

# Spatially Targeted and Differentiated Pesticide Policy: The Case of the Groundwater Protection Program

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## Abstract

When market-based instruments are impractical for addressing agricultural non-point source pollution, economists recommend regulations that incorporate farm management practices and environmental services to mitigate pollution. In this paper, we examine the adjustments farmers make to their pesticide programs in response to a policy delineating two types of regulated regions that differ in the required practices for pesticide usage based on local environmental conditions. Empirically, this study addresses the Groundwater Protection Program, which created a natural experiment through abrupt and uneven changes in the regulations governing the application of seven pesticides. Utilizing twenty-five years of field-level data, we estimate the program's impacts on the use of regulated active ingredients and the consequent environmental effects in the perennial crops almonds, citrus, and grapes using a difference-in-differences regression framework. Our analysis reveals that the program led to meaningful reductions in the use of regulated active ingredients in fields in regulated regions. However, the extent to which almond, citrus, and grape growers responded to the program varied substantially across crops. Additionally, we find evidence that the program induced almond growers to alter the mix and quantity of active ingredients used in orchards, resulting in no change in an aggregate measure of environmental impact that considers the potential harm of pesticides to water systems, human health, and wildlife. On the other hand, we find evidence that the environmental impact of regulated and alternative ingredients decreased in citrus groves and grape vineyards relative to control fields.

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# 1 Introduction

Pollution from pesticide residues has troubled citizens for decades (White, 1933) due to their link to adverse health outcomes (Qiao et al., 2012; Larsen, Gaines, and Deschênes, 2017) and environmental degradation (Grogan and Goodhue, 2012). Among the most pressing environmental issues posed by pesticide usage is the contamination of water supplies. Research has extensively documented the contamination of water resources, especially groundwater, by pesticides in the United States (U.S.) and elsewhere (Gilliom et al., 2006; Bexfield et al., 2020).

Identifying the source of pesticide contamination in groundwater is particularly difficult because of the long travel time between emission and detection and the indeterminate flow paths of water bodies and their contaminants. Environmental features like permeable soils, high rainfall, and shallow water tables increase groundwater susceptibility to contamination (Gilliom et al., 2006) and influence the external cost of pesticide sprays. Furthermore, the human and environmental costs of pesticides depend on the quantity of chemicals used, the application method and timing relative to other cultural practices like cultivation and irrigation, and the local population of people and wildlife. However, natural and management factors combine to make field-level measurements of pesticide emissions impractical and market-based instruments like taxes infeasible. Consequently, governments typically resort to uniform interventions, like chemical bans (Anderson, Opaluch, and Sullivan, 1985; Carter et al., 2005; Butler, 2018).

Ideally, policy instruments should vary according to the characteristics that influence pesticide emissions, like local environmental conditions and agricultural management practices (Zilberman and Millock, 1997). The challenge lies in achieving this variation without incurring prohibitive administrative costs. Zoning—whereby regulators target vulnerable regions with input controls—offers a potential compromise between uniform regulation and field-level controls (Falconer, 1998).

In 2004, the California Department of Pesticide Regulation (CDPR) implemented a zon-

ing program called the Groundwater Protection Program to conserve groundwater resources from pesticide contamination. In total, the program designated 2.4 million acres of land as Groundwater Protection Areas (GWPA), equivalent to 2.4% of California land area (USCB 2024) and 10% of crop and ranch land (CDFA 2023).<sup>1</sup> In designing the program, regulators and scientists used environmental characteristics to identify groundwater regions vulnerable to pesticide contamination via two pathways. The CDPR designated areas as either leaching GWPA, where residues move downward in percolating water, or runoff GWPA, where residues move offsite to sensitive sites such as drainage wells. Inside GWPA, growers choosing to apply any of the regulated active ingredients, i.e., simazine, diuron, norflurazon, bromacil, atrazine, prometon, or bentazon, all of which are herbicides, must comply with certain conditions, including costly cultural practices, restrictions on application and irrigation timing, and obtaining a permit from their County Agricultural Commissioner. The rules for applying a regulated ingredient to fields differ between runoff and leaching GWPA.

Chemical analyses of groundwater collected annually in 2000–2012 from 67 domestic wells in GWPA reveal decreasing concentrations of simazine, diuron, and bromacil, which the researchers attribute to changes in pesticide use resulting from the Groundwater Protection Program (Troiano et al., 2013). However, the study falls short of comparing groundwater contaminant concentrations in GWPA and non-regulated regions to provide the appropriate counterfactual trends required for causal inference.

Using reduced-form techniques, we exploit the natural experiment created by the Groundwater Protection Program to study the extent to which almond, citrus, and grape growers adjust their pesticide regime in response to the program, including differences in leaching and runoff areas and the associated environmental impacts. To this end, we leverage twenty-five years of Pesticide Use Reporting data, a database of California agricultural pesticide applications, and exploit changes in pesticide usage within GWPA compared to changes outside GWPA regions in a difference-in-differences regression framework.

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<sup>1</sup>Data limitations prevent us from calculating the share of cropland inside GWPA.

We analyze the impacts of the Groundwater Protection Program on three outcomes. The first is a binary outcome indicating whether a field was treated with a regulated active ingredient. The second analysis explores the program’s consequences on human health and environmental quality dimensions using the environmental impact of regulated active ingredients, which we calculate using the Environmental Impact Quotient (EIQ)—an aggregate measure of the potential harm posed by an active ingredient to farm workers, consumers, fish, birds, beneficial insects, and groundwater (Kovach et al., 1992) providing a measure of the hazard inherent to an active ingredient. We calculate the environmental impact by multiplying the pounds of active ingredient per planted acre by the corresponding ingredient EIQ, then summing over the active ingredients used at the field level. While the Groundwater Protection Program aims to safeguard groundwater, the fact that it targets a handful of active ingredients means that growers may switch to other chemicals with potentially worse outcomes for human and environmental health. Thus, our third analysis examines the impact of the program on the total environmental impact of regulated and alternative active ingredients.

To address the external cost of diffuse pesticide pollution, governments have introduced non-market solutions to address some environmental problems of pesticides, such as regulatory reviews of new products (Zilberman and Millock, 1997), Integrated Pest Management (IPM) programs (Burrows, 1983), grower education (Goodhue, Klonsky, and Mohapatra, 2010; Jacquet, Butault, and Guichard, 2011; Zhou et al., 2020) and chemical bans (Anderson, Opaluch, and Sullivan, 1985; Carter et al., 2005; Butler, 2018) with varying degrees of effectiveness (Lee, den Uyl, and Runhaar, 2019). However, economists have shown that spatially targeted policies provide economic advantages over uniform instrumentation in a number of agricultural settings, including externalities from groundwater pumping (Kuwayama and Brozović, 2013), nitrate leaching (Mapp et al., 1994; Martínez and Albiac, 2006), nutrient runoff (Lankoski and Ollikainen, 2003), and soil carbon sequestration (Antle et al., 2003). Most literature in this area focuses on ex-ante evaluations of policies integrating field-level

characteristics and management, details which are expensive to monitor, verify, and administer. Zoning offers a practical solution by delineating areas with relevant environmental characteristics.

Our study contributes to the small but growing literature on input zoning, whereby regulators restrict inputs on land with local features like permeable soils and groundwater wells (Thomsen and Thorling, 2003; Thomsen, Søndergaard, and Sørensen, 2004), rivers (Sieber et al., 2010), urban developments and highways (Goodhue, Schweisguth, and Klonsky, 2016), and schools (Goodhue et al., 2020). The Groundwater Protection Program is an example of such a zoning program. However, it differs from most other zoning programs, which tend to ban pesticide use in the defined areas and often fail to account for local environmental characteristics.

This paper also contributes to the growing literature on practice-based regulations (Ribaud, 2008; Shortle and Horan, 2013; Zhang, 2018). Motivated by a ban on the pesticide Aldicarb, Anderson, Opaluch, and Sullivan (1985) developed a model for determining field-level pesticide management practices for meeting drinking water standards. Anderson, Opaluch, and Sullivan (1985) shows that chemical bans, which are common in many agricultural regions (Donley, 2019), remove the opportunity for adjustments in pollution mitigation while keeping food affordable and might not be necessary to achieve drinking water standards. Furthermore, regulating a limited set of pesticides might lead to perverse outcomes. In one relevant example, Anderson et al. (2018) suggests that strict monitoring of organophosphate pesticides in California waterways led to toxic concentrations of the alternative active ingredient imidacloprid—a neonicotinoid.

Our study contributes to the zoning and practice-based regulation literature by providing insights into the extent to which growers in leaching and runoff GWPA differ in their response to the program. Our findings indicate that the Groundwater Protection Program markedly reduced the use of regulated active ingredients, resulting in a reduction in the probability that growers treated leaching (runoff) GWPA fields by 10 (11) percentage points

in almond orchards, 5 (11) percentage points in citrus orchards, and 19 (13) percentage points in vineyards. The reductions in active ingredient use translate to a 73% reduction in the associated environmental impacts in almond orchards in leaching GWPAs and a 54% reduction in the associated environmental impacts in almond orchards in runoff areas. In grape vineyards in leaching and runoff areas, the program led to a 44% and 39% reduction in the environmental impact of regulated pesticides, respectively. In citrus groves, the program led to a 41% reduction in runoff GWPAs, but we found no significant effect in leaching areas. We also find evidence of within-farm spillover effects in citrus farms where growers with orchards in GWPAs reduced the environmental impact of regulated active ingredients by 14% in their fields outside GWPAs. But we find no evidence of within-farm spillovers in almonds and grapes.

Another key contribution is our assessment of the perverse outcomes of the program by switching to other chemicals. Accounting for growers switching to alternative active ingredients, we find the program effect on the environmental impact varied by crop. By analyzing the environmental impact of total herbicide use (regulated and alternative active ingredients) per planted acre, we find the program led to no meaningful change in almond orchards in leaching and runoff GWPAs relative to control orchards. In grape vineyards, we observed a 15% and 11% drop in the environmental impact of herbicides per planted acre in leaching and runoff GWPAs, respectively. In citrus, the program led to a 19% drop in the environmental impact of herbicides used in runoff GWPAs but had no effect among groves in leaching areas.

Policy reforms are vital to meeting environmental quality goals ([Shortle and Horan, 2013](#)). Consequently, the status quo of agricultural exemptions from environmental regulations is slowly changing ([Zhang, 2018](#)). Examining existing agricultural environmental regulations can provide vital insights for the future design of regulations. The Groundwater Protection Program offers a unique opportunity to study the grower response to a mandatory policy over sixteen years. This paper provides critical insights into growers' responses to a pesticide

policy to prevent environmental degradation. These insights will help inform future regulatory efforts and enhance the performance of interventions designed to protect environmental quality in other regions.

The remainder of the paper is structured as follows. The next section discusses the regulatory background. Next, we describe the data sources, followed by the econometric methods. Subsequently, we present our main findings supported by several robustness checks. Finally, the last section concludes the paper.

## 2 Background

Since the passage of the Federal Water Pollution Control Act Amendments of 1972 (Clean Water Act), state and federal legislators have implemented a patchwork of regulations to address groundwater pollution from agricultural sources. Legislation regarding clean water has focused on point sources, primarily factory and sewage treatment discharges and confined animal feeding operations such as large dairies. As a result, many water quality problems remain. The 1974 Safe Drinking Water Act requires the U.S. Environmental Protection Agency to set water quality standards in public water systems, including maximum permitted concentrations of many pesticides. However, no legally enforceable standards exist for private drinking water wells or small water systems, such as those serving water to less than 25 people, which are relevant in many rural communities. Federal water quality laws have largely passed responsibility for developing non-point source programs to state governments (Ribaud, 2008).

### 2.1 The Pesticide Contamination Prevention Act

The Pesticide Contamination Prevention Act, passed by the California legislature in 1985, directed the California Department of Pesticide Regulation (CDPR) to identify pesticide active ingredients present in groundwater, pinpoint pesticide use cases that pose a risk to

groundwater, and regulate those active ingredients to mitigate or prevent further pollution.<sup>2</sup> Following their mandate, the CDPR established the Groundwater Protection Lists (a) and (b).<sup>3</sup> List (a) includes seven active ingredients detected in groundwater, which CDPR regulates to mitigate groundwater contamination and prevent further pollution of critical water resources. The list comprises seven herbicides: atrazine, bentazon, bromacil, diuron, norflurazon, prometon, and simazine.<sup>4</sup> Henceforth, we refer to the List (a) pesticides as regulated active ingredients. The seven regulated active ingredients include several products of national importance. In particular, atrazine and simazine were the most frequently detected pesticides in a national survey of surface and groundwater systems (Gilliom et al., 2006) and among the most widely used pesticides (in terms of pounds of active ingredient) in the U.S.(Weiben, 2021).

List (b) includes pesticides that CDPR deems to be a high risk for water contamination.<sup>5</sup> The CDPR monitors groundwater for List (b) active ingredients and, if detected, reviews the pesticide’s use to determine whether it should be banned, added to List (a), or allowed to be used as currently permitted.

In addition to establishing the Groundwater Protection List, CDPR began a groundwater testing and pesticide review program and subsequently banned the active ingredient atrazine in the regions where it was detected in 1987 (CDPR n.d.). These regions, called Pesticide Management Zones, follow the approximately one-square-mile section boundaries mapped in the Bureau of Land Management Public Land Survey System grid. By 1997, regulators, in collaboration with university and government researchers, detected residues or breakdown products of seven active ingredients in California groundwater. In most cases, growers could continue to use these chemicals if they agreed to follow specific management practices. By

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<sup>2</sup>The Pesticide Contamination Prevention Act extended the Farm and Agriculture Code to include sections 13141–13152. For further details, see <https://www.cdpr.ca.gov/docs/emon/grndwtr/atrazine.htm>

<sup>3</sup>The current Groundwater Protection Lists are printed in Title 3 of the California Code of Regulations Section 6800 (a) and (b).

<sup>4</sup>It exempts products with less than 7% diuron applied to foliage (mostly cotton defoliants).

<sup>5</sup>Section 6800(b) pesticides exceed certain thresholds for water solubility, soil adsorption, hydrolysis half-life, aerobic soil metabolism half-life, and anaerobic soil metabolism half-life.



2001, the CDPR extended the number of Pesticide Management Zones to 489 sections.

## 2.2 Groundwater Protection Program

In May 2004, the CDPR implemented the Groundwater Protection Program, converted the existing Pesticide Management Zones to Groundwater Protection Areas (GWPA), and added 3,129 more sections to the inventory of regulated regions, taking the total number of GWPA to 3,618.<sup>6</sup> The CDPR worked with environmental scientists to identify two pathways through which pesticides contaminate groundwater. They found that pesticides mainly enter groundwater in areas with coarse-textured soils by leaching residues from surface applications (Troiano et al., 2013). In areas with low-permeability soils, pesticides are carried by runoff water to sensitive sites such as dry wells, which provide a direct route to the groundwater. Using soil and groundwater data, CDPR mapped regions vulnerable to leaching and runoff and designated these as GWPA. As shown in Figure 1, GWPA are spread across the state, with most located in the San Joaquin Valley, the heartland of California’s agricultural production.

The Groundwater Protection Program prohibits the application of the seven regulated active ingredients in GWPA unless the grower obtains a Restricted Materials Permit from their County Agricultural Commissioner’s office specifying the management practice option that the grower agrees to adhere to.<sup>7</sup> Table 1 describes the GWPA categories with examples of management practices for regulated ingredients.

In leaching GWPA, the percolation of pesticides through coarse-textured soils is the primary concern of regulators, and growers face constraints on the cultural practices related to irrigation management when applying a regulated active ingredient. Leaching GWPA management option (1) in Table 1 is not relevant to citrus, almonds, or grapes because they are not planted in furrows, and growers typically apply regulated ingredients along tree and

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<sup>6</sup>The CDPR added a further 122 GWPA in 2020.

<sup>7</sup>Additional statewide restrictions apply to pesticides applied in canals, ditches, and artificial recharge basins; these mostly apply to non-agricultural landscape management practices.

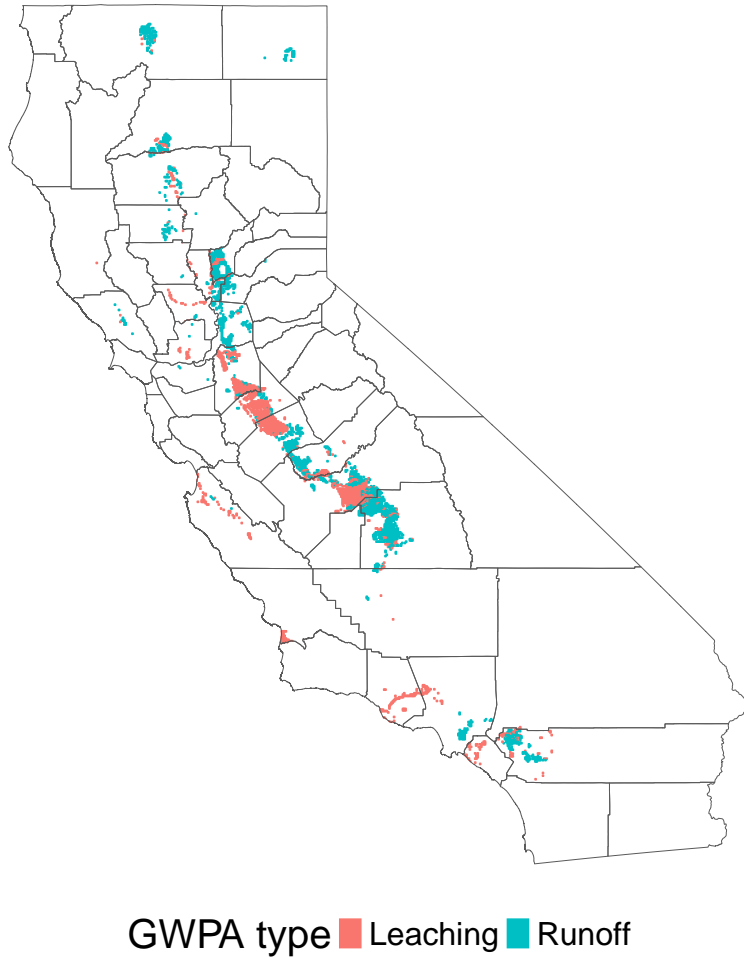


Figure 1: Groundwater Protection Areas in 2005

Note: each square represents the location of an approximately one square mile section designated as a GWPA.

vine rows where irrigation water is applied. Leaching option (2) is extremely restrictive because almost all citrus, grapes, and almonds are irrigated ([USDA 2004](#)), and San Joaquin Valley growers typically irrigate orchards, groves, and vineyards in seven to eight months of the year ([Haviland et al., 2019](#); [Murdock, Goodrich, and Sumner, 2022](#); [Kallsen et al., 2021](#)). The extent to which growers exceed crop irrigation requirements by a factor of 1.33, as in option (3), is unclear.

In runoff GWPA, growers face four management options when using a regulated ingre-

dient. Runoff option (1) in Table 1 requires growers to apply regulated ingredients in low rainfall months. However, the regulated active ingredients are all pre-emergent herbicides and only kill germinating plants. By April, enough weeds will have typically germinated to create a canopy that prevents chemicals from reaching the soil, lowering the efficacy of the spray. Option (2) requires costly infrastructure in most cases. In management options (3) and (4), growers can comply with the program by incorporating the spray into the land surface, where chemicals bind with soil particles to prevent runoff. However, land tilling around established trees and vines is a costly practice. Option (4) also allows growers to incorporate the ingredients into the soil surface by applying irrigation water by drip or micro-sprinkler. This might suit growers who can coordinate a regulated ingredient application with October irrigation. October is typically the last month almond, citrus, and grape growers irrigate fields before the dormant fall and winter months (Haviland et al., 2019; Murdock, Goodrich, and Sumner, 2022; Kallsen et al., 2021).

## 2.3 Weed Management in Almond, Citrus, and Grape Production

We apply our econometric framework to data from almonds, citrus, and grapes for four key reasons. First, they represent the leading crops by the value of production throughout the past two decades and occupy a large share of the cultivated cropland (CDFA 2003; CDFA 2022).<sup>8</sup> Second, regulated active ingredients are important herbicides in the growers' weed management toolbox, as measured by the acres treated with regulated and alternative active ingredients in 1996–2004 (see Appendix Table A1). In particular, citrus growers treated more acres with simazine and diuron than most other active ingredients, except for glyphosate, oxyfluorfen, and paraquat—three alternative herbicides. Third, almond, citrus, and grape crops represent key markets for the regulated active ingredients bromacil, diuron, norflurazon, and simazine, as shown in Appendix Table A2. Specifically, citrus growers

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<sup>8</sup>Grapes and almonds ranked as the second and third largest crops, respectively, in terms of farm receipts in 2003 and 2022 (CDFA 2003; CDFA 2022). Oranges—the top citrus crop—were the fourth largest commodity in 2022. Other major citrus crops include lemons and grapefruit.

use nearly all of the bromacil applied in pre- and post-program years. Additionally, citrus orchards are the dominant market for diuron products, almonds are the top market for norflurazone, while grape, citrus, and almond growers apply 39%, 35%, and 10% of the simazine, respectively. Lastly, concentrating on perennial crops allows us to track fields over time.

To further contextualize the Groundwater Protection Program and the relevance of herbicide restrictions to growers, it is worth highlighting some key facts about weed management common to almond, grape, and citrus cultivation. Weeds compete with crops for nutrients and water. They also block irrigation systems, provide habitat for insect pests and diseases, and impede other agricultural practices and harvest. The presence of weed seeds in the soil and seeds deposited in fields by the wind or animals makes weed management a perpetual challenge. To prevent infestations and eliminate established weeds, growers may use a combination of cultural and chemical practices, many of which are consistent with Integrated Pest Management programming. Examples include monitoring fields to identify weed species and locations and target plants with the appropriate herbicide at the correct time. Mowing weeds before seed set prevents their spread and kills some species. Irrigation management can also play a role. Allowing the top two inches of soil to dry out between irrigation applications limits weed establishment ([Grafton-Cardwell et al., 2003](#)) and preventing water pooling in fields eliminates an ideal environment for weed growth.

### 3 Data

The CDPR began mandatory reporting of agricultural pesticide applications in 1990. These data are published in the Pesticide Use Report (PUR), which we use as our primary data source. This detailed database includes over thirty variables at the field level, including the active ingredients, treated acres, planted acres, crop, and the date of each application.<sup>9</sup>

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<sup>9</sup>Growers may treat a portion of the field during a pesticide application. Therefore, the treated acres can be less than or equal to the field size—called planted acres in the PUR data.

Table 1: Groundwater Protection Area Overview

GWPA category	Category description	Management practice options
Leaching	Pesticide residues and their breakdown products move from the land surface downward through the soil with percolating water to reach groundwater. Soils in these areas are coarse with relatively rapid infiltration rates.	(1) Growers can apply pesticides to the planting bed above the level of irrigation water in the furrow so it has no contact with leaching irrigation water. (2) No irrigation water is applied for six months. (3) The volume of irrigation water divided by the crop irrigation requirement is less than 1.33 for six months.
Runoff	Pesticide residues and their breakdown products are carried in runoff water through direct routes to groundwater, such as dry wells or drainage wells, poorly sealed production wells, soil cracks, or areas where leaching can occur. Soils in these areas may have a hardpan layer and/or low infiltration rates.	(1) The pesticide is applied between April 1 and July 31. (2) All irrigation runoff and all precipitation on and drainage through the field are retained onsite for six months after application (the retention area on the field should not have a percolation rate of more than 0.2 inches per hour). (3) The soil is disturbed within seven days before pesticide application by using a disc, harrow, rotary tiller, or other mechanical method. (4) The pesticide is incorporated on at least 90% of the area treated within seven days after pesticide application by a mechanical method or by low-flow irrigation (1/4 to 1 inch of water).

Source: Adapted from Cal. Code Regs. Tit. 3, §6487.4 and §6487.5

Combining a unique grower number, field name, and crop provides a unique field identifier, allowing us to track pesticide use on each field over time.

We limit our analysis to the years 1996 through 2020 due to inaccurate reporting of key variables in the early years of PUR. Similarly, we exclude Monterey County fields from our analysis due to persistent data issues.<sup>10</sup> Moreover, the variable for planted acres contains numerous inconsistent observations. To address this issue, we utilize the maximum treated

<sup>10</sup>In 2003, Monterey County contained about 4% of California harvested grape acres, 0.4% of citrus acres, and no almond orchards ([California Department of Food and Agriculture, 2004](#))

acres within a field each year to obtain a more accurate estimate of field size and refer to this measurement as planted acres.

In the raw data, we observe several entries with extreme pounds per acre when dividing the quantity of active ingredients by the treated acre. We anticipate a low variance in the application rate, as growers typically adhere to the product label’s recommended application rate. To address this issue, we winsorize the data, which involves replacing application rates below the first percentile with values equal to the first percentile and setting application rates above the 99th percentile equal to the 99th percentile for each product. Visually appraising the data and using our best judgment, we believe that the extreme pounds per acre are due to misreported quantities of product. Therefore, we recovered a reliable quantity of active ingredients by multiplying the winsorized pounds per acre by the reported treated acres.

We include orange, lemon, tangerine, grapefruit, lime, tangelo, and pomelo crops in the citrus category. We focus on the aggregate citrus category because the plant varieties require similar herbicide management strategies (Grafton-Cardwell et al., 2003, 2019). Similarly, grapes include table, raisin, and wine grapes, which require similar weed management practices (Bentley et al., 2003; Haviland et al., 2015).

Pesticide Management Zones (PMZs)—the precursor to the Groundwater Protection Program—predate our available data and introduce a potential source of bias to our econometrics. We exclude growers with fields inside PMZs from the econometric analysis to overcome the potential bias that the PMZ program introduces.

We use two additional datasets from government sources. First is a spatial database of the geographic coordinates of section boundaries mapped by the Bureau of Land Management, called the California Public Land Survey System, which we match to pesticide use data using the section code. Second is a database of sections in GWPA from the CDPR.

A small proportion of fields lie inside the CDPR-defined GWPA category called leaching/runoff.<sup>11</sup> In the combined leaching/runoff GWPA, growers that wish to use a regulated

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<sup>11</sup>About 1% of almond orchards, 0.3% of citrus groves, and 0.4% of grape vineyards lie inside leaching/runoff GWPA in our effective sample of fields with observations in the pre-program and post-program

active ingredient must adopt management practices from the leaching and runoff options listed in Table 1. To include these observations in the analysis, we recode them as leaching GWPAs because leaching areas have a more stringent set of restrictions, and most leaching/runoff GWPAs are located close to leaching GWPAs.

### 3.1 Definition of Herbicide Application Year

The CDPR began enforcing GWPA rules in May 2004 (Troiano et al., 2013), which coincides with the middle of the almond and grape growing season and the start of the summer months when growers do not typically apply regulated active ingredients. We find that growers typically apply pre-emergent herbicides—herbicides applied to soil and kill germinating plants—including all regulated ingredients during the fall and winter months, as shown in Appendix Figure A2. This finding is corroborated by the University of California’s Cost Studies, which detail typical weed management practices (Haviland et al., 2019; Kallsen et al., 2021; Murdock, Goodrich, and Sumner, 2022). Therefore, we define annual periods from October 1st through September 30th to capture a typical regulated herbicide application season for almonds, citrus, and grapes. This definition means that almost all regulated active ingredient applications in the 2004 season occurred before the program enforcement in May. Thus, we use October 2003 through September 2004 as the reference year in the regressions and name the period 2004.

Post-emergent herbicides—sprayed on the leaves of growing weed plants—like glyphosate applied in the summer months before almond and grape harvest challenge our econometric estimation of the program impact on the environmental impact of regulated plus alternative herbicides. For regressions involving the environmental impact of regulated plus alternative herbicides as the outcome variable, we estimate regressions with annual periods defined as June through May as a robustness check.

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periods.

### 3.2 Aggregation of Pesticides: Environmental Impact Quotient

Pesticides are difficult to aggregate. The heterogeneity of pesticide qualities, such as formulation with other chemicals and efficacy, means that the manufacturer’s recommended quantity of active ingredient applied per acre can vary by an order of magnitude or more between two chemicals targeting similar pests. In addition, the quantity of product is inadequate for evaluating the environmental consequences of pesticide practices (Barnard et al., 1997). For these reasons, summing over the pounds of chemicals used provides an inappropriate single measure of pesticide quantities (Mullenn et al., 2005; Grogan and Goodhue, 2012). To overcome these issues, we use the Environmental Impact Quotient (EIQ) (Kovach et al., 1992) to aggregate active ingredients and to capture the potential environmental harm from a chemical. Each active ingredient in our study has an associated EIQ, which considers potential harm to farm workers, aquatic life, beneficial insects, and consumers. Larger EIQs are associated with more environmental harm. We multiply the EIQ by the pounds of the regulated active ingredient, then sum over the active ingredients, and divide by the planted acres to produce a measure of environmental impact per planted acre at the field level according to the following formula:

$$\text{Environmental impact} = \frac{1}{\text{planted acres}} \sum_i EIQ_i lb_i$$

where  $i$  denotes the active ingredient and  $lb$  denotes the annual pounds of active ingredient applied to the field. We follow a similar calculation for alternative (non-regulated) herbicides. The EIQ for relevant herbicides can be found in Appendix B Table A1.

Understanding growers’ use of alternative herbicides involves identifying active ingredients that target similar weeds as regulated chemicals. We use the manufacturers-specified target weed descriptions published by the CDPR to address this analytical challenge. Our list of 95 alternative herbicide active ingredients share at least one target weed species with a regulated chemical. Many alternative ingredients are minor, and we present the top 27 chem-



icals in Appendix Table A1. The main alternative herbicides are glyphosate, oxyfluorfen, paraquat, oryzalin, and 2,4-d. These top alternatives appear in the University of California Integrated Pest Management Guidelines for almonds, citrus, and grapes, further supporting our list of alternative active ingredients (Haviland et al., 2015, 2017; Grafton-Cardwell et al., 2019).

## 4 Econometric Methods

We estimate several regression models based on the difference-in-difference framework to analyze the impacts of GWPA on three outcomes: (1) the probability that a grower sprays a field with a regulated active ingredient within a year, (2) the environmental impact of regulated active ingredients per planted acre, and (3) the environmental impact of regulated and alternative herbicide active ingredients per planted acre. We use a fixed effects linear probability model using field, year, and county-by-year controls to evaluate the impact of GWPA on the likelihood of growers using a regulated active ingredient. For the environmental outcomes, we employ fixed effects Poisson regression models. Additionally, we expanded the two-period difference-in-difference regressions to event study models with one treatment cohort to measure how treatment effects varied by year, thereby revealing how growers responded to the policy over time.

The Groundwater Protection Program is exogenous to trends in pesticide use in individual fields. However, we make the stronger assumption that unobservable field-level time-varying factors do not affect GWPA assignment. Therefore, in the absence of the program, the treatment and control groups adjust their pesticide use in similar ways, and fields outside GWPA within the same county serve as an appropriate counterfactual. We test for parallel pre-trends and present these results in section 5.3. In addition, we employ the Stable Unit Treatment Value Assumption (SUTVA), which ensures that the analysis adequately distinguishes between treatment and control groups. Growers with some fields inside and others

outside GWPAs may violate SUTVA if the grower alters their pesticide practices across the whole farm in response to the program. To address concerns about potential violations of this assumption, we add controls for within-farm spillover effects in some of our regressions.

To further strengthen our identification strategy, we include county-by-year fixed effects. These controls address concerns regarding time-varying county-specific bias from weather and local administration of the Groundwater Protection Program. Weather is difficult to control econometrically in the current setting because growers face a broad window of opportunity—six months or more—to apply herbicides. Therefore, average or cumulative weather does not adequately reflect weed growth or practical issues like field access. Pre-emergent and post-emergent herbicides further complicate the identification of a relevant spraying window and associated weather variables. Furthermore, county agricultural commissioners administer the program by issuing permits with designated alternative management practices within GWPAs. During our long study period, the relative stringency and convenience of permitting across counties might change over time.

## 4.1 Difference-in-Differences

To construct the base regression equations, let  $Y_{it}$  denote the outcome variable for field  $i$  in year  $t$  and  $G_{it}$  denote the program treatment variable that equals one when field  $i$  is inside a GWPA in 2005 onwards and zero otherwise. Additionally, the symbol  $\gamma_i$  captures field fixed effects,  $\tau_t$  denotes the year effect common across fields,  $\delta_c$  denotes county fixed effects, and  $\varepsilon_{it}$  represents the idiosyncratic error. This notation is common to the econometric models specified below.

The linear probability model, given in Equation (1), contains the dependent variable  $Y_{it}$ , which equals one if the grower applies one or more regulated active ingredients to field  $i$  in year  $t$ .

$$P(Y_{it} = 1|G_{it}, W_{it}, \gamma_i, \tau_t, \delta_c) = \gamma_i + \tau_t + \delta_c\tau_t + \alpha G_{it} + \varepsilon_{it} \quad (1)$$

The treatment coefficient  $\alpha$  captures the average GWPA program effect from 2005 through 2020. The average treatment effect  $\alpha$  is identified from within-field changes in regulated active ingredient use in GWPA fields relative to fields in the same county that are outside a GWPA.

To examine the effect of the GWPA program on the environmental impact of regulated and alternative active ingredients, we use a fixed effects Poisson regression of the following form:

$$Y_{it} = \exp\{\gamma_i + \tau_t + \delta_c \tau_t + \beta G_{it}\} \varepsilon_{it} \quad (2)$$

where the treatment coefficient  $\beta$  captures the change in the log of environmental impacts per planted acre due to the GWPA policy. In the results tables, we transform the coefficient  $\beta$  into a percentage impact, which we calculate as  $e^\beta - 1$ . We use a Poisson estimator because it effectively deals with nonnegative outcomes, particularly zero values and rightward skewed distributions of the environmental impact outcomes. While the Poisson model is commonly used for count data, the dependent variable doesn't have to be an integer and provides a consistent estimate so long as the expected mean is correctly specified, that is  $E[Y_{it}|x] = \exp(\beta x_{it})$  (Silva and Tenreiro, 2006).

During the study period, some counties introduced permitting requirements and other restrictions on alternative herbicides, such as paraquat and 2-4D, due to local environmental and health concerns (Zalom et al., 2002; Grafton-Cardwell et al., 2003; Bentley et al., 2003). In our econometric models, the county-by-year fixed effects absorb the variation from regulatory shocks common to all growers in a county.

As described in Table 1, the rules for using regulated active ingredients differ according to the GWPA type. To distinguish the effects of leaching and runoff GWPAs, we extend our base regressions defined in Equations 1 and 2 with models that replace  $\alpha G_{it}$  with the terms  $\alpha_r G_{it}^{runoff} + \alpha_l G_{it}^{leaching}$ . Here,  $\alpha_r$  and  $\alpha_l$  capture the treatment effect of runoff and leaching GWPAs, respectively.

In a second extension to our base equations, we control for potential within-farm spillover

effects of the policy. To do this, we add the variable  $W_{it}$  that equals one if the field is outside a GWPA managed by a grower with a field inside a GWPA in 2005 onwards and zero otherwise. In all regressions, we cluster standard errors by the field to allow for heteroskedasticity across fields and autocorrelation of the error terms over time for a field.

## 4.2 Event Study

We use event study regressions to explore how growers respond to leaching and runoff GWPA over time, controlling for within-farm spillover effects. The event study has one treatment cohort regulated in the first year of the Groundwater Protection Program and affecting pesticide use from 2005—defined as October 2004 through September 2005—onwards. Although the event study framework is routinely applied to investigate events staggered over time, it has been utilized in prior literature to analyze interventions involving one treatment cohort (Earnhart and Hendricks, 2023).

The event study model introduces additional notation, namely,  $G_i^{runoff}$  representing the time-invariant runoff treatment variable that equals one when field  $i$  is inside a runoff GWPA and zero otherwise,  $G_i^{leaching}$  that equals one when field  $i$  is inside a leaching GWPA and zero otherwise,  $W_i$  denoting the time-invariant within-farm spillover control variable that equals one if the field is outside a GWPA managed by a grower with a field inside a GWPA, and  $T_t$  denoting a year dummy equal to one when  $T = t$  and zero otherwise.

For regressions involving the binary outcome variable of field treated with a regulated active ingredient, we estimate a fixed effects linear probability model of the following form:

$$P(Y_{it} = 1 | G_i^{leaching}, G_i^{runoff}, W_i, \gamma_i, \tau_t, \delta_c) = \gamma_i + \tau_t + \delta_c \tau_t + \sum_{\substack{T=1996 \\ T \neq 2004}}^{2020} (\alpha_l^T G_i^{leaching} T_t + \alpha_r^T G_i^{runoff} T_t + \omega^T W_i T_t) + \varepsilon_{it} \quad (3)$$

where the treatment coefficient  $\alpha_l^T$  identifies the change in the probability that growers spray leaching GWPA fields with regulated active ingredients in year  $T$  compared to the change in regulated active ingredient use in control fields in year  $T$  relative to the baseline year 2004. The treatment coefficients for runoff areas,  $\alpha_r^T$ , and within farm spillover control fields,  $\omega^T$ , have similar interpretations.

To examine the effect of the GWPA policy on the environmental impact of herbicides over time, we estimate the following fixed effects Poisson model:

$$Y_{it} = \exp(\gamma_i + \tau_t + \delta_c \tau_t + \sum_{\substack{T=1996 \\ T \neq 2004}}^{2020} (\beta_l^T G_i^{\text{leaching}} T_t + \beta_r^T G_i^{\text{runoff}} T_t + \omega^T W_i T_t)) \varepsilon_{it}. \quad (4)$$

Here, the leaching treatment coefficient,  $\beta_l^T$ , has the interpretation of a  $(e^{\beta_l^T} - 1) * 100$  percent change in the environmental impact per planted acre in year  $T$  relative to 2004.

## 5 Results and Discussion

We observe 9,482 almond orchards, 4,550 citrus groves, and 18,797 grape vineyards with observations in the pre-program (1996–2004) and post-program (2005–2020) periods with a meaningful share of fields treated. Table 2 provides the count and proportion of fields in each GWPA category.

Table 2: Summary of Effective Sample of Fields by Groundwater Protection Area Regulation

GWPA category	Count of fields			Share of fields (%)		
	Almond	Citrus	Grape	Almond	Citrus	Grape
Leaching	2801	218	2144	29.54	4.79	11.4
Runoff	294	812	1005	3.10	17.85	5.35
Non-GWPA	6387	3520	15648	67.36	77.36	83.25

Given our lengthy twenty-six-year panel, growers plant new almond orchards and remove old ones, and some orchards change hands. Removing old orchards and changes in ownership lead to attrition in our sample and an unbalanced panel. It is a similar story for citrus groves

and vineyards.<sup>12</sup> We assume that attrition is unrelated to GWPA treatment because weed management is a small share of the production costs, and growers face other opportunities to adapt to the program at a lower cost compared to removing the established perennial crop or selling the field.<sup>13</sup>

Table 3 presents summary statistics of the dependent variables for the period before the program (1996–2004). It shows that growers sprayed a higher proportion of GWPA fields with regulated active ingredients compared to fields outside GWPAs (control fields), resulting in a higher environmental impact of regulated active ingredients per planted acre. We consider fields as sprayed with a regulated active ingredient if they receive any amount of regulated active ingredient within the year.<sup>14</sup> The mean environmental impact of herbicides (regulated and alternatives) is slightly larger in almond GWPA (44) and compared to control (43) fields, and in citrus GWPA fields (72) compared to citrus control fields (70), but lower in grape GWPA fields (32) relative to grape control fields (35). Notably, the mean environmental impact of regulated active ingredients per planted acre is roughly 8–10% of the mean environmental impact of herbicides per planted acres among almond fields compared to 24–38% in grapes and 58–63% in citrus. While the mix and quantity of active ingredients play a role in the environmental impact, it is clear that regulated ingredients play a dominant role in chemical weed management in citrus production in pre-program years compared to almonds and grapes. The extensive use of regulated active ingredients in citrus groves compared to almond orchards and vineyards is further supported by data in Appendix Table A1. Dividing the acres treated with regulated active ingredients by the acres treated with regulated and alternative ingredients in Appendix Table A1 reveals that regulated active ingredients account for 34% of citrus acres treated with herbicides, compared to 21% in

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<sup>12</sup>The life of almond orchards and vineyards is around 25 years while a typical orange and lemon grove will last for 40 years (Haviland et al., 2019; Kallsen et al., 2021; Murdock, Goodrich, and Sumner, 2022).

<sup>13</sup>Weed management is about 1% of almond production costs, 1.5% of orange costs, and 2% of of the cost to produce wine grapes (Haviland et al., 2019; Kallsen et al., 2021; Murdock, Goodrich, and Sumner, 2022).

<sup>14</sup>This definition means that if one acre of a ten-acre field is treated with a regulated active ingredient, we count the field as treated. Similarly, if a grower sprays the whole field multiple times with different regulated active ingredients, we count it as treated.

vineyards, and 8% in almond orchards.

During the pre-program period of 1996–2004, citrus, grape, and almond growers had access to several alternative chemicals, including some recommended in the University of California Integrated Pest Management (UC IPM) guidelines—a public resource used by pest control advisers, growers, and farm advisers. The UC IPM guidelines from around 2003 recommend 12 active ingredients for weed control in almond orchards (Zalom et al., 2002), 18 active ingredients for weed control in citrus groves (Grafton-Cardwell et al., 2003), and 15 active ingredients for weed control in grape vineyards (Bentley et al., 2003). Additionally, as shown in Appendix Table A1, growers use a long list of alternative herbicide chemicals, with most ingredients used on a small proportion of treated acres. Of course, the number of alternative herbicide products is more nuanced than the UC IPM guidelines and data indicate as regulators approve pesticide formulations for specific crops rather than approving active ingredients.

As the next step in our analysis, we plot the three dependent variables for almond, citrus, and grape fields inside and outside GWPAs over time in Figures 2, 3, and 4. Figures 2 and 3 reveal kinks in the GWPA trends in 2005, the first year of the program. The almond GWPA trend exhibits the most dramatic effect, with the share of fields sprayed decreasing from about 30% to about 5% in 2007 before gradually declining through 2020. In contrast, the drop in the share of fields treated is less pronounced in citrus and grape GWPA fields, with both groups showing a slight increase in 2006 before dropping again in 2007. The control field trends do not reveal any response to the program in 2005 but trend toward zero throughout the length of the panel.

The trends in the environmental impact of regulated active ingredients in Figure 3 follow a broadly similar pattern in almonds, citrus, and grapes to those in Figure 2. Differences in the patterns of trend lines between the figures are driven by the pounds per acre applied, although the mix of active ingredients also plays a role.

Overall, Figures 2 and 3 provide evidence that changes in regulated active ingredient use

Table 3: Summary Statistics: 1996–2004

Crop	Dependent variable	Control Fields		GWPA Fields	
		Mean	Std. Dev.	Mean	Std. Dev.
Almond	Share of fields sprayed with regulated active ingredients	0.22	0.42	0.32	0.47
Almond	Environmental impact of regulated active ingredients per planted acre	3.5	9.3	4.3	9.4
Almond	Environmental impact of herbicide active ingredients per planted acre	43	49	44	61
Citrus	Share of fields sprayed with regulated active ingredients	0.44	0.5	0.46	0.5
Citrus	Environmental impact of regulated active ingredients per planted acre	41	72	45	81
Citrus	Environmental impact of herbicide active ingredients per planted acre	70	94	72	110
Grape	Share of fields sprayed with regulated active ingredients	0.33	0.47	0.52	0.5
Grape	Environmental impact of regulated active ingredients per planted acre	8.3	20	12	19
Grape	Environmental impact of herbicide active ingredients per planted acre	35	62	32	58

Note: Statistics calculated using annual periods that coincide with pre-emergent herbicide application season beginning in October each year. For example, 1996 includes observations from October 1995 through September 1996.

around 2005 result from the Groundwater Protection Program. The similar trends in 1996–2004 add further validity to our assumption that GWPA-treated and control fields would have followed similar trends in the absence of the program. We formally test the parallel pre-trends assumption in a series of robustness checks that follow our results.

Figure 4 shows the trends in the environmental impact of herbicides (regulated and alternative active ingredients) per planted acre. There is no obvious discontinuity in the trends resulting from the program. However, the environmental impact of herbicides in almond orchards increased from around 40 in 1996–2004 to 80 in recent years. Zhan and Zhang (2014) also observed a significant rise in the kilograms of herbicides used per planted acre in almond orchards starting in 2001, which they attribute to a shift in weed management



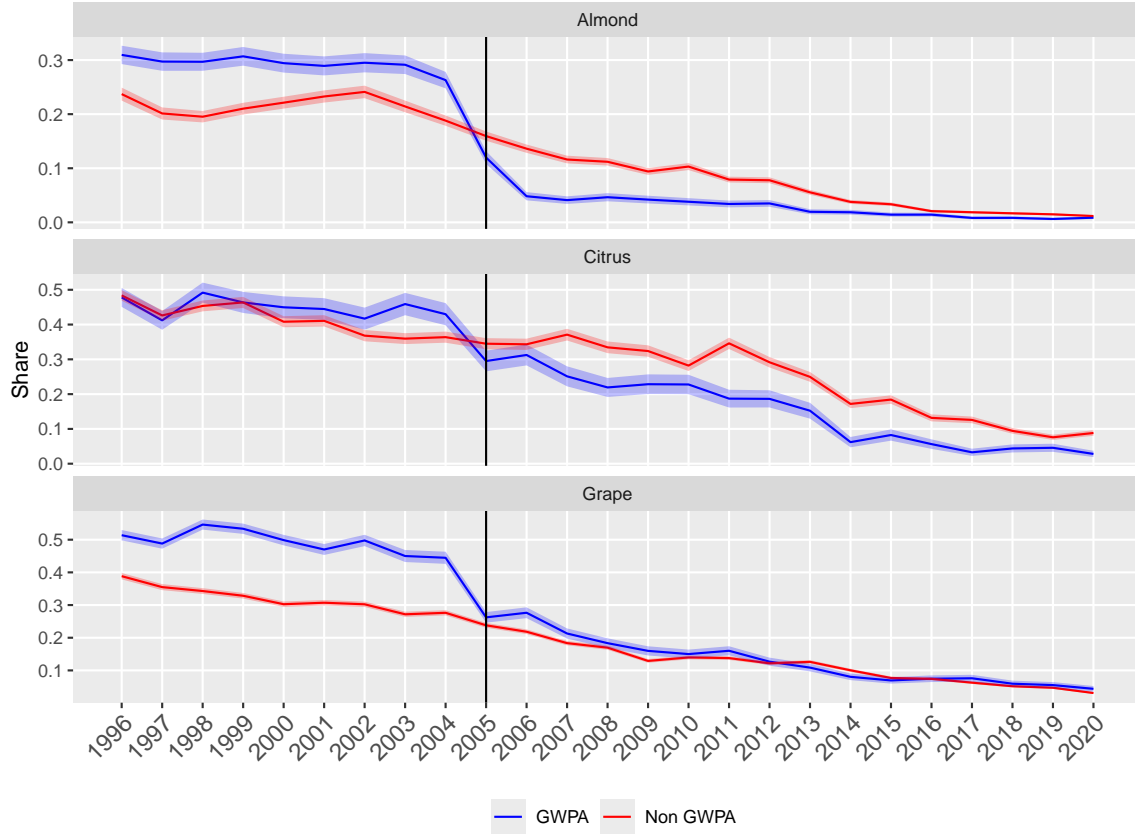


Figure 2: Share of fields treated with regulated active ingredient.

practices and increasing weed resistance to glyphosate. The authors mention that simazine and norflurazone, two regulated ingredients, were replaced with herbicides that were less likely to leach. Still, they do not provide any policy context for this change.

Over the 1996–2021 study period, the quantity of regulated active ingredients used in California decreased significantly, as shown in Appendix Figure A1.<sup>15</sup> Explaining the drop in regulated active ingredient use among growers not directly affected by the Groundwater Protection Program is difficult because of the lack of appropriate data from other regions to serve as a control group. Therefore, ascribing the extent to which the program affected statewide regulated active ingredient use is beyond the scope of this study. Nonetheless, herbicide use in fields in non-program regions serves as an appropriate counterfactual.

<sup>15</sup>The ingredient bentazon is the exception, and the quantity used in California increased from about one thousand pounds in 1996 to eight thousand pounds in 2020. However, growers use bentazon on a small share of cropland, primarily legumes.

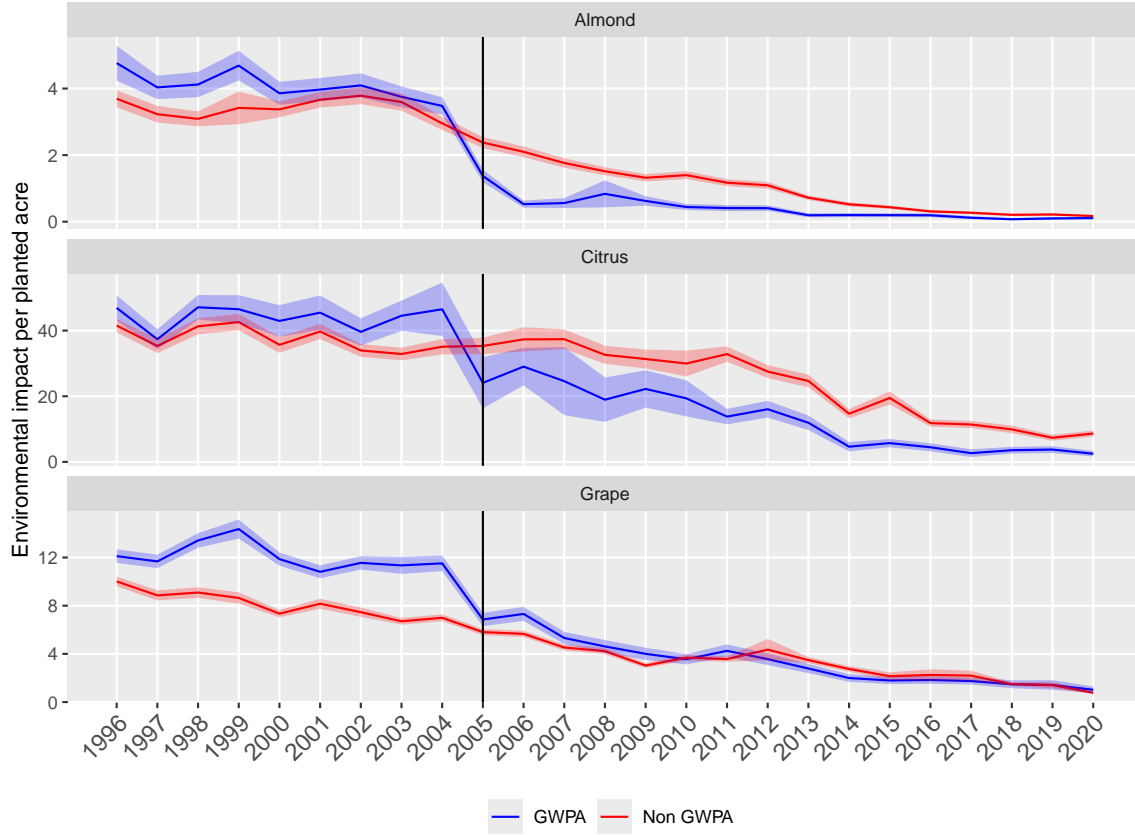


Figure 3: Environmental impact of regulated active ingredients per planted acre.

## 5.1 Difference-in-Differences

Results tables 4, 5, and 6 include estimates of three model specifications for each crop that provide the following estimates: (1) the average treatment effect of a field being assigned to a GWPA, (2) the average treatment effects of a field being assigned to a leaching or runoff GWPA, and (3) the average treatment effects of a field being assigned to a leaching or runoff GWPA and the within-farm spillover effect of a field outside a GWPA that is managed by a grower with a field inside a GWPA. Comparing estimates across these specifications reveals meaningful differences in the effects of leaching and runoff GWPA treatments and the impact of within-farm spillover controls on the GWPA treatment effects.

Estimation results of Equation 1, presented in Table 4, strongly indicate that the Groundwater Protection Program led to a decrease in applications containing regulated active ingre-

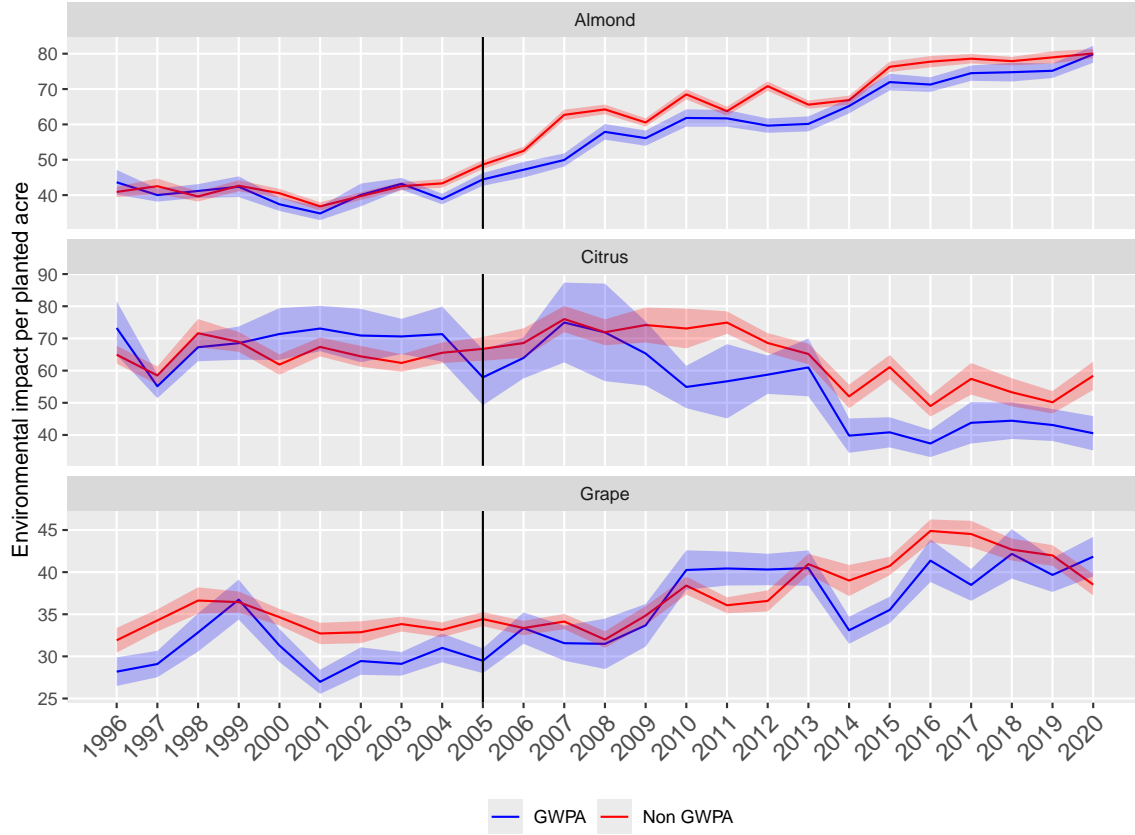


Figure 4: Environmental impact of regulated plus alternative active ingredients per planted acre.

dients relative to control fields. Panel A contains estimates of the average treatment effect of GWPA and shows that the probability that grape growers applied a regulated active ingredient decreased by 16 percentage points. The program effect was slightly smaller in citrus and almond fields. However, the mean share of almond fields sprayed with a regulated active ingredient in the pre-program period was small (32%) compared to citrus (46%) and grapes (52%). Therefore, in percentage terms, GWPA treatment led to a 31% decrease in the share of almond fields treated with regulated active ingredients, a 31% decrease in the share of grape fields treated, and a 13% drop in the share of citrus fields treated.

Distinguishing between GWPA types, as in Panel B of Table 4, we find the largest effect on grape fields in leaching GWPA. For instance, the probability that growers treated grape fields in leaching GWPA with a regulated active ingredient decreased by 18 percentage

points compared to an 11 percentage point drop among fields in runoff areas. In almonds, the coefficients on leaching and runoff are similar. We find no significant change in the probability that growers treated citrus fields in leaching GWPA with regulated active ingredients and an 8 percentage point drop in runoff areas. These results provide evidence that growers respond differently to the leaching and runoff rules. In particular, grape growers are more likely to respond to the leaching area rules by eliminating regulated active ingredients from their pesticide program.

Table 4: Impact of the Groundwater Protection Program on the Probability Growers Treated Field With Regulated Active Ingredients

	Almond (1)	Citrus (2)	Grape (3)
<i>Panel A: Average GWPA treatment effect</i>			
GWPA	-0.10*** (0.01)	-0.06*** (0.02)	-0.16*** (0.01)
Observations	130,292	58,378	177,879
R <sup>2</sup>	0.41	0.47	0.46
<i>Panel B: Average effect of leaching and runoff GWPA</i>			
Leaching GWPA	-0.10*** (0.01)	-0.01 (0.02)	-0.18*** (0.01)
Runoff GWPA	-0.11*** (0.03)	-0.08*** (0.02)	-0.11*** (0.01)
Observations	130,292	58,378	177,879
R <sup>2</sup>	0.41	0.47	0.46
<i>Panel C: Average effect of GWPA with spillover control</i>			
Leaching GWPA	-0.10*** (0.01)	-0.05* (0.03)	-0.19*** (0.01)
Runoff GWPA	-0.11*** (0.03)	-0.11*** (0.02)	-0.13*** (0.02)
Field outside GWPA, grower has field inside a GWPA	-0.01 (0.01)	-0.09*** (0.02)	-0.03*** (0.01)
Observations	130,292	58,378	177,879
R <sup>2</sup>	0.41	0.47	0.46

Note: Regressions include year, field, and county by year fixed effects. Standard errors in parentheses are clustered by field. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

Panel C reveals that the program effect spills over into citrus and grape fields outside GWPA that are managed by growers with fields inside GWPA. These “weakly-treated”

citrus and grape fields exhibit a 9 and 3 percentage point drop, respectively, in the probability of being sprayed with a regulated active ingredient. The coefficients on fields outside GWPAs have the same sign as the leaching and runoff point estimates, leading to an increase in the magnitude of the GWPA treatment effects and demonstrating the full extent of the Groundwater Protection Program compared to control fields. The sign of the within-farm spillover effect is not surprising for several reasons. First, many of the regulated active ingredients are used on other crops and in other regions. Therefore, we do not expect large or persistent price effects that may incentivize growers to use regulated active ingredients in non-GWPA fields. Second, it is inconvenient for a grower to purchase, store, and apply different herbicide products across their farm. Lastly, the program likely increased awareness of pesticide groundwater contamination among farmers in GWPAs. This potential explanation is supported by the findings of [Beach and Carlson \(1993\)](#), who show that herbicide leaching and water quality characteristics are important factors in explaining farmer pesticide purchases. In addition, many growers hire professional pest control advisers, who likely consider similar price, convenience, and environmental factors when providing pest management recommendations.

Next, we turn to the effect of the program on the environmental impact of regulated active ingredients per planted acre, which we estimate by fixed-effect Poisson regression as defined in Equation 2. Panel A of Table 5 reveals that GWPA treatment decreased the environmental impact of regulated active ingredients per planted acre by 70%, 35%, and 44% in almond, citrus, and grape fields, respectively. Panel B shows that leaching GWPAs have a larger effect than runoff areas for almonds and grapes. Controlling for within-farm spillovers, as in Panel C, we find a 14% reduction in the environmental impact per acre among citrus fields outside GWPAs that are managed by a grower with a field inside a GWPA. However, the within-farm spillover effect among almond and grape fields is small and insignificant.

We find that 81% of almond orchards, 63% of citrus groves, and 74% of grape vineyards in our sample never receive a regulated active ingredient application. For these fields, the

environmental impact outcome equals zero in all periods and is perfectly predicted by the field fixed effect. Such fields provide no information for estimating the treatment effects and are dropped before estimating the Poisson model (Silva and Tenreyro, 2010). Hence, the regressions presented in Table 5 include fewer observations than those estimated by the linear probability model.

Table 5: Impact of the Groundwater Protection Program on the Environmental Impact of Regulated Active Ingredients Applied per Planted Acre

	Almond (1)	Citrus (2)	Grape (3)
<i>Panel A: Average GWPA effect</i>			
GWPA	-0.70*** (0.02)	-0.35*** (0.05)	-0.44*** (0.02)
Observations	67,294	45,448	115,764
Pseudo R <sup>2</sup>	0.39	0.47	0.37
<i>Panel B: Average effect of leaching and runoff GWPAs</i>			
Leaching GWPA	-0.73*** (0.02)	-0.09 (0.18)	-0.45*** (0.03)
Runoff GWPA	-0.54*** (0.07)	-0.37*** (0.05)	-0.40*** (0.04)
Observations	67,294	45,448	115,764
Pseudo R <sup>2</sup>	0.40	0.47	0.37
<i>Panel C: Average effect of GWPAs with spillover control</i>			
Leaching GWPA	-0.73*** (0.03)	-0.16 (0.16)	-0.44*** (0.03)
Runoff GWPA	-0.54*** (0.07)	-0.41*** (0.05)	-0.39*** (0.04)
Field outside GWPA, grower has field inside a GWPA	0.01 (0.06)	-0.14** (0.06)	0.05 (0.04)
Observations	67,294	45,448	115,764
Pseudo R <sup>2</sup>	0.40	0.47	0.37

Note: Regressions include year, field, and county by year fixed effects. Estimates presented here equal the relative impacts of a discrete change in GWPA treatment calculated using the formula  $e^{\beta} - 1$ . Multiplying the point estimate presented by 100 equals the effect in percentage terms. We calculated the standard errors of the relative impacts using the Delta method. Standard errors in parentheses are clustered by field. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

The third outcome we focus on is the environmental impact of regulated plus alternative active ingredients per planted acre. Alternative herbicides target weeds similar to regulated

actives, so we estimate the net impact of these herbicide treatments on the environment. Focusing on Panel C of Table 6, we find that almond growers adjusted their pesticide use in such a way that the program led to no effect on the environmental impact of herbicides, with point estimates that are small and not statistically different from zero. On the other hand, grape growers changed the mix and quantity of herbicides used, resulting in a 15% drop in the associated environmental impacts in leaching areas and an 11% drop in runoff areas. We also find evidence of program spillover effects among grape growers, with a 12% increase in the environmental impact of herbicides per planted acre in fields outside GWPAs managed by growers with fields inside a GWPA. In citrus crops, the environmental impact of herbicides decreased by 19% in runoff GWPAs and did not significantly change in leaching areas.

## 5.2 Event Study

We extend our difference-in-differences regressions by conducting event study plots as defined in Equations 3 and 4. The plots show year-specific treatment effects for leaching and runoff GWPAs relative to the base year 2004, the year immediately before the program. The regressions that generate Figures 5, 6, and 7 include controls for within-farm spillovers, which we exclude from the figures for clarity.

As shown in Figure 5, the leaching and runoff treatment effects on the share of fields sprayed with a regulated active ingredient prove significantly negative in each year of the policy for almonds and grapes. In citrus, runoff GWPA treatment resulted in significantly negative effects in all but the last two years post-program implementation. In almonds, fields in GWPAs exhibit an 18–20% reduction in the probability growers sprayed a regulated active ingredient in 2006, an effect that diminishes through 2020. In citrus fields, the treatment effect is larger in magnitude in runoff GWPAs in all program years relative to leaching areas.

Figure 6 displays the treatment effects on the environmental impacts of regulated active ingredients per planted acre and shows significant reductions in almond and citrus fields in

Table 6: Impact of the Groundwater Protection Program on the Environmental Impact of Herbicide Active Ingredients Applied per Planted Acre

	Almond (1)	Citrus (2)	Grape (3)
<i>Panel A: Average GWPA effect</i>			
GWPA	0.01 (0.03)	-0.16*** (0.04)	-0.19*** (0.02)
Observations	128,662	55,368	168,201
Pseudo R <sup>2</sup>	0.37	0.48	0.41
<i>Panel B: Average effect of leaching and runoff GWPAs</i>			
Leaching GWPA	0.01 (0.03)	-0.07 (0.13)	-0.20*** (0.03)
Runoff GWPA	0.02 (0.04)	-0.19*** (0.04)	-0.16*** (0.03)
Observations	128,662	55,368	168,201
Pseudo R <sup>2</sup>	0.37	0.48	0.41
<i>Panel C: Average effect of GWPAs with spillover control</i>			
Leaching GWPA	0.02 (0.03)	-0.08 (0.12)	-0.15*** (0.03)
Runoff GWPA	0.03 (0.05)	-0.19*** (0.05)	-0.11*** (0.04)
Field outside GWPA, grower has field inside a GWPA	0.02 (0.02)	-0.02 (0.05)	0.12*** (0.03)
Observations	128,662	55,368	168,201
Pseudo R <sup>2</sup>	0.37	0.48	0.41

Note: Regressions include year, field, and county by year fixed effects. Estimates presented here equal the relative impacts of a discrete change in GWPA treatment calculated using the formula  $e^{\beta} - 1$ . Multiplying the point estimate presented by 100 equals the effect in percentage terms. We calculated the standard errors of the relative impacts using the Delta method. Standard errors in parentheses are clustered by field. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

most years of the policy. Multiplying the point estimate by 100 gives the treatment effect in percentage terms. For example, the environmental impact of regulated ingredients used in almond leaching GWPA fields declined by 50% in 2005 and 84% in 2006, relative to 2004, and remained around -75% through 2019. Grape leaching and runoff GWPA fields show a significant drop in the environmental impact in 2005 of 25%, an effect that increases in magnitude in most years through 2015.

Figure 7 depicts the results for the environmental impact of regulated plus alternative



herbicides. The citrus estimates reveal significant negative runoff treatment effects in 2007–2011 and 2014. We can see that the citrus leaching GWPA point estimates tend to be negative in 2005 through 2011, with a significant estimate in 2010, then tend to be positive in later years, with a significant estimate in 2017. This apparent jump in environmental impacts is driven by the extensive use of glyphosate in lemon and orange orchards, which increased the mean environmental impact of herbicides in leaching GWPA citrus fields between 2004 and 2017. During the same period, the mean environmental impact of herbicides in control fields dropped, contributing to the large relative change in treated fields. The almond treatment effects are close to zero throughout the program. In grape fields, the runoff GWPA treatment effect ranges from -10% to -25% through 2014, with effects that are significantly different from zero in seven of the ten years, then increases in magnitude to about -30% from 2015 through 2020. During the 2015–2020 period the grape runoff GWPA point estimates are significantly different from zero. Grape leaching GWPAs follow a similar pattern.

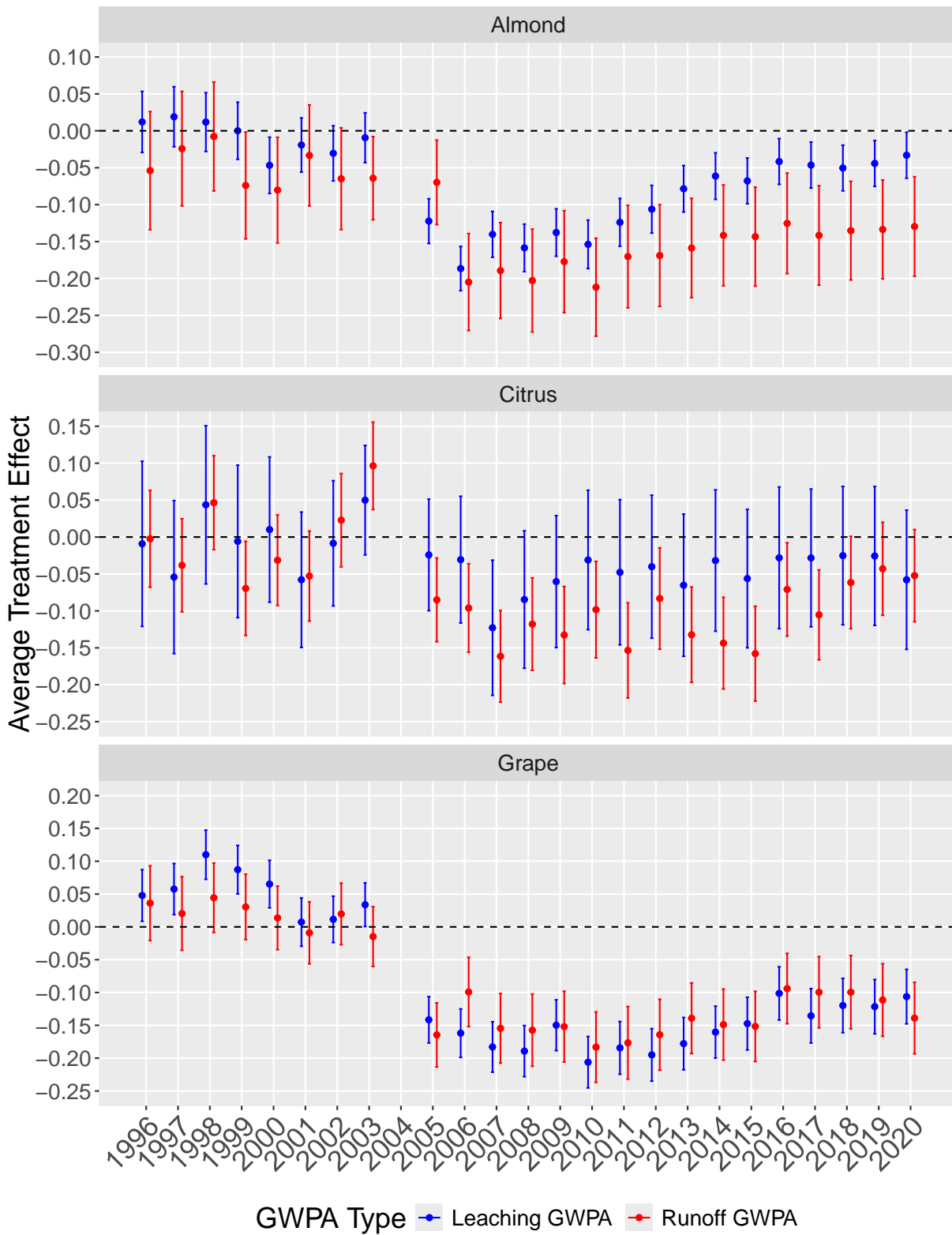


Figure 5: Effect of the Groundwater Protection Program on the probability growers sprayed fields with regulated active ingredients.

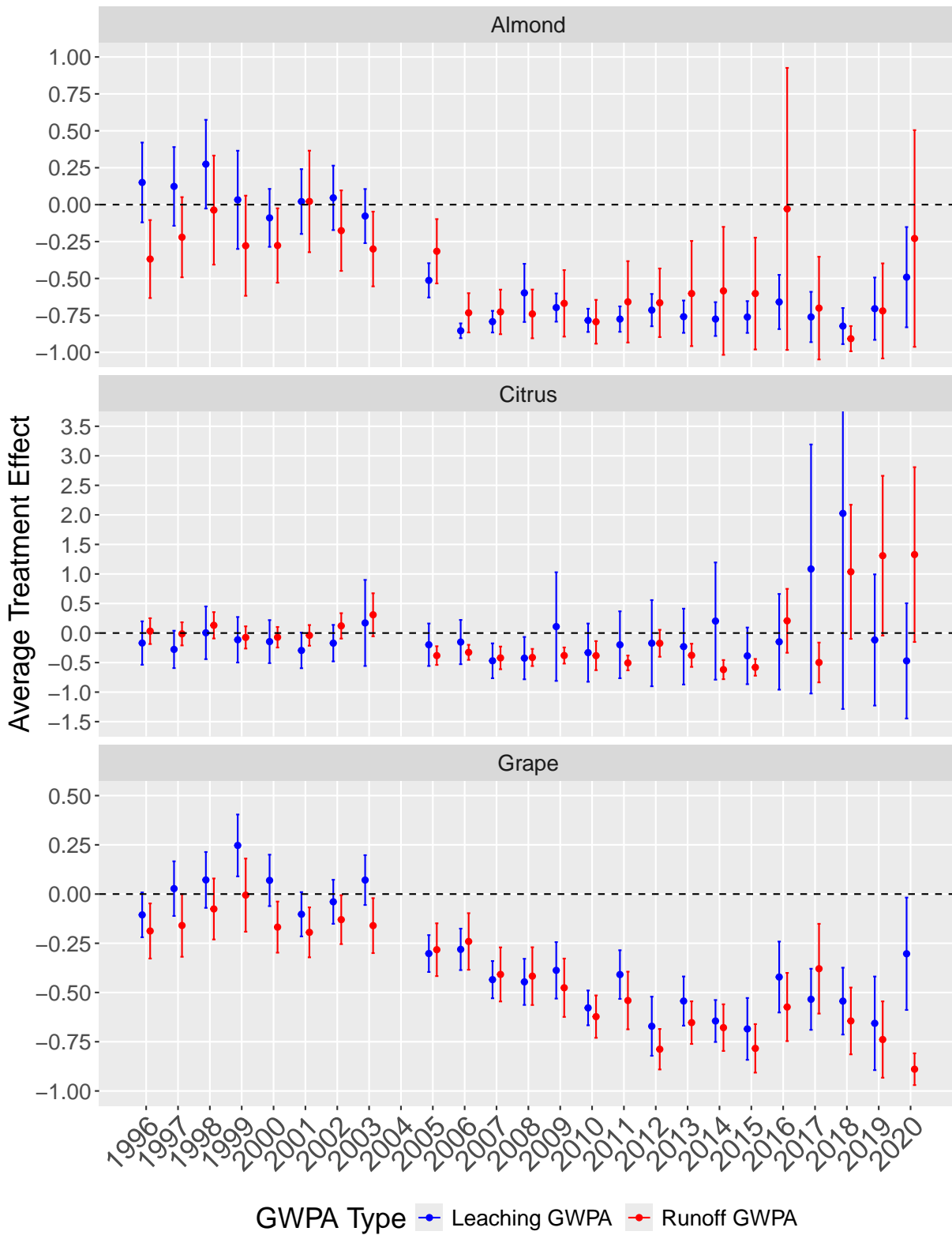


Figure 6: Effect of the Groundwater Protection Program on the environmental impact per planted acre of regulated active ingredients.

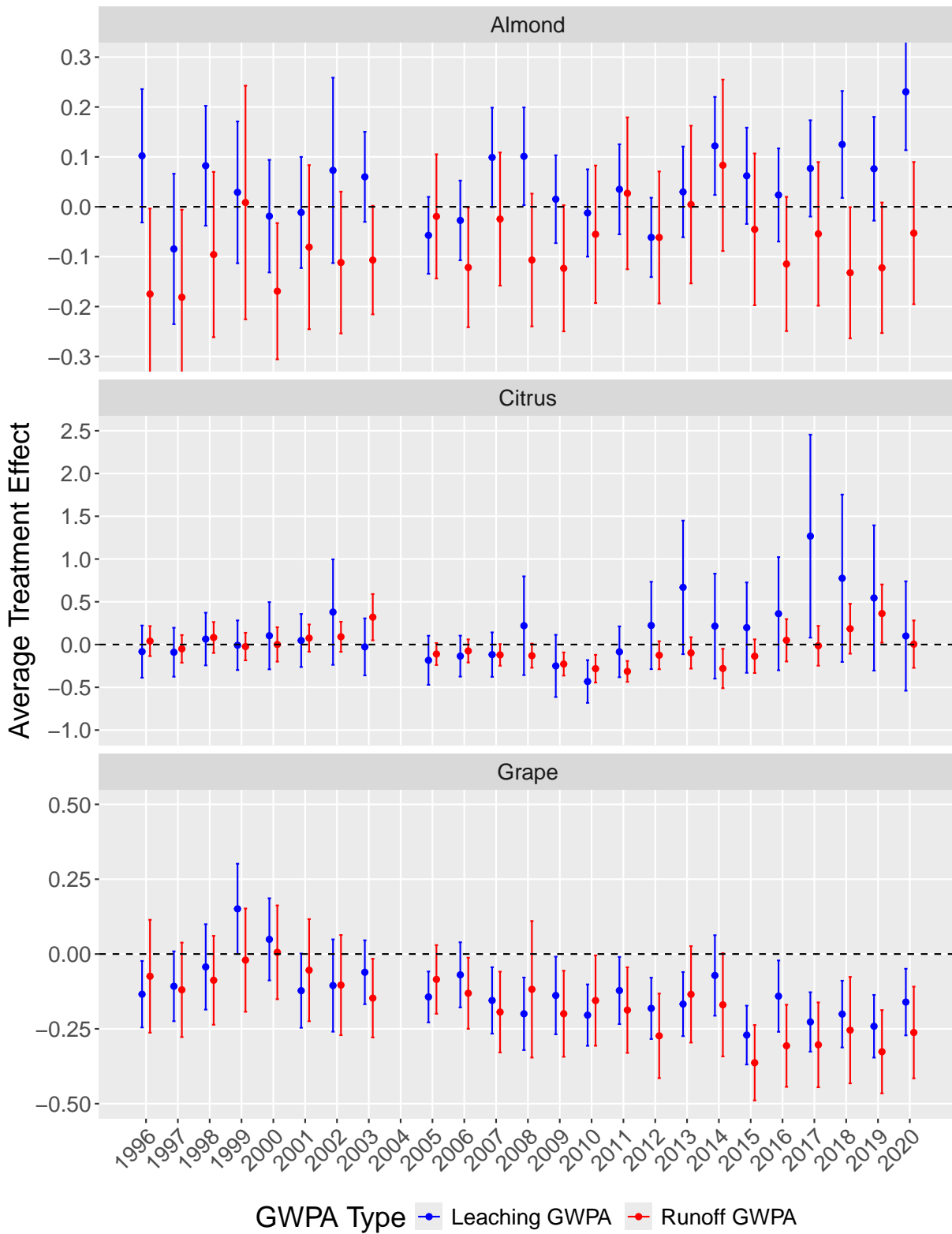


Figure 7: Effect of the Groundwater Protection Program on the environmental impact per planted acre of herbicides.

### 5.3 Robustness Checks

Identifying the program treatment effect hinges on the assumption that treated and control fields follow parallel trends in 1996–2004. To formally test this assumption, we conduct a series of regressions that augment the difference-in-differences models with terms that capture the differences in slopes between treated and control groups. The augmenting version of equation (1) used to capture pre-trend slopes takes the following form:

$$P(Y_{it} = 1) = \gamma_i + \tau_t + \delta_c \tau_t + \alpha^{pre} Year D_t^{pre} G_i + \alpha^{post} Year D_t^{post} G_i + \varepsilon_{it} \quad (5)$$

where  $Year$  denotes the year variable,  $D_t^{pre}$  and  $D_t^{post}$  denote indicator variables that equal one for observations in the pre-treatment and post-treatment periods, respectively, and  $G_i$  denotes an indicator variable equal to one for fields in a GWPA. Coefficient  $\alpha^{pre}$  captures the difference in slopes between GWPA and control fields in 1996–2004.

To test the parallel pre-trends assumption for regressions of the effect GWPA program on the environmental impact of regulated and alternative active ingredients, we alter equation (2) as follows:

$$Y_{it} = \exp\{\gamma_i + \tau_t + \delta_c \tau_t + \beta^{pre} Year D_t^{pre} G_i + \beta^{post} Year D_t^{post} G_i\} \varepsilon_{it} \quad (6)$$

where variables have the same definition as those in equation (5) and the coefficient of interest,  $\beta^{pre}$ , captures the difference in pre-program trends between GWPA and control fields.

We extend equations (5) and (6) with terms that capture differences in pre-trends between control fields and fields in leaching GWPAs, runoff GWPAs, and fields outside GWPAs that are managed by a grower with a field inside a GWPA. For clarity, we only present estimates of the coefficients that capture differences in pre-trends. These results are presented in Appendix Table A3, A4, and A5.

With respect to the share of fields treated with regulated active ingredients, we find parallel pre-trends in treated and control fields in almond orchards as shown in Appendix Table A3. The citrus regressions reveal that the probability a field was treated with a regulated ingredient increased in GWPA fields in the pre-program period. However, the runoff GWPA pre-trend coefficient in our preferred regression in panel C is only significant at the 10% level. In grapes, there is evidence of small negative pre-trends in leaching GWPA fields relative to control fields in regressions that control for within-farm spillovers (see panel C), which is significant at the 5% level and biases our estimates.

The pre-trend estimates for the regressions with the environmental impact of regulated active ingredients per planted acre as the dependent variable (shown in Appendix Table A4) reveal positive pre-trends in almond and grape runoff GWPA (see panel B) which lose significance when controlling for within-farm spillover effects (panel C). In the pre-trends test of our preferred regressions, shown in panel C, we find pre-trends in almond leaching and weakly treated fields and citrus weakly treated fields, but these are only significant at the 10% level. However, as we show in Figure 6, the yearly point estimates for almond leaching GWPA in 1996–2004 are not statistically different from zero, and the negative pre-trend is the result of large positive point estimates for 1996–1998. In the pre-trend test of the impact of the program on the environmental impact of herbicides per planted acre, we find the pre-trend for almond orchards outside GWPA managed by growers with fields inside a GWPA is negative and significant at the 5% level (as shown in Appendix Table A5, panel C).

Turning to the environmental impact of regulated and alternative active ingredients, we find parallel pre-trends between treated and control fields across all crops (see Appendix Table A5). However, the test of the almond orchards outside GWPA managed by growers with a field inside a GWPA reveals a negative and significant pre-trend.

In a second set of robustness checks, we redefine the annual periods as June through May and estimate models involving the environmental impact of herbicides (regulated and

alternative ingredients) per planted acre. As shown in Appendix Table A6, the summer months of June through September account for a meaningful share of the acres treated with alternative active ingredients. Our definition of annual periods of October through September used for our primary regressions means that we include herbicide applications in June through September 2004 as pre-program applications, despite the program beginning in May 2004. Estimating equation (2) using years defined as June through May, we find no notable differences in the point estimates or standard errors, as shown in Appendix Table A7, compared to the results estimated using the October through September period definition presented in Table 6. Estimating the event study model given in equation (4) using years defined as June through May produces a pattern of point estimates shown in Appendix Figure A3 similar to the estimates in Figure 7.

## 6 Concluding Remarks

Pesticides protect crops against disease, predation, and competitive species, prevent food-borne illness from vector-borne disease and microbial contamination (Cooper and Dobson, 2007), and support low-cost food production and farm profitability. When faced with environmental degradation from non-point source emissions of pesticides, regional and national governments often implement uniform regulations (Finger et al., 2017), including product bans (Donley, 2019). However, pesticide bans might not be necessary to achieve environmental quality goals (Anderson, Opaluch, and Sullivan, 1985). Targeting regulatory efforts towards the most vulnerable zones can achieve environmental quality goals at a lower cost than if conducted elsewhere. Incorporating a menu of cultural practices differentiated by targeted region further reduces compliance costs relative to product bans.

The Groundwater Protection Program set pesticide management standards for seven herbicide active ingredients detected in groundwater. The program standards vary depending on the local environmental conditions and the pathway—leaching or runoff—to groundwater

contamination. [Troiano et al. \(2013\)](#) pointed to decreasing trends in groundwater concentrations of simazine, diuron, and bromacil as evidence of the success of the program. However, until now, little was known about the extent to which farmers responded to the program and whether the response differed in leaching or runoff areas.

Using 25 years of pesticide use data, we show that the program substantially reduced the share of fields treated with regulated active ingredients and their environmental impacts. The largest reductions were seen in leaching GWPAs, which required strict irrigation management standards to prevent pesticides from moving through coarse-textured soils into groundwater. Growers in runoff GWPAs also reduced the use of regulated active ingredients, which require specific land cultivation practices to prevent chemicals from moving across the land surface to sensitive sites like dry irrigation wells. We find some evidence that the program spilled over into citrus fields outside GWPAs managed by growers with fields in GWPAs.

A major concern regarding policies that focus on a handful of inputs is that producers increase the use of other environmentally harmful practices. Here, we find that the environmental impact of herbicides per planted acre in almond orchards did not change in response to the program and decreased in citrus groves and grape vineyards.

Governments seek practical, politically feasible policy options to address worsening environmental quality from diffuse agricultural emissions. Targeting regions with measured pollution or environmental features characteristic of vulnerable zones offers a compromise between impractical field-level measurement of emissions and costly regional input bans. Offering a menu of management options differentiated by pollution pathway can further lower the cost of achieving environmental goals while providing more opportunities for growers to adapt to the regulation. This paper provides critical insights into a spatially targeted and differentiated pesticide program. Given the adjustment opportunities inherent in the program, our results highlight the extent to which crop industries respond differently, likely due to relative differences in pest pressure and market conditions.



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## A Appendix Tables



Table A1: Herbicide EIQ and Total Acres Treated in 1996–2004

Active ingredient	EIQ	Almond	Citrus	Grape
		100,000	acres treated	
<i>Panel A. Regulated active ingredients</i>				
Simazine	21.52	9.491	11.416	23.935
Diuron	26.47	0.008	12.486	6.598
Norflurazon	17.50	4.598	1.639	4.203
Bromacil	12.63	0.001	3.777	0.001
Atrazine	22.85	0.008	0.000	0.001
Prometon	24.46	0.000	0.000	0.001
Bentazon, sodium salt	18.67	0.000	0.000	0.000
<i>Panel B. Alternative herbicides</i>				
Glyphosate, isopropylamine salt	15.33	69.494	47.613	56.038
Oxyfluorfen	33.82	38.367	2.470	27.745
Paraquat dichloride	24.73	18.725	2.831	25.832
Oryzalin	18.10	6.163	0.768	8.442
2,4-d, dimethylamine salt	20.67	6.869	0.563	1.528
Trifluralin	18.83	1.812	0.699	2.053
Glyphosate-trimesium	15.33	2.442	0.246	1.104
Pendimethalin	30.17	1.354	0.294	0.844
Glyphosate, diammonium salt	15.33	2.186	0.157	0.137
2,4-d, diethanolamine salt	16.67	1.964	0.034	0.002
Napropamide	12.57	0.567	0.136	0.940
Glyphosate, monoammonium salt	15.33	0.613	0.639	0.266
Glyphosate	15.33	0.583	0.188	0.422
Sethoxydim	20.89	0.095	0.002	1.088
2,4-d	17.33	0.895	0.050	0.185
2,4-d, triethylamine salt	27.23	0.895	0.050	0.185
Glufosinate-ammonium	20.20	0.162	0.000	0.574
Glyphosate, potassium salt	15.33	0.382	0.048	0.078
Eptc	9.43	0.349	0.000	0.000
Halosulfuron	20.20	0.308	0.002	0.001
Msma	18.00	0.084	0.182	0.004
Fluazifop-p-butyl	28.71	0.056	0.016	0.145
Thiazopyr	15.07	0.078	0.039	0.087
Isoxaben	23.67	0.045	0.008	0.032
Diquat dibromide	39.20	0.005	0.002	0.061
Clethodim	17.00	0.011	0.002	0.013
Mcpa, dimethylamine salt	22.67	0.016	0.000	0.004
Others	—	0.061	0.024	0.088

Note: We use the EIQ of a similar chemical when the EIQ data does not contain an exact match. For example, we use the glyphosate EIQ for all glyphosate salts. There are 68 other alternative herbicide active ingredients not listed here, each used to treat less than 2,000 acres in 1996–2004 with EIQ values ranging from 11 to 47. We include these other chemicals in our analysis.

Table A2: Pounds and Share of Regulated Active Ingredients Used on Almond Orchards, Citrus Groves, Grape Vineyards, and Other Crops in 1996–2004

Active Ingredient	Crop	Pounds	Share (%)
Atrazine	Almond	181	0.04
Atrazine	Citrus	32	0.01
Atrazine	Grape	67	0.01
Atrazine	Others	470,991	99.94
Bromacil	Almond	56	0.01
Bromacil	Citrus	432,451	99.02
Bromacil	Grape	59	0.01
Bromacil	Others	4,178	0.96
Diuron	Almond	669	0.01
Diuron	Citrus	2,127,211	39.95
Diuron	Grape	482,266	9.06
Diuron	Others	2,714,918	50.98
Norflurazon	Almond	408,676	24.64
Norflurazon	Citrus	211,361	12.74
Norflurazon	Grape	323,689	19.52
Norflurazon	Others	714,782	43.10
Prometon	Almond	0	0.00
Prometon	Citrus	0	0.00
Prometon	Grape	2	7.14
Prometon	Others	26	92.86
Simazine	Almond	495,011	8.25
Simazine	Citrus	2,108,251	35.12
Simazine	Grape	2,329,290	38.80
Simazine	Others	1,070,952	17.84

Table A3: Pre-Trends Test of the Impact of the Groundwater Protection Program on the Probability Growers Treated Field With Regulated Active Ingredients

	Almond (1)	Citrus (2)	Grape (3)
<i>Panel A: GWPA</i>			
Year $\times$ Pre-treatment $\times$ GWPA	0.002 (0.002)	0.007** (0.004)	-0.003 (0.002)
<i>Panel B: Leaching and runoff GWPA</i>			
Year $\times$ Pre-treatment $\times$ Leaching GWPA	-0.008 (0.017)	0.008 (0.007)	-0.077 (0.680)
Year $\times$ Pre-treatment $\times$ Runoff GWPA	0.0001 (0.018)	0.007* (0.004)	-0.071 (0.679)
<i>Panel C: Leaching and runoff GWPA with spillover control</i>			
Year $\times$ Pre-treatment $\times$ Leaching GWPA	-0.992 (3.975)	0.008 (0.008)	-0.007** (0.003)
Year $\times$ Pre-treatment $\times$ Runoff GWPA	-0.984 (3.975)	0.007* (0.004)	-0.001 (0.004)
Year $\times$ Pre-treatment $\times$ Field outside GWPA	-0.995 (3.975)	-0.002 (0.004)	-0.004 (0.002)

Note: Regressions that produce estimates in Panel A are defined in equation (5). Panels B and C show pre-trend estimates of regressions that extend equation (5) to include leaching, runoff, and field outside GWPA that is managed by a grower with a field inside GWPA variables and associated interaction variables. We only show estimates for pre-trends here for brevity and clarity. Standard errors in parentheses are clustered by field. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

Table A4: Pre-Trends Test of the Impact of the Groundwater Protection Program on the Environmental Impact of Regulated Active Ingredients Applied per Planted Acre

	Almond (1)	Citrus (2)	Grape (3)
<i>Panel A: GWPA</i>			
Year $\times$ Pre-treatment $\times$ GWPA	-0.005 (0.012)	0.006 (0.013)	0.009 (0.006)
<i>Panel B: Leaching and runoff GWPAs</i>			
Year $\times$ Pre-treatment $\times$ Leaching GWPA	-0.016 (0.013)	0.028 (0.029)	0.005 (0.007)
Year $\times$ Pre-treatment $\times$ Runoff GWPA	0.047** (0.024)	0.003 (0.014)	0.019* (0.011)
<i>Panel C: Leaching and runoff GWPAs with spillover control</i>			
Year $\times$ Pre-treatment $\times$ Leaching GWPA	-0.028* (0.015)	0.042 (0.030)	0.003 (0.008)
Year $\times$ Pre-treatment $\times$ Runoff GWPA	0.036 (0.025)	0.014 (0.015)	0.017 (0.012)
Year $\times$ Pre-treatment $\times$ Field outside GWPA	-0.026* (0.014)	0.025* (0.014)	-0.004 (0.009)

Note: Regressions that produce estimates in Panel A are defined in equation (6). Panels B and C show pre-trend estimates of regressions that extend equation (6) to include leaching, runoff, and field outside GWPA that is managed by a grower with a field inside GWPA variables and associated interaction variables. We only show estimates for pre-trends here for brevity and clarity. Standard errors in parentheses are clustered by field. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

Table A5: Pre-Trends Test of the Impact of the Groundwater Protection Program on the Environmental Impact of Herbicide Active Ingredients Applied per Planted Acre

	Almond (1)	Citrus (2)	Grape (3)
<i>Panel A: GWPA</i>			
Year $\times$ Pre-treatment $\times$ GWPA	0.01 (0.01)	0.01 (0.01)	0.001 (0.01)
<i>Panel B: Leaching and runoff GWPAs</i>			
Year $\times$ Pre-treatment $\times$ Leaching GWPA	0.008 (0.006)	0.011 (0.023)	0.004 (0.007)
Year $\times$ Pre-treatment $\times$ Runoff GWPA	0.014 (0.012)	0.008 (0.010)	0.008 (0.009)
<i>Panel C: Leaching and runoff GWPAs with spillover control</i>			
Year $\times$ Pre-treatment $\times$ Leaching GWPA	0.001 (0.007)	0.019 (0.024)	0.004 (0.008)
Year $\times$ Pre-treatment $\times$ Runoff GWPA	0.008 (0.012)	0.015 (0.011)	0.008 (0.010)
Year $\times$ Pre-treatment $\times$ Field outside GWPA	-0.014** (0.006)	0.016 (0.011)	0.001 (0.007)

Note: Regressions that produce estimates in Panel A are defined in equation (6). Panels B and C show pre-trend estimates of regressions that extend equation (6) to include leaching, runoff, and field outside GWPA that is managed by a grower with a field inside GWPA variables and associated interaction variables. We only show estimates for pre-trends here for brevity and clarity. Standard errors in parentheses are clustered by field. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

Table A6: Monthly Share of 2004 Acres Sprayed With Herbicides

Month	Alternative AIs			Regulated AIs		
	Almond	Citrus	Grape	Almond	Citrus	Grape
	%					
Jan	9.9	3.7	14.5	19.5	14.7	19.9
Feb	7.4	5.4	18.1	10.6	17.4	29.1
Mar	6.8	7.8	14.7	6.7	14.4	25.9
Apr	10.9	8.4	9.4	6.5	3.0	2.5
May	11.1	9.9	10.2	5.3	1.2	0.4
Jun	12.6	14.3	7.6	2.3	0.8	0.7
Jul	13.3	13.2	5.3	4.4	0.7	0.1
Aug	5.1	12.4	1.5	0.6	0.3	0.1
Sep	1.6	8.7	1.2	0.2	0.3	0
Oct	3.6	4.4	1.6	3.9	3.7	0.4
Nov	9.5	6.2	7.0	20.4	26.4	7.3
Dec	8.1	5.7	9.0	19.6	17.1	13.6

Note: Monthly shares calculated as the sum of crop acres sprayed with alternative herbicide active ingredients divided by the crop acres sprayed with alternative ingredients in 2004. We use similar calculations for regulated active ingredients. Columns sum to 100.

Table A7: Robustness Check of the Impact of the Groundwater Protection Program on the Environmental Impact of Herbicide Active Ingredients Applied per Planted Acre Using Annual Period June through May

	Almond (1)	Citrus (2)	Grape (3)
<i>Panel A: Average GWPA effect</i>			
GWPA	0.003 (0.03)	-0.17*** (0.04)	-0.19*** (0.02)
Observations	124,678	52,350	163,719
Pseudo R <sup>2</sup>	0.37	0.48	0.41
<i>Panel B: Average effect of leaching and runoff GWPAs</i>			
Leaching GWPA	-0.01 (0.03)	-0.10 (0.12)	-0.20*** (0.03)
Runoff GWPA	0.01 (0.04)	-0.18*** (0.04)	-0.16*** (0.03)
Observations	124,678	52,350	163,719
Pseudo R <sup>2</sup>	0.37	0.48	0.41
<i>Panel C: Average effect of GWPAs with spillover control</i>			
Leaching GWPA	0.01 (0.03)	-0.12 (0.12)	-0.15*** (0.03)
Runoff GWPA	0.03 (0.05)	-0.20*** (0.05)	-0.11*** (0.04)
Field outside GWPA, grower has field inside a GWPA	0.04 (0.02)	-0.04 (0.05)	0.12*** (0.03)
Observations	124,678	52,350	163,719
Pseudo R <sup>2</sup>	0.37	0.48	0.41

Note: Regressions include year, field, and county by year fixed effects. Estimates presented here equal the relative impacts of a discrete change in GWPA treatment calculated using the formula  $e^{\beta} - 1$ . Multiplying the point estimate presented by 100 equals the effect in percentage terms. We calculated the standard errors of the relative impacts using the Delta method. Standard errors in parentheses are clustered by field. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

## B Appendix Figures

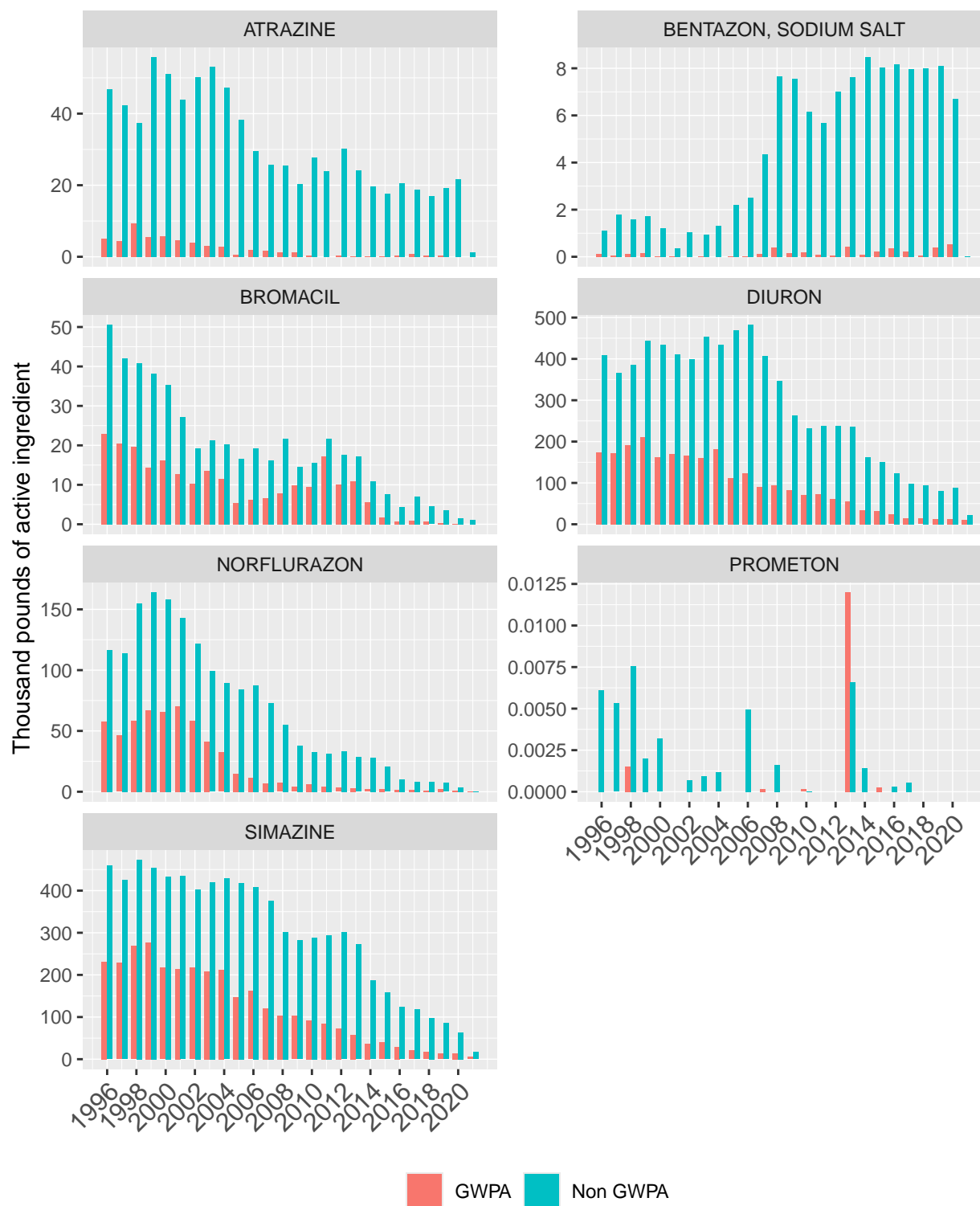


Figure A1: Annual quantity of regulated active ingredients used in California



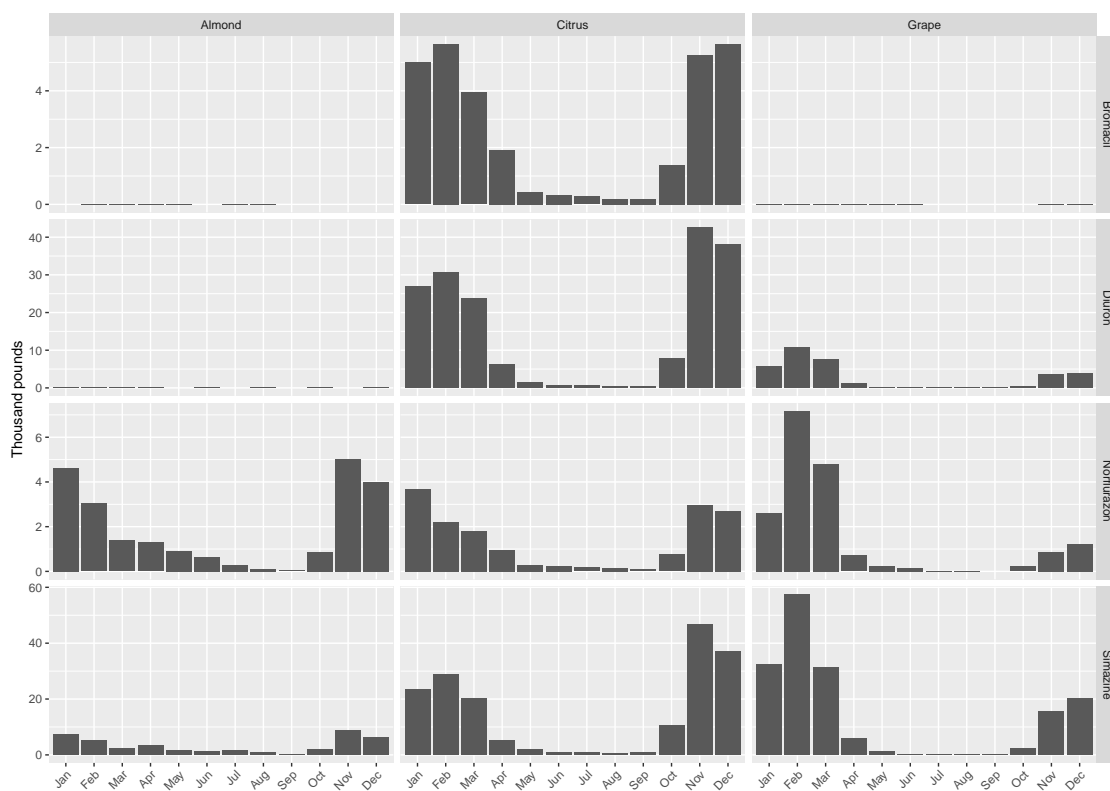


Figure A2: Mean pounds of regulated active ingredient used in 1996–2020 by month.

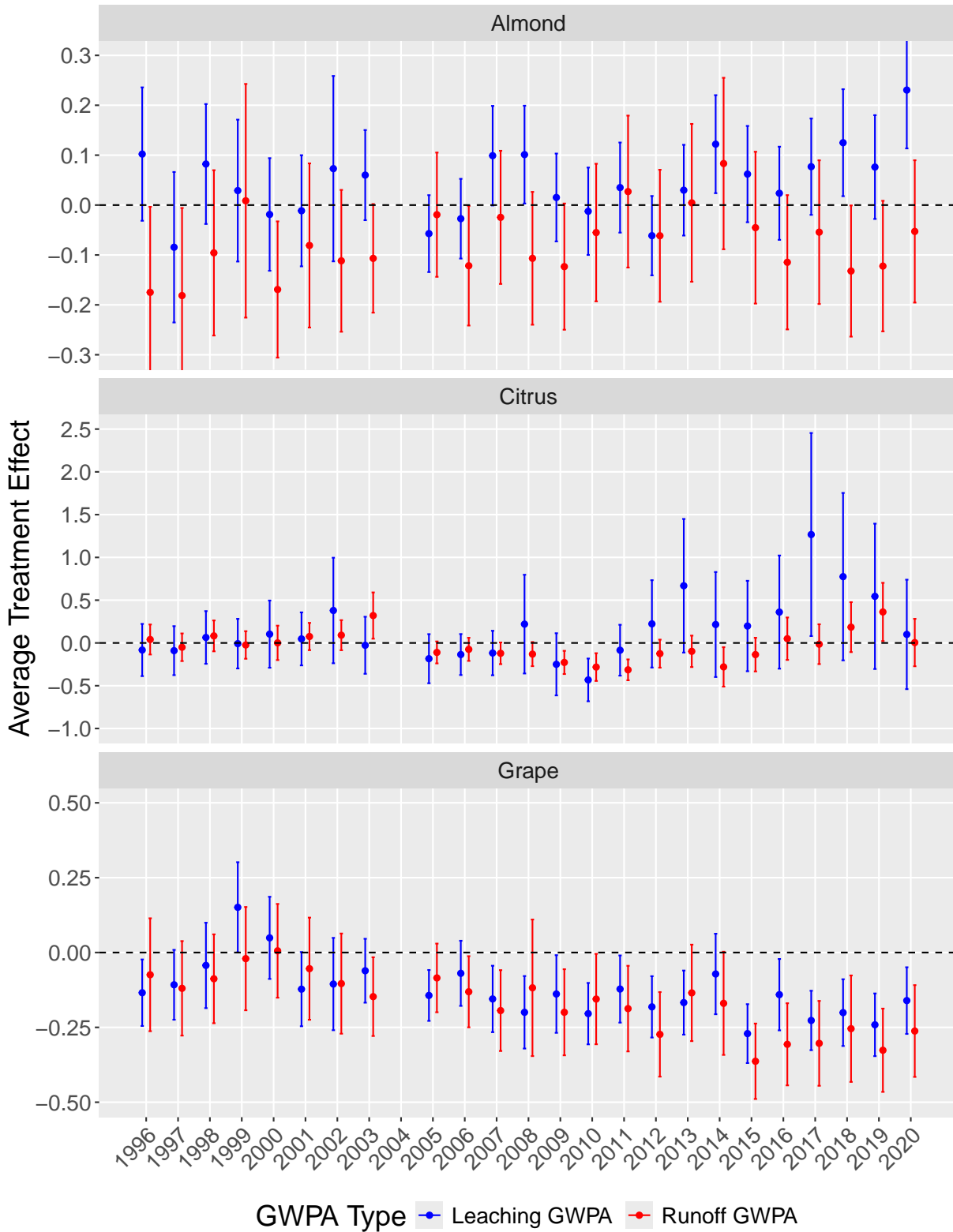


Figure A3: Robustness check of the effect of the Groundwater Protection Program on the environmental impact of herbicides per planted acre using annual periods of June through May