0.02)
	Exp	0.48***	0.29**	-0.50***	-0.66***	-0.65***
		(0.07)	(0.10)	(0.10)	(0.09)	(0.08)
	$_0$	16.41***	32.50***	84.81***	79.36***	38.46***
		(1.82)	(1.66)	(1.86)	(1.83)	(1.51)
	N	2,007,597	2,007,597	2,007,597	2,007,597	2,007,597
	R^2	0.59	0.52	0.61	0.55	0.56

Robust standard errors are reported in parentheses. ***p<0.01; **p<0.05; *p<0.1. Year and crop fixed effects are included in all models. Field and grower fixed effects are included accordingly as indicated in the first column.

The sub-sample estimation yields similar results (Table 3). Namely, (1) the environmental impacts associated with pesticide use in conventional agriculture decreased on surface water and groundwater over time, (2) pesticides used in organic agriculture significantly reduced the environmental impacts measured by the PURE risk score, (3) the difference between conventional and organic pesticide use decreased.

The intercept is smaller in both sub-sample estimations, which supports our hypothesis that when using conventional practices, fields that were later converted into organic farming had less pesticide use than to other conventional fields that were not converted in our study period. The intercept is smaller than the coefficient of *Organic* occasionally because the crop and time fixed effects are oftentimes positive and significant and the impact on those dimensions in organic fields are small. The coefficients of *Organic* in table 3 are similar or larger, in absolute value, than those in the full sample estimation, which imply that the difference between two production systems are larger in the sub-sample than full sample.

For the sub-sample with fields that have transited between production systems, total farm acreage is no longer significantly associated with impacts to groundwater, soil, and pollinators and the environmental on surface water is negatively correlated with farm acreage. The main reason for this seemly drastic difference is the change in crop portfolio and their associated pest management practices. There are significantly more vegetable fields and tree nut orchards and fewer field crop fields in this sub-sample because commodities have different organic price premiums (Carlson and Jaenicke, 2016). Crops with larger organic price premiums are more likely to be produced organically.

4.2 Results for Selected Crops

Differences in environmental impacts between organic and conventional production vary across crops. Equation 2 is estimated for lettuce and equation 1 is estimated for other selected crops separately to highlight important patterns of pesticide use in conventional and organic production. The specification in equation 3 and 4 provides similar results and therefore results are not presented here for individual crops.

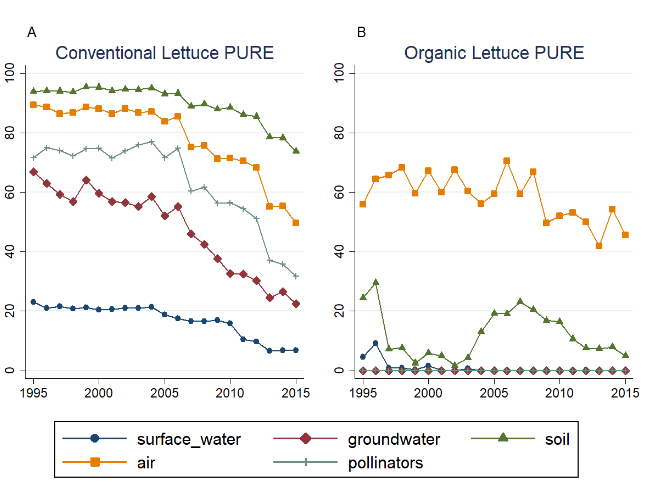

Figure 4: PURE risk score for conventional (A) and organic (B) lettuce fields

The PURE risk score values are plotted for conventional and organic lettuce fields in figure 4. The risk score from pesticides used in conventional lettuce fields decreased since growers have gradually transitioned from organophosphates to pyrethroid and neonicotinoid insecticides over the past twenty years and organophosphorus insecticides are more toxic than their pyrethroid and neonicotinoid alternatives (PPDB, 2020).

Prior to 2005, diazinon (an organophosphate) was the most used insecticide in conventional lettuce production while the usage of lambda-cyhalothrin (a pyrethroid), was limited in lettuce. However, by 2015, lambda-cyhalothrin was the most used insecticide in conventional lettuce fields while fewer than 30 acres of lettuce were treated with diazinon. Therefore in table 4, the coefficients for *Organic 06_15* are significant and positive showing that the difference in the environmental impacts from pesticides use between conventional and organic lettuce production decreased in the second half of the study period. The estimation result for lettuce using equation 1 is presented in the appendix, which does not differ from results in table 4.

In table 5, differences in environmental impacts between conventional and organic strawberries are largely driven by the environmental impacts of pre-plant soil fumigation, which is

Table 4: The effect of organic pesticide use on PURE index values: lettuce

Variable	Surface water	Groundwater	Soil	Air	Pollinators
Organic	-19.31***	-49.20***	-67.41***	-39.60***	-64.40***
	(1.07)	(1.52)	(2.02)	(2.30)	(1.53)
Organic *06_15*	1.10**	1.41*	8.82***	7.47***	6.98***
	(0.38)	(0.59)	(1.15)	(1.54)	(0.61)
Organic *t*	0.80***	1.91***	0.40*	0.63**	1.82***
	(0.08)	(0.11)	(0.17)	(0.21)	(0.11)
t	0.93	-0.53	-2.28*	-2.38	-1.34
	(0.85)	(1.24)	(0.92)	(1.30)	(1.02)
Acreage	0.66***	0.81***	0.51***	0.81***	1.10***
	(0.05)	(0.06)	(0.04)	(0.04)	(0.05)
Exp	-1.92*	-1.42	1.56	1.12	-0.28
	(0.85)	(1.24)	(0.92)	(1.30)	(1.02)
0	18.61***	59.16***	95.21***	87.56***	66.93***
	(2.49)	(3.62)	(2.67)	(3.77)	(2.97)
N	270,688	270,688	270,688	270,688	270,688
R^2	0.54	0.57	0.61	0.57	0.58

Robust standard errors are reported in parentheses. ***p<0.01; **p<0.05; *p<0.1. Grower, field, year, and crop fixed effects are included in all models.

used by conventional but not organic strawberry growers. Soil fumigation is a common practice for managing pathogens, nematodes, and weeds in conventional strawberry fields. while soil fumigants are most commonly regulated due to their negative effects on human health, most soil fumigants are also highly toxic to earthworms (PPDB, 2020). Accordingly, the PURE risk score for soil is large. Consequently organic strawberry production achieves a 78% reduction in the environmental impact to soil. Conventional strawberry production also poses higher impacts on surface water because several AIs are highly toxic to fish and aquatic invertebrates (PPDB, 2020), which includes: abamectin for controlling spider mites (Dybas, 1989), malathion for whiteflies (Bi and Toscano, 2007), and pyraclostrobin for gray mold (Mercier, Kong, and Cook, 2010). As a result, the coefficient of *Organic* for surface water is larger than average. The difference in the PURE risk score for air is smaller because azadirachtin and clarified neem oil, two primary AIs contributing to VOC emissions in the nonattainment area of Ventura (CDPR, 2020, Rosemary, 2008), a major strawberry producing county, together accounted for 18% of treated acreage for organic strawberries.

Table 5: The effect of organic pesticide use on PURE index values: strawberries

Variable	Surface water	Groundwater	Soil	Air	Pollinators
Organic	-49.52***	-15.51***	-77.08***	-52.59***	-52.50***
	(4.51)	(4.12)	(4.85)	(5.66)	(4.02)
Organic *t*	0.86**	-1.11***	1.19***	1.27**	0.86**
	(0.31)	(0.30)	(0.34)	(0.40)	(0.28)
t	-1.58**	-1.38**	-1.40***	-0.32	-1.09**
	(0.53)	(0.51)	(0.32)	(0.32)	(0.36)
Acreage	-0.55	-1.92	-0.95	-0.76	-1.30
	(1.01)	(1.00)	(0.57)	(0.81)	(0.93)
Exp	0.81	2.82***	0.93**	-0.09	0.12
	(0.55)	(0.53)	(0.33)	(0.32)	(0.38)
$_0$	62.44***	39.70***	101.14***	95.53***	70.52***
	(2.26)	(2.26)	(1.23)	(1.31)	(1.56)
N	28,071	28,071	28,071	28,071	28,071
R^2	0.57	0.55	0.68	0.51	0.59

Robust standard errors are reported in parentheses. ***p<0.01; **p<0.05; *p<0.1. Grower, field, year, and crop fixed effects are included in all models.

In column 2 for groundwater, the coefficient for *Organic* *t* is negative, the opposite of the other environmental dimensions. The difference between conventional and organic production is expanding because pesticide used in conventional strawberry fields is posing more impact on groundwater over time, which is due to the regulation on methyl bromide, a soil fumigant. Based on its ozone depletion effects, the use of methyl bromide was phased out in the U.S. and strawberry growers increased the usage of alternative fumigants, such as 1,3-D and chloropicrin (Ajwa et al., 2003, Fennimore, Haar, and Ajwa, 2003). Those two alternatives are less likely to be retarded by soil and therefore pose more impact on groundwater than methyl bromide (PPDB, 2020).

As shown in table 6, organic processing tomato production reduces the environmental impact to air by a larger percentage than all organic production on average. The key difference between processing tomatoes and other crops is that processing tomatoes are more threatened by diseases than by insects or nematodes (Flint, Klonsky, et al., 1985). The two most common diseases are powdery mildew and bacterial speck, which are treated with sulfur and copper hydroxide respectively in organic production (Zalom, 2007). In 2015, the acreage treated by these two AIs

Table 6: The effect of organic pesticide use on PURE index values: processing tomatoes

Variable	Surface water	Groundwater	Soil	Air	Pollinators
Organic	-10.65***	-43.97***	-73.94***	-88.65***	-12.92***
	(2.04)	(2.80)	(3.54)	(3.44)	(1.84)
Organic *t*	-0.41**	-0.25	0.03	2.38***	-1.02***
	(0.15)	(0.20)	(0.30)	(0.27)	(0.13)
t	4.93**	6.50**	0.63	-0.66	-2.68
	(1.75)	(2.43)	(1.70)	(1.87)	(2.16)
Acreage	0.57***	1.34***	0.54***	0.67***	-0.12
	(0.09)	(0.13)	(0.09)	(0.09)	(0.13)
Exp	-4.31*	-5.72*	-0.46	0.85	4.12
	(1.75)	(2.43)	(1.70)	(1.87)	(2.16)
$_0$	1.42	39.11***	89.55***	88.21***	31.70***
	(1.79)	(2.60)	(1.74)	(1.96)	(2.27)
N	55,106	55,106	55,106	55,106	55,106
R^2	0.70	0.59	0.51	0.42	0.48

Robust standard errors are reported in parentheses. ***p<0.01; **p<0.05; *p<0.1. Grower, field, year, and crop fixed effects are included in all models.

accounted for 42% of total acreage treated for organic processing tomatoes. In comparison, the share of sulfur and copper hydroxide treated acreage is below 10% for production of lettuce and strawberries and 25% for all organic crops. These two AIs have lower VOC emissions than to other AIs used in organic production such as pyrethrins, azadirachtin, and clarified neem oil, which together accounted for nearly 30% of treated acreage for organic lettuce and strawberries, 18% for organic processing tomatoes, and 18% for all crops. However, the impact is increasing as indicated by the positive coefficient for variable *Organic* *t*.

Wine grape production occurs in many regions in California, and pest and disease pressures vary across production regions due to different climate and soil conditions. In the northern production region, which includes Napa and Sonoma counties, powdery mildew is a common disease because the fungus prefers a cooler temperatures, ideally around 21 C, to grow (Yarwood et al., 1954). Measured by treated acreage, 9 out of the 10 most used AIs are fungicides targeting powdery mildew in this area. In the San Joaquin Valley, in contrast, powdery mildew is rarely seen due to high temperature. Due in part to the large number of frost-free days per grow-

Table 7: The effect of organic pesticide use on PURE index values: wine grapes

Region	Variable	Surface water	Groundwater	Soil	Air	Pollinators
State	*Organic*	-4.98***	-28.43***	-42.68***	-31.70***	-4.51***
		(0.45)	(0.88)	(1.23)	(1.22)	(0.41)
	Organic t	0.08**	0.69***	1.30***	1.36***	-0.20***
		(0.03)	(0.06)	(0.09)	(0.08)	(0.03)
	t	-0.32***	-0.17	0.25	-0.67***	-0.32***
		(0.08)	(0.15)	(0.13)	(0.14)	(0.09)
	Acreage	-0.64***	-0.47***	-1.02***	-1.07***	-1.01***
		(0.04)	(0.06)	(0.06)	(0.07)	(0.06)
	Exp	0.24**	0.01	0.27*	0.63***	0.93***
		(0.09)	(0.16)	(0.14)	(0.14)	(0.10)
	β_0	17.01***	54.29***	81.65***	83.48***	15.84***
		(0.41)	(0.69)	(0.53)	(0.53)	(0.40)
	N	206,627	206,627	206,627	206,627	206,627
	R^2	0.50	0.52	0.53	0.52	0.44
Napa and Sonoma Counties	*Organic*	-3.86***	-24.54***	-41.67***	-29.63***	-5.48***
		(0.65)	(1.20)	(1.71)	(1.70)	(0.49)
	Organic t	-0.03	0.62***	1.47***	1.74***	0.14***
		(0.04)	(0.08)	(0.12)	(0.11)	(0.03)
	t	-0.70***	0.01	0.59**	0.01	0.24
		(0.14)	(0.23)	(0.18)	(0.19)	(0.13)
	Acreage	-1.98**	4.33***	0.90*	5.01***	0.15
		(0.69)	(0.84)	(0.45)	(0.56)	(0.60)
	Exp	0.74***	-0.11	-0.04	-0.37	-0.05
		(0.15)	(0.24)	(0.20)	(0.20)	(0.14)
	β_0	20.41***	49.86***	78.22***	78.03***	7.13***
		(0.75)	(1.10)	(0.79)	(0.78)	(0.58)
	N	68,819	68,819	68,819	68,819	68,819
	R^2	0.47	0.53	0.55	0.50	0.37
San Joaquin Valley[1]	*Organic*	-3.81***	-35.09***	-46.16***	-38.59***	-7.81***
		(1.08)	(2.45)	(3.53)	(3.16)	(1.27)
	Organic t	0.04	0.33	0.58*	0.25	-0.48***
		(0.08)	(0.18)	(0.26)	(0.24)	(0.09)
	t	-0.55**	-1.36*	0.31	-0.99*	-0.08
		(0.21)	(0.57)	(0.44)	(0.47)	(0.38)
	Acreage	-0.34*	0.45	0.29*	0.24	0.55
		(0.16)	(0.28)	(0.14)	(0.17)	(0.29)
	Exp	0.35	0.94	-0.05	1.01*	1.07**
		(0.22)	(0.57)	(0.44)	(0.47)	(0.39)
	β_0	14.58***	65.16***	86.10***	85.41***	16.81***
		(0.58)	(1.31)	(0.88)	(0.95)	(0.88)
	N	62,202	62,202	62,202	62,202	62,202
	R^2	0.57	0.44	0.43	0.48	0.39

Robust standard errors are reported in parentheses. ***p<0.01; **p<0.05; *p<0.1. Grower, field, year, and crop fixed effects are included in all models. [1] The San Joaquin Valley includes Fresno, Kern, Kings, Madera, Merced, San Joaquin, Stanisalus, and Tulare counties.

ing season, insects are the primary concern (Ross, 2009). For wine grapes, the most used AIs beside sulfur are abamectin targeting spider mites, imidacloprid targeting vine mealybugs, and methoxyfenozide targeting lepidoptera (Varela et al., 2015). These insecticide AIs are more toxic for humans, earthworms, and honeybees and have larger VOC emissions than the fungicides used for powdery mildew (PPDB, 2020), so the intercept in table 7 is estimated larger in the San Joaquin Valley than Napa and Sonoma counties and state as a whole for groundwater, soil air, and pollinators. Powdery mildews in grapes are often treated with sulfur (Jepsen, Rosenheim, and Bench, 2007). In 2015, table, wine, and raisin grapes accounted for 77% of acreage treated with sulfur. To control powdery mildew, organic growers also rely on bio-ingredients such as bacillus pumilus and bacillus subtilis, which have larger VOC emissions than sulfur and mineral oils. Thus, organic wine grapes growers in Napa and Sonoma counties only achieve a 38% reduction in the PURE risk score for air while the reduction in the San Joaquin Valley is 45%.

5 Conclusions

Using a consistent index, this study quantifies the environmental impacts of pesticide use in conventional and organic fields and how they have changed over time. The richness of the PUR database and the advanced algorithm of the PURE model allow us to present a confident answer to the research question. Information from this analysis could benefit organic crop production worldwide as California is an important production region with a diverse set of crops and environmental conditions. Previous studies rarely focused on the use of specific AIs or the change in the structure of pesticide use when evaluating the environmental impact of organic agriculture. To the best of my knowledge, the PUR database has never been used to compare pesticide usage for conventional and organic production.

The U.S. organic agriculture sector has grown significantly over the past two decades partially due to the launch of the NOP in 2002. Organic farming continues to be viewed as the epitome of sustainable agriculture and has potential to make greater contribution to the food system in the future. Pesticides are essential for both conventional and organic crop production. However, pesticide use is not static. The pesticide portfolio changed dramatically for both farming systems in our study period. Based on field-level pesticide application information, this paper shows that the environmental impacts of pesticide use declined in conventional fields because pyrethroids gradually replaced organophosphates, which are more toxic in general. The impact of pesticide use to air increased in organic fields due to the adoption of new chemicals and the reduction in the use of sulfur, which has zero VOC emissions.

Pesticides used in organic agriculture significantly reduced environmental impacts to surface water, groundwater, soil, air, and pollinators to different extents depending on the pesticide portfolios for conventional and organic growers. However, the difference between two systems is decreasing for all five dimensions. Notably, they have almost have the same level of VOC emissions in 2015, which suggests that converting to organic production does not benefit air quality due to changes in the pesticide applied. In both production systems, growers' total acreage increased the environmental impacts of pesticide use in all dimensions. Growers' farming experience increased the environmental impacts of pesticide use to surface water and groundwater, and reduced the impacts to soil, air, and pollinators. The effects of these two variables have magnitudes smaller than the organic status of the field.

Pesticide use in organic agriculture is posing more impacts than it was. This is consistent with findings in Läpple and Van Rensburg (2011), which showed that late adopters, those who adopted organic farming after the launch of government supporting program, are more likely to be profit-driven than early adopters. Profit maximizing agents do not incorporate the negative externalities associated with pesticide use when making application decisions (Wilson and Tisdell, 2001).

New policy instruments could alter the current situation. When reviewing pesticide and fertilizer AIs used in organic agriculture, the NOSB could focus on environmental criteria such as VOC emissions, which has not been considered previously. Such policy instruments could partially offset the negative environmental impacts of pesticide used in organic fields.

A limitation of this study is the lack of data regarding grower characteristics. In previous studies, growers' age, gender, and education were shown to be determinants of the adoption of organic farming (Läpple and Van Rensburg, 2011, Mzoughi, 2011, Burton, Rigby, and Young, 1999). Here, these characteristics are addressed by using time-invariant grower fixed effects. More information regarding the determinants of pesticide use decisions might be revealed if those characteristics data were available. Future research could focus on impacts to human health rather then the environment and calculate the monetary value of reduced mortality and morbidity of converting to organic production.

While pesticide use remained an important part for both farming systems, another caveat is that this study does not investigate the environmental impacts of non-chemical pest management practices, such as biological, cultural, and mechanical/physical controls. However, if one were to pursue that direction by collecting data on non-chemical practices, the analysis would necessarily be done one a relative small scale, unlike the comprehensive data used here.

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A Insecticides and Fungicides Used in Conventional and Organic Agriculture

One way to demonstrate the difference in insecticide and fungicide use between conventional and organic agriculture is to group AIs based on their Mode of Action (MoA). There are 31 MoA groups for insecticides classified by the Insecticide Resistance Action Committee (IRAC) (IRAC, 2020) and 78 MoA groups for fungicides classified by the Fungicide Resistance Action Committee (FRAC) (FRAC, 2020).

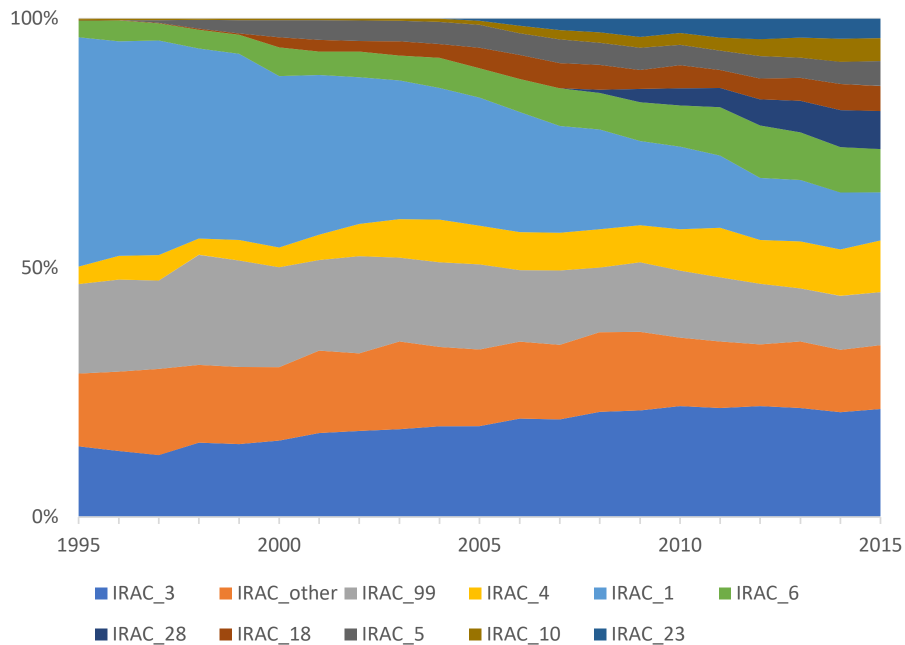

Figure 1: Share of insecticide treated acreage in conventional agriculture by MoA: 1995 - 2015

In figure 1, 18 MoA groups with fewer than 1 million acres treated in 2015 are combined into the category "other". The most used insecticide group in 2015 is IRAC_3, which includes pyrethroids and pyrethrins. The group IRAC_1, organophosphates and carbamates, was widely used in conventional fields but has been largely replaced by other AIs because organophosphates are associated with negative health outcomes and have been regulated (Eskenazi, Bradman, and Castorina, 1999, Lerro et al., 2015). Conventional growers have adopted AIs from different IRAC groups. For example, the diamides, the broad-spectrum insecticides in IRAC_28, were quickly adopted after 2008 when chlorantraniliprole and flubendiamide, the two major AIs in the group, were registered with EPA .

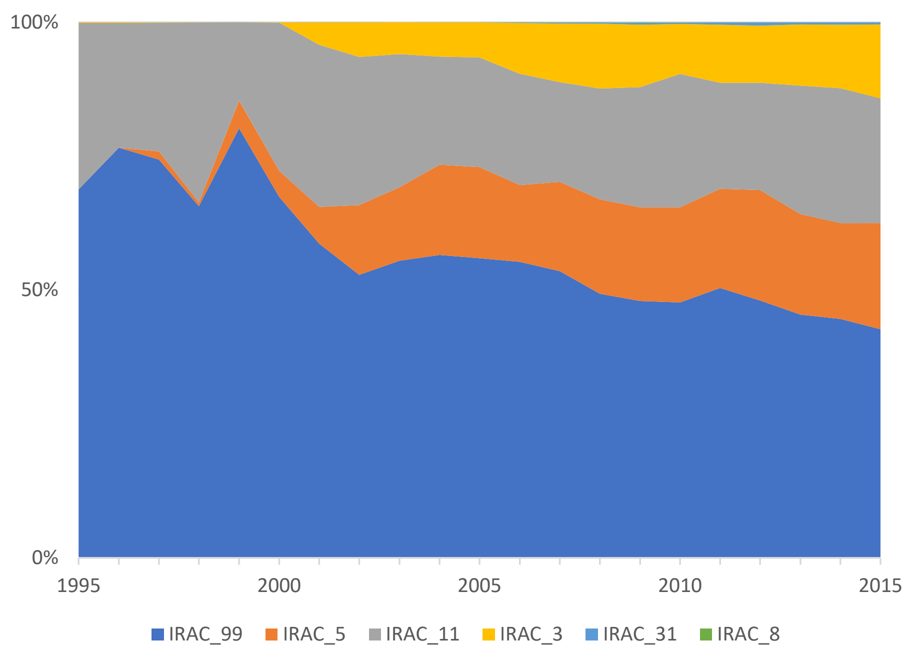

Figure 2: Share of insecticide treated acreage in organic agriculture by MoAs: 1995 - 2015

Organic growers have limited insecticide choices as shown in figure 4. AIs with unknown MoA, such as sulfur and azadirachtin, were widely used in organic fields. Other common AIs include spinosad in group FRAC_5, acillus thuringiensis (Bt.) in group FRAC_11 and pyrethrins in group FRAC_3.

For fungicides, the situation is similar. A variety of MoAs are available for conventional growers as shown in figure 3. For organic growers, copper and sulfur, in group FRAC_M01 and FRAC_M21 respectively, accounted for more than half of the treated acreage for fungicides in

2015.

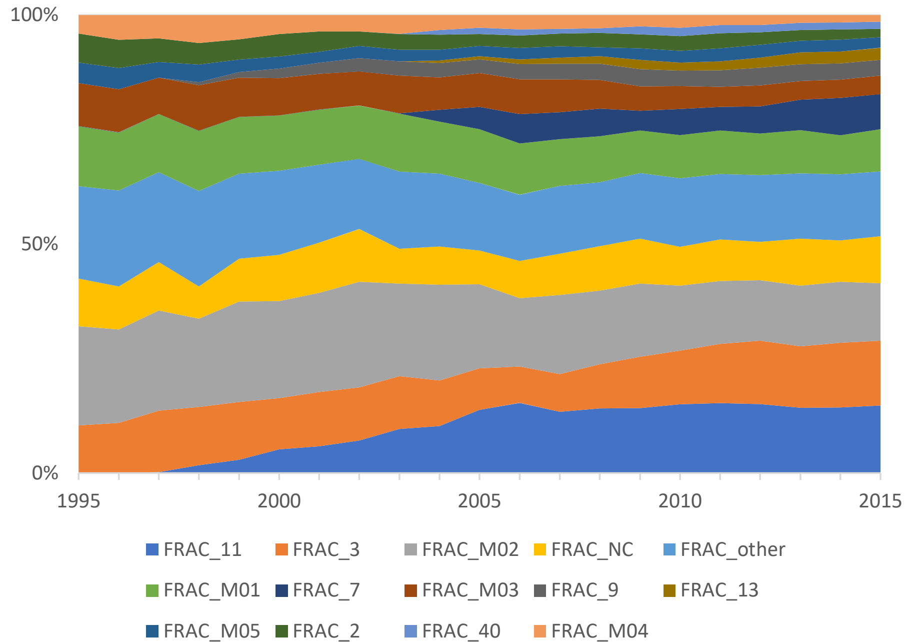

Figure 3: Share of fungicides treated acreage in conventional agriculture by MoAs: 1995 - 2015

Table 8: The effect of organic pesticide use on PURE index values from equation 1: lettuce

Variable	Surface water	Groundwater	Soil	Air	Pollinators
Organic	-19.54***	-49.15***	-71.70***	-42.95***	-67.90***
	(1.01)	(1.45)	(1.92)	(2.19)	(1.48)
Organic *t*	0.88***	2.00***	1.15***	1.26***	2.41***
	(0.06)	(0.08)	(0.14)	(0.17)	(0.09)
t	0.87	-0.64	-2.49**	-2.60*	-1.50
	(0.85)	(1.26)	(0.93)	(1.31)	(1.02)
Acreage	0.67***	0.83***	0.51***	0.82***	1.10***
	(0.05)	(0.06)	(0.04)	(0.04)	(0.05)
Exp	-1.85*	-1.28	1.79	1.34	-0.12
	(0.85)	(1.26)	(0.93)	(1.31)	(1.02)
0	17.58***	56.71***	94.98***	86.45***	67.12***
	(2.50)	(3.67)	(2.70)	(3.81)	(2.98)
N	270688	270688	270688	270688	270688
R^2	0.54	0.57	0.61	0.57	0.58

Robust standard errors are reported in parentheses. ***p<0.01; **p<0.05; *p<0.1. Grower, field, year, and crop fixed effects are included in all models.

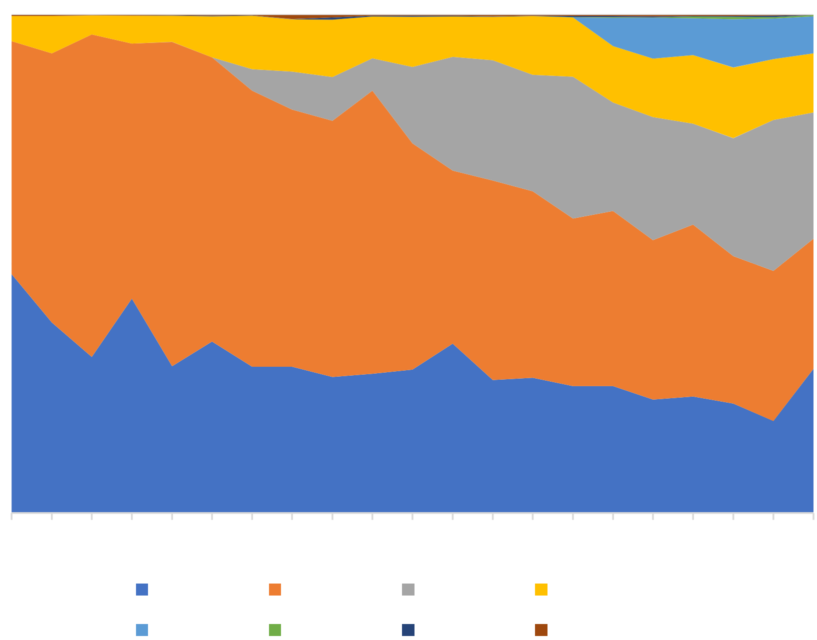

Figure 4: Share of fungicide treated acreage in organic agriculture by MoAs: 1995 - 2015