Intensive or Extensive Margin Effects? Growers' Responses to the Restriction of High-Volatile Organic Compound (VOC) Pesticide Products in the San Joaquin Valley, California

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Abstract

Volatile organic compounds (VOC) are gases emitted by some pesticides. They cause respiratory illness and cancer in humans when combined with nitrogen oxide and sunlight. Due to high VOC emissions in the San Joaquin Valley (SJV), the California Department of Pesticide Regulation has prohibited the use of high-VOC products containing one of four active ingredients (abamectin, chlorpyrifos, gibberellins, and oxyfluorfen) on seven crops including alfalfa, almond, citrus, cotton, grape, pistachio, and walnut during the peak ozone season (May to October) since 2015. Using field-level data on crop production and pesticide applications in the SJV from 2005 to 2018, this study examines growers' behavioral responses to the regulation. We hypothesize that growers made both intensive and extensive margin adjustments by changing pesticide use and acreage allocations, respectively. Our results confirmed the hypothesis. By employing double hurdle models, we further show factors affecting growers' decisions to make both types of adjustments are different from those affecting the number of adjustments.

1. Introduction

Volatile organic compounds (VOC) are gases emitted from certain solids or liquids (United States Environmental Protection Agency (EPA) 2021b). They can combine with nitrogen oxide and sunlight to form ground-level ozone, which can adversely affect crop production and cause respiratory illness and cancer in humans (California Department of Pesticide Regulation (CDPR) 2015; United States Environmental Protection Agency (EPA) 2021a). In California, pesticides account for about two percent of statewide VOC emissions. However, they are among the top ten sources in the San Joaquin Valley (SJV) and Ventura County (Caballero 2007; CDPR 2015).[1] Due to high VOC emissions in the SJV, in 2015 CDPR prohibited the use of high-VOC products containing one of four active ingredients (AIs), abamectin, chlorpyrifos, gibberellins, and oxyfluorfen, during the peak ozone season (May to October) for each year (Title 3, California Code of Regulations, section 6880). Importantly, the regulation does not prohibit the use of all pesticides with the AIs. It only prohibits ones with high-VOC formulations. The regulation applies to seven crops including alfalfa, almond, citrus, cotton, grape, pistachio, and walnut (Title 3, California Code of Regulations, section 6883), which are economically important in the eight counties constituting the SJV with gross receipts exceeding $17.4 billion in 2020 (California Department of Food and Agriculture (CDFA) 2021).

Using field-level data on crop production and pesticide applications in the SJV, this study examines the effect of the regulation on growers' pesticide use and crop production decisions. We hypothesize that there are both intensive and extensive margin effects. The intensive margin effect refers to potential changes in input use. Applications are prohibited from May through October. As a result, there could be greater use of the restricted products before May and/or after October.

[1] The SJV includes all of Fresno, Madera, Merced, Kings, San Joaquin, Stanislaus, and Tulare counties and the western part of Kern county.

Growers may apply non-restricted pesticide products (products containing the same AIs or alternative AIs), which may be less effective and trigger greater use throughout the year. On the other hand, growers may adjust at the extensive margin by reallocating crop acreage. With the exception of cotton, the regulated crops are perennials, so a decision to change acreage allocations has significant impacts on revenue streams over time. We count the number of adjustments made at the intensive and extensive margin respectively and examine the factors influencing growers' decisions to make more adjustments.

This study makes two main contributions. First, it contributes to the literature on the economics of agri-environmental policies by providing in-depth analyses of growers' responses to a pesticide regulation, with the consideration of all affected growers and crop systems. Although there are numerous studies analyzing growers' responses to agricultural policies and technology innovations, they often focus on single-crop systems and/or rely on farm surveys conducted in selected regions (Knapp and Schwabe 2008; Sharma, Bailey and Fraser 2011). Studies with single-crop systems may not be able to provide a full picture of growers' behavior changes because they lack information on growers' adjustments made at the extensive margin. With limited sample regions, the overall effects proxied by those studies may be plagued by selection bias and not reliable because they ignore the spatial variations in the number of adjustments. Second, we employ panel data that allow us to capture the evolution of growers' behavior changes across time. Factors influencing whether or not to adjust to the regulation could be different from those influencing the number of adjustments (Larsen, Claire Powers and McComb 2021). Instead of restricting the same stochastic process for zero and positive adjustments (Cameron and Trivedi 2015), we relax this by employing double hurdle models to analyze factors influencing growers' decisions to adjust and the number of adjustments to the VOC regulation.

Our empirical results suggest growers in the SJV adjusted to the VOC regulation at both the intensive and extensive margin. We find growers with larger farms and more farming experience were more likely to make both intensive and extensive adjustments, and this type of growers also tended to make greater number of adjustments. In accordance with the literature, this study also shows factors affecting the likelihood of adjustments are different from those affecting the number of adjustments. For example, we find weather conditions in the winter months did not affect the likelihood of making intensive margin adjustments, but they did affect the number of adjustments. In addition to farm characteristics and weather conditions, other key factors affecting the likelihood and number of adjustments include crop price and yield, pesticide cost, soil type, and irrigation water availability.

The remainder of this paper is structured as follows. Section 2 provides a review of the relevant literature on growers' behavioral responses to government policies and changes in production conditions. Section 3 describes the study area, data, and empirical approach. Section 4 presents the results, and section 5 concludes.

2. Literature review

In agricultural production, chemical inputs including pesticides and fertilizers are widely used to boost crop production and enhance quality. Although pesticides and fertilizers can bring enormous economic benefits, extensive studies have documented costs related to their adverse effects on terrestrial (such as bees and nontarget insects) and aquatic (such as fish and shrimp) animals, humans, and the environment (Johnson, Adams and Perry 1991; Kuan et al. 2018; Larsen, Gaines and Deschênes 2017; Pimentel 2005). The environmental impacts encompass air, water, and soil contamination through adsorption, emission, spray drift, leaching, and runoff (Ou et al. 2020; Scholtz and Bidleman 2007; Tudi et al. 2021).

Due to the nonpoint source nature of contaminations from pesticides and fertilizers, instead of designing policies that directly restricting emission or leaching from these chemical inputs, indirect policy instruments including taxes, subsidies, and regulations on their use are commonly proposed (Choi and Feinerman 1995; Sexton, Lei and Zilberman 2007; Zilberman et al. 1991). Unlike regulations, input taxes and subsidies provide economic incentives, and growers can adjust their use decisions based on cost and revenue considerations. Although these two policy instruments allow for flexibilities with growers voluntarily deciding whether to use the taxed or subsidized inputs or not, they are less preferred by policymakers, because the voluntary nature leads to uncertainties regarding the abatement results (Jayet and Petsakos 2013). Regulations are typically mandatory. A use ban would completely remove the banned inputs from growers' choice set. Uncertainties could be introduced when growers switch to other inputs or practices that are riskier and may lead to greater environmental hazards. For example, the unavailability of a pesticide may lead to the use of alternative pesticide products that are more toxic to the environment. Specific requirements on use rate and management practices and permissions are other possible regulatory instruments. The literature typically classifies the involuntary input use changes that are caused by those regulatory requirements as intensive margin adjustments (Schwabe, Kan and Knapp 2006). In addition to changes in pesticide use in restricted crops, growers may adjust at the extensive margin by reallocating acreage among restricted crops or shifting production from restricted crops to non-restricted ones (Goetz, Schmid and Lehmann 2006; Mérel et al. 2014). Environmental quality may be degraded if the non-restricted crops are pesticide-intensive.

Not only policies that directly restrict the applications of chemical inputs can lead to changes in the use intensity, others may have some confounding effects and induce farmers to adjust their usage. There exist numerous studies that empirically investigate the relationships between crop insurance and chemical use. Some studies demonstrated that crop insurance led to decreases in fertilizer and/or pesticide use, with the moral hazard argument claiming insurance can disincentivize farmers to apply fertilizers or pesticides, because they regarded insurance as a substitute for risk-reducing chemicals (Mishra, Nimon and El-Osta 2005; Smith and Baquet 1996). Others found the opposite arguing insurance may encourage growers to take riskier farming practices, which in turn led to increasing pesticide applications (Chakir and Hardelin 2014; Horowitz and Lichtenberg 1993). There are also studies showing no significant relationships between crop insurance and pesticide use (Aubert and Enjolras 2014; Weber, Key and O'Donoghue 2016). It is worth noting that the empirical evidences can be crop-, insurance-, pesticide-, and region-specific (Goodwin, Vandeveer and Deal 2004; Möhring et al. 2020).

In addition to the intensive margin effects, crop insurance can have extensive margin effects by changing farmers' crop choice and land use decisions (Goodwin et al. 2004; Shi, Wu and Olen 2020; Walters et al. 2012; Wu 1999). These extensive margin changes could lead to further changes in chemical use. For example, the presence of insurance may incentivize farmers to switch from non-insured crops to insured ones. Some extensive margin adjustments can lead to changes in chemical use intensities for both types of crops (Babcock and Hennessy 1996; Miao et al. 2016). Farmers may grow insured crops on marginal land (e.g., previously fallowed land or land with poor soil quality), thereby resulting in greater pesticide use (Chang and Mishra 2012; Claassen, Langpap and Wu 2017).

Changes in production conditions can also induce farmers to adjust at the intensive and extensive margin. Graveline and Mérel (2014) examined how farmers responded to increasing water scarcity in Beauce, a main cereal production region in France, and the corresponding effects on economic profits. Using simulations under different water scarcity scenarios, the authors found farmers made three types of adjustments: 1) a shift from irrigated to rain-fed crops, 2) among irrigated crops, a shift from water-intensive crops to water-saving crops, and 3) reduced irrigation intensity for irrigated crops. The first two adjustments were made at the extensive margin with changes in acreage allocation among crops, while the third one was at the intensive margin with changes in input use. By decomposing the adjustment margin, the authors demonstrated that a greater portion of farming responses came from extensive margin adjustments.

Although the intensive margin relations between input use and government policies have received considerable attention in the literature, little has been paid to the extensive ones. Because growers may adjust at both the intensive and extensive margin, studies investigating only one margin effect can lead to incomplete conclusions on growers' behavioral changes and inadequate policy recommendations. This study therefore examines both margins to identify growers' responses to the SJV's pesticide use regulation and evaluates how various factors affect growers' adjustment decisions.

3. Study area, data and methods

The SJV is located in the interior of California (Figure 1). All eight counties in the SJV are among California's top 11 agricultural counties. The gross value of agricultural production was estimated to be $37.1 billion in 2020, with the seven regulated crops accounting for 46.8% of the gross value (CDFA 2021).

Due to high VOC emissions, the SJV is listed as one of the five California ozone nonattainment areas (NAAs), which are defined as areas that do not meet the National Ambient Air Quality Standards for ozone as designed in the federal Clean Air Act (CDPR 2021). The State Implementation Plan (SIP) for pesticides requires CDPR to track and control VOC emissions in the SJV, with a goal of emissions not exceeding 18.1 tons per day (tpd). CDPR is also required to implement additional VOC restrictions including the prohibition of certain uses of pesticides if emissions exceed 95% of the SIP goal (i.e., 17.2 tpd). Because VOC emissions in 2013 in the SJV exceeded the SIP goal by 0.183 tpd, in 2014 CDPR announced the prohibition of the use of high-VOC products containing abamectin, chlorpyrifos, gibberellins, and oxyfluorfen during the peak ozone season for seven major crops (alfalfa, almond, citrus, cotton, grape, pistachio, and walnut) (Title 3, California Code of Regulations, section 6880). This VOC regulation came into effect in 2015.

This study examines farm/grower-level crop production and pesticide use in the SJV from 2005 to 2018. We rely on the following data sources: Pesticide use reporting (PUR) data from CDPR for field-level pesticide applications (CDPR 2022b), weather data from University of California Statewide Integrated Pest Management (UC IPM) (UC IPM 2022), crop price and yield data from the County Agricultural Commissioner's (CAC) reports (County of Fresno 2022; County of Kern 2022; County of Kings 2022; County of Madera 2022; County of Merced 2022; County of San Joaquin 2022; County of Stanislaus 2022; County of Tulare 2022), Geographic Information System (GIS) data on crop production from USDA NASS (National Agricultural Statistics Service) Cropland Data Layers (NASS 2022a), soil type data from the National Cooperative Soil Survey (NASS 2022b), water delivery data from the California Department of Water Resources (CDWR) and Congressional Research Service (CRS) report (CDWR 2022b;

CRS 2021), and the spatial boundaries of the water contractors and land sections from California State Geoportal (2022) and CDPR (2022b), respectively. Pesticide prices are collected through the Office of Pesticide Consultation & Analysis (OPCA), CDFA, internet searches, and recent University of California cost and return studies (Baldwin et al. 2020; Duncan et al. 2019; Fidelibus et al. 2018).

3.1 Dependent variables

In California, growers are required to report monthly the pesticides they apply to the CACs, who enter the data in the PUR database. For each pesticide application, PUR data include the time and date; crop, field, grower, and location identification numbers; application method; and the acreage planted and treated, and amount used.

We use PUR data from 2005 to 2018 to create measures of farm-level pesticide use and crop production. Because the regulation came into effect in 2015, we use December 31, 2014 as the demarcation point to define pre- and post-regulation periods and derive the mean acreage and intensities of pesticide use (lbs of AI/acre) for each crop and each AI to determine whether a grower responded to the regulation by making any adjustments regarding crop choice and input use. Gowers who produced one or more of the restricted crops in at least one year before 2015 are examined in this study, while growers who started or quit their farming businesses after 2015 are not examined. We specify adjustments made at the intensive margin as increasing the use of high-VOC products containing the restricted AIs in the non-restricted period (January-April, and November-December), low-VOC and excluded products containing the restricted AIs throughout the year, and products containing alternative AIs year-round.[2] For each affected crop, decreasing

[2] Emission potential (EP), which is an estimate of a product's VOC content, is used to classify pesticide products to high-VOC, low-VOC, and excluded products (California Department of Pesticide Regulation (CDPR) 2022a). The EP thresholds for the four restricted AIs are: 35% for abamectin, 25% for chlorpyrifos, 25% for gibberellins, and 15% for oxyfluorfen. According to CDPR, high-VOC product: a) contains any of the four pesticides as a primary active

acreage of this affected crop, increasing acreage of the non-restricted crops, and increasing acreage of other restricted crops are specified as adjustments made at the extensive margin. We construct the dependent variables by counting the number of adjustments made at the intensive and extensive margin, respectively.

3.2 Explanatory variables

Farm size is measured in acreage and obtained from the PUR dataset. Farming experience is derived as the number of years a grower has been reporting pesticide use to the CACs. Because of the poor data quality prior to 1995 (Wilhoit, Zhang and Ross 2001), we use 1995 as the base farming year. Using cropland and soil type data layers from NASS, we calculate the county-level crop acreage for each crop grown in three different soil types (clay, loam, and sand). In addition to their expectations on factors including crop price and water availability, growers tend to decide whether to keep growing a crop based on its previous performance. Thus, this study uses acreage values from the previous year when analyzing extensive margin effects.

To remove the impacts of inflation, all prices are deflated to real levels using the Producer Price Index (PPI) from 1982 as the base (Federal Reserve Economics Data 2022). There are many pesticide products used by growers. In order to calculate pesticide prices, we classify pesticide products into restricted products (i.e., high-VOC products) and the three types of replacement products: low-VOC products, excluded products, and products containing the alternative AIs. For each type of products used in each crop, we identify a representative product, which is the one used on the most acres during the study period, and collect pesticide prices. Pesticide cost ratio is

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ingredient; and b) labeled for agricultural use; and c) the EP is greater than the threshold. Low-VOC product: a) contains any of the four pesticides as a primary active ingredient; and b) labeled for agricultural use; and c) the EP is equal to or less than the threshold. Excluded product: a) contains any of the four pesticides, but not as a primary active ingredient; or b) labeled only for non-agricultural use.
Available at: https://www.cdpr.ca.gov/docs/emon/vocs/vocproj/nonfum_voc_prod_list.pdf

derived as the price ratio of the restricted pesticide product and the replacement, and the price of the replacement is derived as the weighted average (by acreage) of the three types of replacement products.

Weather data are collected from UC IPM, which provides daily temperature and precipitation for each weather station in the state. Growing degree-days are calculated in degrees Fahrenheit to capture the degree of heat during a 24-hour period. The base temperature is 45°F, which is chosen based on the minimum temperature required for alfalfa growth (34-42°F), cotton growth (58-60°F) and grape growth (50°F), the chilling temperature threshold required for nut trees (32-45°F), and the freezing temperature that requires frost protection for citrus (25-30°F) (California Office of Environmental Health Hazard Assessment (OEHHA) 2018; Geisel and Unruh 2003; Mc Intyre, Kliewer and Lider 1987; Mueller, Frate and Mathews 2007; UC IPM 2013) For each county, we calculate the accumulated degree days (in degrees Fahrenheit) and total precipitation (in inches) during the winter (November to February) and non-winter months (March to October). When evaluating the effects of weather conditions on growers' extensive margin responses, weather conditions during the non-winter months are not considered because production decisions are typically made before that period.

In California, water is delivered to contractors through the Central Valley Project, which is a federal water project, the State Water Project, and smaller private projects. Each water contractor in the state is allocated certain amounts of water that can be sold to growers and other users. Depending on precipitation, runoff, and other water supply conditions, the contractors may not get the full amount of the assigned water in each year. At the beginning of each year, the contractors (and thus the growers) are informed about percentage of their allocations they will get, though the amount is subject to change during the year. For each land section in a county, it may receive water from different contractors and sources.[3] Using the spatial boundaries of the contractors and land sections as well as water delivery data from the CDWR and CRS reports, we derive the ratio of the actual delivery amount and the assigned amount to define irrigation water availability for each section, and then calculate the mean ratio for each county to denote the county-level water availability.

3.3 Methods

We construct a panel of I growers who grew crop c and made adjustments over $T = 4$ years ($t \in (2015,2016,2017,2018)$). The cross-section unit is grower i - crop c, and we suppress subscript c hereafter. The total number of observations is 59,660 ($650 \times 4 = 2{,}600$ for cotton and $14{,}265 \times 4 = 57{,}060$ for perennial crops) (Appendix 1). Because the factors influencing whether or not to adjust to the regulation could be different from those influencing the number of adjustments, a double-hurdle model is estimated to analyze growers' decisions to adjust and the number of adjustments to the VOC regulation. The first hurdle d_{it} is a binary choice indicating whether the grower make any adjustments:

$$d_{it}^{*} = x_{it}\beta + \varepsilon_{1,it},$$

$$d_{it} = 1 \text{ if } d_{it}^{*} > 0,$$

$$d_{it} = 0 \text{ if } d_{it}^{*} \leq 0.$$

The second hurdle y_{it}^{*} is a count variable denoting the number of adjustments made by the growers in the first hurdle:

$$y_{it}^{*} = z_{it}\gamma + u_i + \varepsilon_{2,it},$$

[3] Section is typically a one square mile area (640 acres).

where x_{it} and z_{it} are vectors of explanatory variables as defined in the previous subsection, and they can include the same set of variables. This study employs the same set of explanatory variables. Parameters β and γ are vectors of coefficients for the corresponding vector of variables, and $\varepsilon_{1,it}$ and $\varepsilon_{2,it}$ are the error terms. A summary of the variables and summary statistics is presented in Table 1.

4. Results

Because the seven restricted crops are in two crop groups: annuals (cotton) and perennials (alfalfa, almond, citrus, grape, pistachio, and walnut), we run two sets of regressions for each crop group to evaluate growers' intensive and extensive margin responses. The results are presented in Tables 2 and 3, with the upper panel showing the results for the first hurdle regarding growers' decisions to make adjustments or not, and the lower panel presenting the results for the second hurdle regarding the number of adjustments.

4.1 Cotton

We find that cotton growers with larger farms and more farming experience were more likely to adjust pesticide use (i.e., intensive margin) and acreage allocation (i.e., extensive margin). This type of grower also made a greater number of adjustments. For extensive margin adjustments, cotton growers with larger farms were more likely to reallocate their cotton acreage to other crops. Moreover, we find higher pesticide prices for the replacement products also facilitated growers to transit out of cotton production. Unexpectedly, cotton price and yield did not affect growers' pesticide use and crop production decisions.

In accordance with the literature, our estimation results confirm that factors affecting the decisions to adjust are not necessarily the same as those affecting the number of adjustments. In particular, we find weather conditions were not significant determinants of the likelihood of cotton growers making intensive margin adjustments. However, for growers who did make adjustments, they made more adjustments when the conditions in the non-winter months were more desirable (higher growing degree-days) for cotton growth and pest development. When weather conditions in the winter months were more suitable for pest survival, growers were more likely to make extensive margin adjustments by transiting out of cotton production.

Growers who expected higher water delivery were more likely to make intensive margin adjustments. Cotton is a water-intensive crop, so growers expecting sufficient water supply for its production may be incentivized to adjust pesticide use changes to ensure high crop yield and quality. Soil type is another key determinant. Our estimates show growers in the county with more acreage of clay soils allocated to cotton production were more likely to make intensive margin adjustments. This might be due to the fact that clay soils are more adsorptive to pesticides, and adsorption would lead to reduced pest control (Fishel 2003), so growers need to make a greater number of pesticide use adjustments.

4.2 Perennial crops

Similar to cotton growers, growers who grew perennials and had larger farms and more farming experience were more likely to make intensive and extensive margin adjustments. Growers who expected a higher crop price and yield were more likely to adjust pesticide use and less likely to reallocate their acreage to other crops. A higher cost of the alternative pesticide products (relative to the regulated products) discouraged growers from using these alternatives and encouraged them to reallocate acreage to other crops. Using the mean pre- and post-regulation acreage values for each crop grown by individual growers, we identify the reallocated or alternative crops for each regulated crop and calculate their total acreage changes in the SJV.

Appendix 2 lists the top 10 alternative crops for each regulated crop.[4] Almond, pistachio, corn, and wheat were among the top 10 most popular alternatives for all regulated crops.

When the weather conditions in the non-winter months were suitable for crop growth and pest survival, growers were more likely to adjust pesticide use. Unlike the cotton case, higher degree-days in the winter months did not facilitate production transition from the perennials into other crops. This is not surprising because for perennials, especially tree crops, lower temperatures (thus lower degree-days) in the winter months are needed to meet chilling requirements.

In California, the six restricted perennials are among the top 10 most water-intensive crops (CDWR 2022a). Sufficient water supply through precipitation and water deliveries from the federal and state water projects may encourage growers to keep growing these perennial crops. This is confirmed by our estimates of precipitation and water delivery variables. Soil type is another determinant of growers' extensive margin response. Typically, perennial crops require soils that can retain heat and drain well. In California, loam soil is the most preferred type, followed by sand soil (IPMData 1998; IPMData 1999; Lazaneo 2014; Orloff 2007; Western Institute for Food Safety & Security (WIFSS) 2016a; Western Institute for Food Safety & Security (WIFSS) 2016b). We find growers who had higher acreage of the six crops grown in sand and loam soils were less likely to make extensive adjustments.

Unlike perennial orchard crops, alfalfa is a perennial herbaceous crop and is rotated with annual crops to improve soil structure, increase soil organic matter, and disrupt pest and disease cycles (Lin, Putnam and Deben 2014). Compared with orchard crops, alfalfa acres can easily transit to the production of other crops without significant investment loss. In addition, alfalfa can

[4] Uncultivated agriculture is not included in the list because some growers may report pesticide use in uncultivated agriculture while they indeed apply preplant soil fumigation to a crop. Therefore, the acreage values derived from PUR data for uncultivated agriculture could be over-estimated.

be easily fallowed during dry years (Johnson and Cody 2015). To examine whether alfalfa growers would adjust at the extensive margin differently from the orchard crops, we run another set of regressions for alfalfa and the five orchard crops. Tables 4 and 5 present the estimation results, and the estimates are quite consistent with the previous findings.

Another robustness check is done for farming experience variable. This study uses 1995 as the base year to derive farming experience. Its value for growers who started business prior to 1995 is thus bounded. To validate our estimate results, we remove farming experience from the explanatory variable set and rerun the regressions. The estimation results are shown in Appendices 3-6, and the estimates for the other variables are robust.

5. Conclusion

In this paper, we find that growers of the restricted crops did respond to the VOC regulation by adjusting pesticide use (intensive margin responses) and acreage allocations (extensive margin responses). Factors influencing the likelihood and number of adjustments include farm size and farming experience, weather conditions, crop price and yield, pesticide cost, water availability, and soil type. We also show that the factors influencing whether or not to adjust to the regulation may be different from those influencing the number of adjustments. While we demonstrate that some growers did change acreage allocations in response to the regulation, future work will look directly at the extent of changes and the determinants. CDPR has shown the efficacy of the regulation in maintaining VOC emissions in the SJV below the regulatory maximum (CDPR 2021). By incorporating the Pesticide Use Risk Evaluation (PURE) scores developed by Zhan and Zhang (2012), our future study will evaluate how growers' responses affected other dimensions of environmental quality including surface water, groundwater, soil, and pollinators.

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Figures

Figure 1. Study area: The San Joaquin Valley

Tables

Table 1. Variables and descriptive statistics

Variables	Description	Annuals		Perennials	
		Mean	Sd	Mean	Sd
Intensive margin[5]					
First hurdle	Percent of growers who made intensive margin adjustments	0.93	0.26	0.92	0.27
Second hurdle	Number of adjustments	2.72	1.47	3.02	1.80
Extensive margin[6]					
First hurdle	Percent of growers who made extensive margin adjustments	0.52	0.49	0.11	0.31
Second hurdle	Number of adjustments	0.41	0.69	0.13	0.40
Explanatory variables					
Farm size	Size of the farm in acreage (in 1000s)	0.40	1.20	0.26	0.86
Farming experience	Grower's farming experience (in years)	18.19	5.27	17.36	6.15
Pesticide cost ratio	The price ratio of the restricted pesticide product and its replacements	2.22	0.70	11.07	5.58
Degree-days, non-winter	Accumulated degree days (in degree Fahrenheit) during non-winter months (March to October)	6,279.83	290.74	6,069.14	381.53
Precipitation, non-winter	Total amount of precipitation (in inches) during non-winter months	2.81	1.06	3.43	1.69
Degree-days, winter	Accumulated degree days (in degree Fahrenheit) during winter months (November to February)	1,062.54	77.48	1,043.16	78.65
Precipitation, winter	Total amount of precipitation (in inches) during winter months	4.88	2.36	6.11	2.97
Expected yield	County-level crop yield from the previous year (in tons/acre)	0.76	0.07	5.29	5.03
Expected price	County-level crop price from the previous year (in $/ton)	1,270.25	167.98	1,431.56	1,159.02
Sand acreage	Acreage of the crop(s) grown in sandy soil (in 1000s) in each county	34.21	36.65	58.67	42.78
Clay acreage	Acreage of the crop(s)grown in clay soil (in 1000s) in each county	188.19	112.37	158.61	113.35
Loam acreage	Acreage of the crop(s)grown in loam soil (in 1000s) in each county	517.98	183.36	667.24	263.89
Sand acreage, previous year	Acreage of the crop(s)grown in sandy soil (in 1000s) in each county, from previous year	29.78	30.61	59.59	43.09
Clay acreage, previous year	Acreage of the crop(s)grown in clay soil (in 1000s) in each county, from previous year	185.30	111.62	160.32	115.73
Loam acreage, previous year	Acreage of the crop(s)grown in loam soil (in 1000s) in each county, from previous year	489.68	152.12	683.46	278.41
Water delivery	Average percentage of assigned water that are actually delivered in each county	42.17	36.35	40.13	38.67

[5] **Intensive margin:** increasing use of 1) the high-VOC products containing the restricted AIs in the non-restricted period (January-April), 2) low-VOC products containing the restricted AIs in the restricted (May-October) and non-restricted periods, 3) excluded products containing the restricted AIs in the restricted (May-October) and non-restricted periods, and 4) products containing the alternative AIs in the restricted and non-restricted periods.

[6] **Extensive margin:** decreasing acreage of the target crops, increasing acreage of the non-target, restricted crops, and increasing acreage of the non-restricted crops.

Table 2. Determinants of growers' decisions to adjust and the number of adjustments to the VOC regulation: cotton

	Intensive margin effects			Extensive margin effects		
	Estimate	**Std. Error**		**Estimate**	**Std. Error**	
First hurdle						
Constant	2.2885	3.6756		-3.7723	0.9477	***
Farm size	7.3370	0.8998	***	0.1757	0.0307	***
Farming experience	0.0618	0.0081	***	0.0359	0.0052	***
Pesticide cost ratio	-0.2712	0.1835		-0.0897	0.0847	
Degree-days, non-winter	-0.0006	0.0005				
Precipitation, non-winter	-0.0168	0.0736				
Degree-days, winter	0.0011	0.0012		0.0016	0.0007	***
Precipitation, winter	-0.0263	0.0572		0.0142	0.0252	
Expected yield	-0.9128	0.7587		0.4931	0.5090	
Expected price	0.0004	0.0003		0.0004	0.0002	
Sand acreage	-0.0008	0.0037				
Clay acreage	0.0022	0.0006	***			
Loam acreage	0.0002	0.0004				
Sand acreage, previous year				-0.0018	0.0011	
Clay acreage, previous year				0.0003	0.0003	
Loam acreage, previous year				0.0006	0.0002	***
Water availability	0.0053	0.0026	***	0.0004	0.0011	
Second hurdle						
Constant	-0.9742	0.7430		0.0703	0.4044	
Farm size	0.1301	0.0573	***	0.0149	0.0071	***
Farming experience	0.0119	0.0022	***	0.0022	0.0027	
Pesticide cost ratio	0.0542	0.0405		-0.1234	0.0321	***
Degree-days, non-winter	0.0002	0.0001	**			
Precipitation, non-winter	0.0049	0.0166				
Degree-days, winter	-0.0007	0.0003	***	0.0005	0.0003	**
Precipitation, winter	0.0041	0.0126		-0.0117	0.0092	
Expected yield	-0.0919	0.2020		-0.1426	0.1902	
Expected price	-0.0001	0.0001		-0.0001	0.0001	
Sand acreage	0.00001	0.0007				
Clay acreage	0.0009	0.0001				
Loam acreage	-0.0001	0.0001	***			
Sand acreage, previous year				0.0005	0.0004	
Clay acreage, previous year				0.00003	0.0001	
Loam acreage, previous year				0.00001	0.0001	
Water availability	-0.0003	0.0006		-0.0005	0.0004	

Asterisks denote levels of significance (**for 5 percent, ***for 1 percent).

Table 3. Determinants of growers' decisions to adjust and the number of adjustments to the VOC regulation: perennials

	Intensive margin effects			Extensive margin effects		
	Estimate	**Std. Error**		**Estimate**	**Std. Error**	
First hurdle						
Constant	0.4685	0.4758		1.2507	0.2278	***
Farm size	0.0842	0.0133	***	2.5185	0.0599	***
Farming experience	0.0158	0.0016	***	0.0401	0.0013	***
Pesticide cost	-0.0180	0.0020	***	0.0144	0.0017	***
Degree-days, non-winter	-0.0001	0.0001				
Precipitation, non-winter	0.0397	0.0095	***			
Degree-days, winter	0.0001	0.0002		-0.0008	0.0002	***
Precipitation, winter	0.0008	0.0063		-0.0409	0.0051	***
Expected yield	0.0561	0.0038	***	-0.0192	0.0030	***
Expected price	0.0004	0.00002	***	-0.00002	0.00001	
Sand acreage	0.0006	0.0004				
Clay acreage	-0.0003	0.0002	*			
Loam acreage	0.0001	0.0001				
Sand acreage, previous year				-0.0015	0.0003	***
Clay acreage, previous year				-0.00003	0.0001	
Loam acreage, previous year				-0.0003	0.0001	***
Water availability	0.0022	0.0003	***	0.0007	0.0002	***
Second hurdle						
Constant	0.8828	0.1667	***	0.2831	0.0607	***
Farm size	0.1413	0.0042	***	0.0462	0.0067	***
Farming experience	0.0121	0.0006	***	0.0070	0.0004	***
Pesticide cost	-0.0127	0.0008	***	0.0083	0.0005	***
Degree-days, non-winter	-0.0001	0.00002	***			
Precipitation, non-winter	0.0225	0.0034	***			
Degree-days, winter	0.0001	0.0001		-0.0002	0.0001	***
Precipitation, winter	-0.0002	0.0023		-0.0141	0.0014	***
Expected yield	0.0341	0.0014	***	-0.0190	0.0008	***
Expected price	0.0001	0.00001	***	-0.0001	0.000003	***
Sand acreage	0.0006	0.0001	***			
Clay acreage	-0.0002	0.0001	***			
Loam acreage	0.0001	0.00003	***			
Sand acreage, previous year				-0.0006	0.0001	***
Clay acreage, previous year				0.0003	0.00004	***
Loam acreage, previous year				0.00003	0.00002	*
Water availability	0.0008	0.0001	***	-0.0003	0.0001	***

Asterisks denote levels of significance (*for 10 percent, **for 5 percent, ***for 1 percent).

Table 4. Determinants of growers' decisions to adjust and the number of adjustments to the VOC regulation: alfalfa

	Intensive margin effects			Extensive margin effects		
	Estimate	Std. Error		Estimate	Std. Error	
First hurdle						
Constant	-3.5228	0.9070	***	0.3491	0.6248	
Farm size	2.2101	0.0950	***	16.5710	0.7630	***
Farming experience	0.0353	0.0030	***	0.0448	0.0035	***
Pesticide cost	0.0024	0.0110		0.0411	0.0116	***
Degree-days, non-winter	0.0004	0.0001	***			
Precipitation, non-winter	-0.0270	0.0190				
Degree-days, winter	-0.0007	0.0004	**	-0.0009	0.0005	*
Precipitation, winter	-0.0114	0.0153		-0.0673	0.0149	***
Expected yield	0.0955	0.0199	***	0.0352	0.0275	
Expected price	-0.0019	0.0030		-0.0015	0.0030	
Sand acreage	0.0004	0.0006				
Clay acreage	-0.0005	0.0003	*			
Loam acreage	0.0006	0.0001	***			
Water availability				-0.0023	0.0006	***
Second hurdle				0.0006	0.0003	*
Constant				-0.00002	0.0002	
Farm size	-0.0008	0.0015		-0.0051	0.0018	***
Farming experience						
Pesticide cost	0.6109	0.3816		-0.3536	0.1549	**
Degree-days, non-winter	0.1587	0.0226	***	0.4215	0.0550	***
Precipitation, non-winter	-0.0018	0.0014		0.0062	0.0010	***
Degree-days, winter	0.0205	0.0044	***	0.0039	0.0028	
Precipitation, winter	-0.0001	0.00005	**			
Expected yield	-0.0059	0.0082				
Expected price	-0.0003	0.0001	***	0.00004	0.0001	
Sand acreage	-0.0155	0.0064	***	-0.0033	0.0037	
Clay acreage	-0.0263	0.0078	***	0.0232	0.0067	***
Loam acreage	0.0024	0.0012	***	-0.00003	0.0007	
Water availability	-0.0005	0.0003	**			

Asterisks denote levels of significance (*for 10 percent, **for 5 percent, ***for 1 percent).

Table 5. Determinants of growers' decisions to adjust and the number of adjustments to the VOC regulation: perennials other than alfalfa

	Intensive margin effects			Extensive margin effects		
	Estimate	Std. Error		Estimate	Std. Error	
First hurdle						
Constant	0.7570	0.3867	*	0.9520	0.2076	***
Farm size	0.1176	0.0035	***	2.3905	0.0639	***
Farming experience	0.0019	0.0014		0.0407	0.0013	***
Pesticide cost	-0.0046	0.0020	**	0.0071	0.000112	***
Degree-days, non-winter	0.00005	0.00005				
Precipitation, non-winter	0.0228	0.0088	***			
Degree-days, winter	0.0001	0.0002		-0.0007	0.0002	***
Precipitation, winter	0.0033	0.0053		-0.0368	0.0048	***
Expected yield	0.0156	0.0033	***	-0.0115	0.0030	***
Expected price	0.0001	0.00001	***	0.00004	0.00001	***
Sand acreage	0.0004	0.0004				
Clay acreage	-0.0001	0.0002				
Loam acreage	-0.000003	0.0001				
Sand acreage, previous year				-0.0015	0.0003	***
Clay acreage, previous year				0.00004	0.0001	
Loam acreage, previous year				-0.0002	0.0001	***
Water availability	-0.0002	0.0003		0.0010	0.0002	***
Second hurdle						
Constant	0.1674	0.1451		0.0823	0.0570	
Farm size	0.1031	0.0039	***	0.0580	0.0065	***
Farming experience	0.0076	0.0005	***	0.0079	0.0004	***
Pesticide cost	-0.0023	0.0008	***	0.0037	0.0005	***
Degree-days, non-winter	-0.0001	0.00002	***			
Precipitation, non-winter	0.0038	0.0031				
Degree-days, winter	-0.0001	0.0001		-0.0001	0.00005	**
Precipitation, winter	-0.0022	0.0020		-0.0114	0.0013	***
Expected yield	0.0176	0.0012	***	-0.0140	0.0008	***
Expected price	0.0001	0.000005	***	-0.00003	0.000003	***
Sand acreage	0.0005	0.0001	***			
Clay acreage	-0.0003	0.0001	***			
Loam acreage	0.00003	0.00003				
Sand acreage, previous year				-0.0009	0.0001	***
Clay acreage, previous year				0.0004	0.00004	***
Loam acreage, previous year				0.00005	0.00002	***
Water availability	0.0003	0.0001	***	0.000002	0.0001	

Asterisks denote levels of significance (*for 10 percent, **for 5 percent, ***for 1 percent).

Appendix

Appendix 1. Number of growers and observations, by crop

Crop	**Number of growers**	**Number of observations**
Annual		
Cotton	650	2,600
Perennial		
Alfalfa	1,564	6,256
Almond	4,996	19,984
Citrus	1,895	7,580
Grape	2,937	11,748
Pistachio	1,024	4,096
Walnut	1,849	7,396
Subtotal	***14,265***	57,060
Total	**14,915**	**59,660**

Appendix 2. Top 10 reallocated crops for each regulated crop

Rank	Alfalfa		Almond		Citrus		Cotton	
	Crop name	***Crop type***	***Crop name***	***Crop type***	***Crop name***	***Crop type***	***Crop name***	***Crop type***
1	almond	P	pistachio	P	pistachio	P	almond	P
2	wheat	A	grape	P	almond	P	pistachio	P
3	pistachio	P	wheat	A	grape	P	tomato, processing	A
4	corn	A	corn	A	wheat	A	wheat	A
5	tomato, processing	A	walnut	P	sorghum	A	safflower	A
6	cotton	A	tomato, processing	A	walnut	P	garlic	A
7	sorghum	A	cotton	A	barley	A	corn	A
8	walnut	P	oat	A	blueberry	P	grape	A
9	safflower	A	triticale	A	corn	A	sorghum	A
10	grape	P	garlic	A	garlic	A	onion	A

Rank	Grape		Pistachio		Walnut	
	Crop name	***Crop type***	***Crop name***	***Crop type***	***Crop name***	***Crop type***
1	almond	P	almond	P	almond	P
2	pistachio	P	grape	P	corn	A
3	walnut	P	citrus	P	wheat	A
4	citrus	P	triticale	A	grape	P
5	wheat	A	cotton	A	pistachio	P
6	tomato, processing	A	corn	A	alfalfa	P
7	corn	A	walnut	P	oat	A
8	onion	A	barley	A	cotton	A
9	garlic	A	wheat	A	tomato, fresh	A
10	alfalfa	P	sudangrass	A	sorghum	A

Note: A for Annual, P for Perennial.

Appendix 3. Excluding farming experience, determinants of growers' decisions to adjust and the number of adjustments to the VOC regulation: cotton

	Intensive margin effects			Extensive margin effects		
	Estimate	**Std. Error**		**Estimate**	**Std. Error**	
First hurdle						
Constant	3.3993	3.6686		-3.3447	0.9416	***
Farm size	7.4707	0.6724	***	0.1989	0.0309	***
Pesticide cost	-0.2048	0.1814		-0.0090	0.0835	
Degree-days, non-winter	-0.0007	0.0005				
Precipitation, non-winter	0.0063	0.0721				
Degree-days, winter	0.0015	0.0012		0.0017	0.0007	**
Precipitation, winter	-0.0201	0.0565		0.0231	0.0251	
Expected yield	-0.7653	0.7346		0.5620	0.5054	
Expected price	0.0003	0.0003		0.0003	0.0002	
Sand acreage	-0.0030	0.0037				
Clay acreage	0.0020	0.0006	***			
Loam acreage	0.0004	0.0004				
Sand acreage, previous year				-0.0015	0.0011	
Clay acreage, previous year				0.0002	0.0003	
Loam acreage, previous year				0.0007	0.0002	***
Water availability	0.0058	0.0026	**	0.0004	0.0011	
Second hurdle						
Constant	-0.6889	0.7318		0.0835	0.4006	
Farm size	0.1711	0.0485	***	0.0160	0.0077	**
Pesticide cost	0.0694	0.0399	*	-0.1169	0.0314	***
Degree-days, non-winter	0.0002	0.0001	**			
Precipitation, non-winter	0.0057	0.0163				
Degree-days, winter	-0.0007	0.0003	**	0.0005	0.0003	*
Precipitation, winter	0.0059	0.0124		-0.0112	0.0093	
Expected yield	-0.0902	0.1984		-0.1300	0.1908	
Expected price	-0.0002	0.0001	*	-0.0001	0.0001	
Sand acreage						
Clay acreage						
Loam acreage						
Sand acreage, previous year	-0.0001	0.0007		0.0005	0.0004	
Clay acreage, previous year	0.0007	0.0001	***	0.00003	0.0001	
Loam acreage, previous year	-0.00005	0.0001		0.00003	0.0001	
Water availability	-0.0004	0.0005		-0.0005	0.0004	

Asterisks denote levels of significance (*for 10 percent, **for 5 percent, ***for 1 percent).

Appendix 4. Excluding farming experience, determinants of growers' decisions to adjust and the number of adjustments to the VOC regulation: perennials

	Intensive margin effects			Extensive margin effects		
	Estimate	**Std. Error**		**Estimate**	**Std. Error**	
First hurdle						
Constant	0.9723	0.4728	**	1.6879	0.2115	***
Farm size	0.0881	0.0134	***	2.5868	0.0213	***
Pesticide cost	-0.0173	0.0020	***	0.0167	0.0018	***
Degree-days, non-winter	-0.0001	0.0001	*			
Precipitation, non-winter	0.0414	0.0095	***			
Degree-days, winter	0.0002	0.0002		-0.0006	0.0002	***
Precipitation, winter	0.00004	0.0063		-0.0334	0.0049	***
Expected yield	0.0538	0.0037	***	-0.0239	0.0029	***
Expected price	0.0003	0.00002	***	-0.0001	0.00001	***
Sand acreage	0.0005	0.0004				
Clay acreage	-0.0003	0.0002	*			
Loam acreage	0.0001	0.0001				
Sand acreage, previous year				-0.0014	0.0003	***
Clay acreage, previous year				-0.0002	0.0001	
Loam acreage, previous year				-0.0003	0.0001	***
Water availability	0.0024	0.0003	***	0.0012	0.0002	***
Second hurdle						
Constant	1.2694	0.1680	***	0.3819	0.0609	***
Farm size	0.1432	0.0043	***	0.0421	0.0083	***
Pesticide cost	-0.0122	0.0008	***	0.0088	0.0005	***
Degree-days, non-winter	-0.0001	0.00002	***			
Precipitation, non-winter	0.0230	0.0035	***			
Degree-days, winter	0.0002	0.0001	**	-0.0001	0.0001	**
Precipitation, winter	-0.0002	0.0023		-0.0137	0.0014	***
Expected yield	0.0330	0.0014	***	-0.0208	0.0010	***
Expected price	0.0001	0.00001	***	-0.0001	0.000003	***
Sand acreage	0.0005	0.0001	***			
Clay acreage	-0.0002	0.0001	***			
Loam acreage	0.0001	0.00003	***			
Sand acreage, previous year				-0.0006	0.0001	***
Clay acreage, previous year				0.0003	0.00004	***
Loam acreage, previous year				0.00002	0.00001	
Water availability	0.0009	0.0001	***	-0.0002	0.0001	***

Asterisks denote levels of significance (*for 10 percent, **for 5 percent, ***for 1 percent).

Appendix 5 Excluding farming experience, determinants of growers' decisions to adjust and the number of adjustments to the VOC regulation: alfalfa

	Intensive margin effects			Extensive margin effects		
	Estimate	Std. Error		Estimate	Std. Error	
First hurdle						
Constant	-2.2134	0.8917	**	1.0934	0.6164	*
Farm size	2.3282	0.0949	***	16.6090	0.7370	***
Pesticide cost	0.0013	0.0109		0.0248	0.0114	**
Degree-days, non-winter	0.0003	0.0001	***			
Precipitation, non-winter	-0.0272	0.0189				
Degree-days, winter	-0.0005	0.0004		-0.0006	0.0005	
Precipitation, winter	-0.0132	0.0152		-0.0526	0.0147	***
Expected yield	0.1010	0.0197	***	0.0489	0.0271	*
Expected price	-0.0035	0.0030		-0.0052	0.0029	*
Sand acreage	0.0004	0.0006				
Clay acreage	-0.0004	0.0003				
Loam acreage	0.0006	0.0001	***			
Sand acreage, previous year				-0.0019	0.0006	***
Clay acreage, previous year				0.0005	0.0003	
Loam acreage, previous year				-0.000002	0.0002	
Water availability	-0.0004	0.0015		-0.0028	0.0018	
Second hurdle						
Constant	0.5499	0.3768		-0.2293	0.1528	
Farm size	0.1421	0.0239	***	0.3439	0.0559	***
Pesticide cost	0.0209	0.0044	***	0.0018	0.0027	
Degree-days, non-winter	-0.0001	0.00004	*			
Precipitation, non-winter	-0.0056	0.0082				
Degree-days, winter	-0.0003	0.0001	**	0.0001	0.0001	
Precipitation, winter	-0.0154	0.0064	**	-0.0008	0.0036	
Expected yield	-0.0273	0.0078	***	0.0227	0.0066	***
Expected price	0.0025	0.0012	**	-0.0002	0.0007	
Sand acreage	-0.0005	0.0003	*			
Clay acreage	0.0004	0.0001	***			
Loam acreage	0.0001	0.00005	***			
Sand acreage, previous year				0.0001	0.0002	
Clay acreage, previous year				0.0003	0.0001	***
Loam acreage, previous year				-0.00003	0.00004	
Water availability	-0.0027	0.0006	***	-0.0002	0.0004	

Asterisks denote levels of significance (*for 10 percent, **for 5 percent, ***for 1 percent).

Appendix 6. Excluding farming experience, determinants of growers' decisions to adjust and the extent of adjustments to the VOC regulation: perennials other than alfalfa

	Intensive margin effects			Extensive margin effects		
	Estimate	**Std. Error**		**Estimate**	**Std. Error**	
First hurdle						
Constant	0.9286	0.4608	**	1.3834	0.2165	***
Farm size	0.1238	0.0022	***	2.4527	0.0223	***
Pesticide cost	-0.0046	0.0020	**	0.0099	0.0018	***
Degree-days, non-winter	0.00003	0.0001				
Precipitation, non-winter	0.0210	0.0093	**			
Degree-days, winter	0.0001	0.0002		-0.0005	0.0002	***
Precipitation, winter	0.0030	0.0061		-0.0282	0.0050	***
Expected yield	0.0142	0.0035	***	-0.0164	0.0029	***
Expected price	0.0001	0.00001	***	0.000003	0.00001	
Sand acreage	0.0001	0.0004				
Clay acreage	-0.0001	0.0002				
Loam acreage	-0.000001	0.0001				
Sand acreage, previous year				-0.0014	0.0003	***
Clay acreage, previous year				-0.0001	0.0001	
Loam acreage, previous year				-0.0002	0.0001	***
Water availability	-0.0002	0.0003		0.0014	0.0002	***
Second hurdle						
Constant	0.4129	0.1609	**	0.1684	0.0625	***
Farm size	0.1071	0.0010	***	0.0461	0.0086	***
Pesticide cost	-0.0022	0.0008	***	0.0040	0.0005	***
Degree-days, non-winter	-0.0001	0.00002	***			
Precipitation, non-winter	0.0043	0.0032				
Degree-days, winter	-0.00002	0.0001		-0.00004	0.0001	
Precipitation, winter	-0.0022	0.0022		-0.0101	0.0015	***
Expected yield	0.0172	0.0013	***	-0.0146	0.0009	***
Expected price	0.0001	0.00001	***	-0.00003	0.000003	***
Sand acreage	0.0005	0.0001	***			
Clay acreage	-0.0003	0.0001	***			
Loam acreage	0.00004	0.00002	*			
Sand acreage, previous year				-0.0008	0.0001	***
Clay acreage, previous year				0.0004	0.00004	***
Loam acreage, previous year				0.00004	0.00001	***
Water availability	0.0004	0.0001	***			

Asterisks denote levels of significance (*for 10 percent, **for 5 percent, ***for 1 percent).