The Effects of Pierce Disease on the Spatial Pattern of Grape Production in California

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Abstract

The spread of crop diseases poses significant challenges to the stability and location of agriculture. This paper examines how pest pressure influences the spatial patterns of crop production. Using detailed spatial data on pest infestations and crop acreage, we study the impact of Pierce's Disease and its vector, the Glassy-Winged Sharpshooter, on the spatial patterns of grape (the target of the disease) and citrus (the host of the vector) production in California. We combine crop maps and pesticide use reports to estimate how pest outbreaks affect growers' location decisions. Our results show that pest pressure leads to spatial avoidance behavior: grape acreage tends to decline in infested areas, and the distance between citrus and grape production increases. We also find that pest control programs mitigate some of these effects, supporting their role in stabilizing agricultural land use. These findings highlight the importance of incorporating pest dynamics into models of agricultural spatial decision-making.

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1 Introduction

Pierce's Disease (PD) is one of the most harmful diseases affecting grapes in California. According to Alston et al. (2013), an outbreak of PD across California would cause an estimated $185 million in losses without policy implementations. At the peak of the PD outbreak, approximately 10% of the total grape acreage in the Temecula Valley disappeared (Siebert, 2001). The vectors of PD vary across the state: the glassy-winged sharpshooter (GWSS) serves as the primary vector of PD in southern California, the blue-green sharpshooter is prevalent in coastal areas, and the green sharpshooter and the red-headed sharpshooter are more significant vectors in the Central Valley.

GWSS is a significant vector of Xylella fastidiosa, the xylem-limited bacterium responsible for PD in grapes. While feeding, GWSS transfers the bacteria to other plants. PD symptoms include chlorosis and scorching of leaves, with entire grapevines dying within one to five years. Although PD has been present in California for over a century, native vectors do not transmit the bacterium as extensively as GWSS. Compared to the native vectors, GWSS raises greater concerns due to two main factors: it can fly longer distances and overwinter in various host vegetations (Alston et al., 2013).

The GWSS is originally native to the southeastern United States and northeastern Mexico. Although it was first reported in California in 1994, it likely arrived in the late 1980s. California's first indication of the severe threat posed by the GWSS occurred in Temecula, Riverside County, in August of 1999. Over 300 acres of grapevines infested with GWSS were destroyed at that time due to the infestation of PD. By 2000, eight counties in southern California had detected the GWSS. The significant threat the GWSS posed to grape production prompted the initiation of the California Department of Agriculture and Food (CDFA) Pierce's Disease Control Program. Its current distribution includes southern California and Kern, Tulare, and Fresno counties. The GWSS is becoming a potential threat to the northern region as it gradually spreads northward in response to climate change (Rossi & Rasplus, 2023).

One important feature of GWSS is their overwintering in citrus, which leads to citrus farms acting as a source of sharpshooters in the spring for neighboring vineyards. In 2001, the U.S. Department of Agriculture Animal and Plant Health Inspection Service (USDA APHIS) implemented an area-wide treatment program involving the coordinated control of GWSS on citrus in infested areas where citrus is grown near grapes. The area-wide treatments aim to reduce the impacts of PD on grapes in the infested area and mitigate the outward spread pressure of PD and GWSS. Areas with active area-wide programs included Kern County, the Temecula and Coachella valleys, and parts of Ventura, Fresno, Madera, and Tulare counties. These five counties are partially infested, with many acres planted with grapes adjacent to citrus trees. The area-wide management programs in Riverside County have been discontinued due to budget issues and decreased GWSS populations. More resources are being redirected to the Central Valley because the risk here has increased[1].

In managed areas, GWSS populations are monitored, and when they exceed treatment thresholds, they are treated before they can disperse into vineyards and transmit the PD bacterium. Any citrus grove located within one-quarter mile of a trapped grapevine (i.e., a trap that has captured a GWSS) is considered for treatment. As GWSS cannot cause significant economic losses to citrus growers, citrus growers are unlikely to apply pesticides to control GWSS voluntarily. Their motivation primarily stems from direct reimbursement in the area-wide treatment program. Under the public program, citrus producers are reimbursed for the total cost of their GWSS treatments, including all materials, labor, and application costs. Although treatments are voluntary, treatments are applied simultaneously in large areas to prevent GWSS from escaping treatments. However, there are still limita-

[1]This information was obtained from interviews with the PD Board.

tions in the area-wide pest management programs related to the effectiveness of treatment options for organic citrus and the obtention of voluntary cooperation[2].

Since citrus is the primary overwintering host for GWSS, citrus orchards have played a crucial role in the spread of PD in Southern California. Grape growers adjacent to citrus production can suffer significant losses due to the spatial externality. Perring et al. (2001) conducted vineyard surveys to examine the roles of citrus in the Temecula Valley PD epidemic. They found that grapevines closer to citrus experienced significantly higher disease severity, while grapevines further away from citrus experienced less severity. This spatial externality fits the characteristics of an edge-effect externality, which refers to spatial externalities with marginal impacts decreasing as the distance from the border generating the negative impact increases (Parker and Munroe, 2007). According to Parker and Munroe (2007), more land may be occupied by externality-generating use than is socially optimal in the presence of edge-effect externalities. This result suggests that the free-market land use pattern may be socially inefficient.

In our case, without pest management programs, grape growers would suffer significant yield loss from being proximate to citrus trees. Due to the spatial externalities, we expect grape growers to adapt their production to minimize losses from PD. Adaptation could include planting new grapevines in non-infested areas either within or outside a region and minimizing production in infested areas, particularly those adjacent to citrus productions.

In this study, we empirically analyze these two channels of the effects of PD on the spatial patterns of grape production. To the extent that implementing pest management programs reduces the edge-effect externalities, we would expect growers to be less inclined to change the locations under the area-wide pest management programs. At the same time, implementing

[2]This information was obtained from interviews with the PD Board.

PD management programs may impose additional costs on citrus production, leading citrus growers to consider planting citrus further away from grape production in regulated areas. Thus, PD and the management programs jointly contribute to the spatial pattern changes of grape and citrus production after the implementation of PD programs. Hence, the net effects of PD management programs on the geographical pattern of crop production are ambiguous.

Location changes in grape production entail various costs. First, location changes lead to significant establishment expenses. Additionally, since grapevines are perennial vegetation, young grapevines will take several years to bear fruit, leading to potential yield losses immediately after relocation. To plant grapes further away from citrus, growers may also face yield or quality losses due to displacement from optimal soil and climate conditions. Area-wide pest management programs can reduce the negative externality caused by the proximity of grapes and citrus, thus potentially mitigating these market failures. This paper aims to estimate the effects of pest pressure and pest management programs on the spatial patterns of citrus and grape production in California.

Externalities have been a significant topic of economic analysis, given their profound impacts on welfare, resource allocation, and policy formulation (Pigou, 1920; Coase, 1960; Cropper and Oates, 1992). Some researchers have investigated the relationship between agricultural externalities and spatial patterns of agricultural production. Parker and Munroe (2007) analyze how the proximity to non-organic farming operations can affect the location choice of organic farms. Their results suggest that buffer zone requirements are necessary to protect organic farms. Brown et al. (2002) investigated two potential biological control methods to mitigate the effects of PD, showing that growers can increase their profits by planting barrier crops next to the source area or by removing the source of the Disease.

First, the current research contributes to the existing literature on agricultural externalities. Two types of externalities related to pest control are widely discussed. First, pesticide use creates negative externalities in the environment. For example, Integrated Pest Management (IPM) programs are designed to minimize the negative externalities associated with pest control. Waterfield and Zilberman (2012) review the economic theories of pest management and analyze the economic benefits of IPM, highlighting its potential to reduce negative externalities. Second, there are spatial externalities between growers due to pest mobility. Singerman et al. (2017) analyze the effects of area-wide pest management programs using the case of citrus greening. They state that area-wide pest management programs can prompt coordination among growers and encourage them to internalize externalities. This paper explores the complex interactions between pest pressure, growers' avoidance behaviors, and the spatial dynamics of agricultural production. It also provides empirical evidence on the effectiveness of area-wide pest management in mitigating externalities by evaluating how the programs influence the spatial patterns of grape and citrus production.

Second, previous literature has focused on the effects of socio-economic factors (Siegle et al., 2024) and other natural factors, such as climate change (Leeuwen et al., 2019), soil quality, and water availability, on the spatial patterns of perennial crops. However, limited research has analyzed the effects of pest pressure. Perennial crops differ from annual or biennial crops because they require high initial establishment costs and long-term maintenance, necessitating a long-term investment perspective. Understanding these spatial dynamics is crucial for sustainable agricultural planning and policy-making in the long run. This paper enriches the literature related to the spatial dynamics of perennial crops.

Third, many previous studies have explored the effects of externalities on avoidance behaviors, such as relocating residences or investing in protective measures. Some researchers have applied residential sorting models to analyze the effects of disamenities on demographic composition. Heblich et al. (2021) applied dynamic sorting models to analyze the long-run relationship between historical pollution and neighborhood sorting. They found that industrial coal pollution persistently increased the share of low-skilled workers in England. Bayer et al. (2009) constructed a dynamic sorting model to explore the role of air pollution, violent crime, and racial composition in neighborhood choices. Zivin et al. (2011) examine the impact of poor water quality on avoidance behavior and find an increase in bottled water sales due to water pollution. Burke et al. (2022) show that people are more likely to stay home and reduce outdoor activities in response to wildfire smoke. He et al. (2020) find that increased air pollution leads to higher daily residential energy consumption due to increased indoor activities.

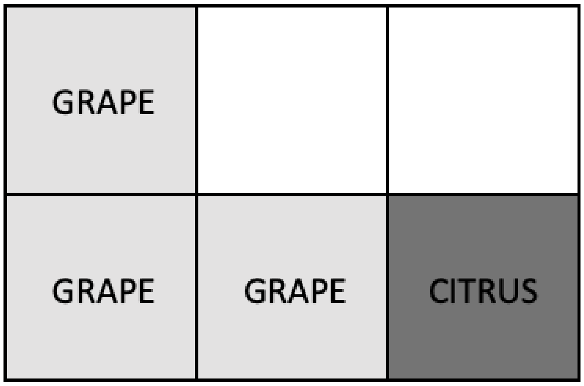
However, few previous studies have examined avoidance behavior in the context of agriculture. This paper uses the distance between citrus and grape production as a measure of grape growers' spatial avoidance, providing empirical evidence on how producers respond to increased pest threats. By analyzing avoidance behavior in an agricultural setting, we contribute to the broader literature on responses to environmental threats and spatial externalities.

2 Example of Joint Relocation: Average Distance Less Than Intended

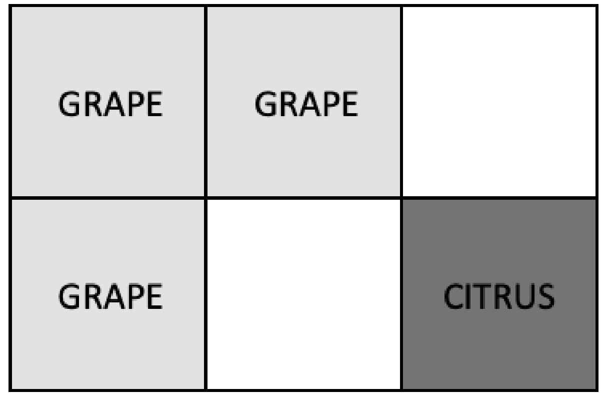
As discussed above, the edge-effect externality caused by PD would motivate grape growers to plant grapes away from citrus. However, since grapes and citrus require similar environments to grow, the location change of grape production may induce the location change of citrus production, as citrus growers may be willing to take advantage of parcels abandoned by grape growers. Considering the potential location change of citrus production, the effects of PD on the average distance between grape and citrus production are still undetermined. For example, three scenarios could unfold after grape growers abandon parcels adjacent to citrus due to PD

- Citrus growers plant citrus in abandoned grape parcels, and the average distance between citrus and grapes becomes smaller than what the grape growers initially intended to achieve.
- Citrus growers plant citrus in abandoned grape parcels, and the average distance between citrus and grapes becomes greater than what the grape growers initially intended to achieve.
- Citrus growers choose not to plant citrus in the abandoned grape parcels.

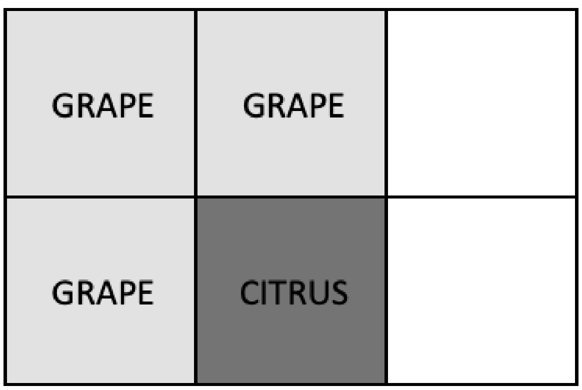
Before GWSS infested the area, some grape parcels were adjacent to citrus parcels. However, after the infestation, grape growers may cease planting grapes in parcels adjacent to citrus to minimize losses. This reduction in production could attract new growers or encourage existing ones to plant grapes in non-adjacent parcels. However, grape growers can only base their decisions on the current location of citrus parcels and cannot influence citrus growers' future behavior. Citrus growers might utilize the abandoned grape parcels, decreasing the average minimum distance between citrus and grapes.



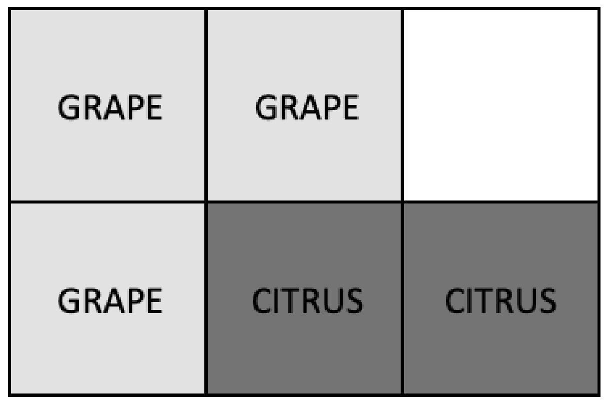
(a) Case 0: No Infestation



(b) Case 1



(c) Case 2



(d) Case 3

Figure 1: Examples for Positive and Negative Effects

Panel (a) in Figure 1 shows the case (case 0) when there is no infestation. There are three grape parcels and one citrus parcel, with one grape parcel adjacent to the citrus parcel. Assume that the side length of a square is d. D_0 shows the original distance without any interventions. Thus, the average minimum distance for the three grape parcels to the citrus parcel in Case 0 is

$$D_0 = \frac{(\sqrt{5} + 2 + 1)d}{3}$$

Panel (b) in Figure 1 illustrates the first case (Case 1) when this area is infested by GWSS. In this scenario, grape growers cease planting adjacent to citrus, and a new grape parcel appears in the top-right corner. Citrus growers choose not to plant citrus in the abandoned parcel or fail to occupy this parcel. Finally, the only citrus parcel in the Panel remains the closest to the three grape parcels. The observed distance in Case 1, D_1, is equal to the distance that grape growers intended to achieve and greater than the original distance, D_0.

$$D_1 = \frac{(\sqrt{5} + \sqrt{2} + 2)d}{3} > D_0$$

Panel (c) in Figure 1 depicts the second case (Case 2). In this scenario, the abandoned grape parcel is more profitable than the original citrus parcel owned by the citrus growers, so citrus growers decided to utilize the abandoned parcel. Consequently, the bottom-medium citrus parcel becomes the closest citrus parcel for all grape parcels, with two grape parcels adjacent to the citrus parcel. The observed distance, D_2, is smaller than the distance that grape growers intended to achieve, D_1, and the original distance, so $D_2 < D_0 < D_1$.

$$D_2 = \frac{(\sqrt{2} + 1 + 1)d}{3} < D_0 < D_1$$

Panel (d) in Figure 1 shows the third case (Case 3). In this scenario, citrus production is expanded. Now, the citrus growers occupy two bottom parcels. The distance that grape growers achieved, D_3, is smaller than the distance that grape growers intended to achieve and the original distance.

$$D_3 = \frac{(\sqrt{2} + 1 + 1)d}{3} = D_2 < D_0 < D_1$$

In summary, due to the location change of citrus production, grape growers may be less distant from citrus than they intended. Additionally, the effects of PD on the average observed distance between grape and citrus can be positive, negative, or zero, depending on the prevalence of the three cases outlined. If Case 1 dominates, positive effects will be observed. However, if Case 2 or 3 dominates, negative effects will be observed, although grape growers have relocated to avoid being proximate to citrus production.

Combining the two examples in this section and those explored in Appendix A, we conclude that the relocation of citrus orchards could lead to the average minimum distance being greater or smaller than what grape growers initially intended to achieve. In addition, one may estimate positive, negative, or zero effects of infestation on the observed distance. However, the observed distance does not purely reveal grape growers' decision-making process on relocation due to citrus growers' plausible relocation decisions. Thus, separately estimating the impact of PD on the observed distance and the distance that growers intended to achieve can provide more insights into how grape growers decide on location choices, and avoidance behaviors.

The analysis only considers cases where changes in grape parcels induce changes in citrus parcels. However, if some citrus parcels change due to reasons unrelated to grapes (i.e., citrus growers choose not to occupy the abandoned grape parcels and plant citrus in other places due to unrelated reasons), their location choices would introduce noise rather than change the magnitude of the estimated effects. If citrus growers intended to plant citrus away from grape production due to the implementation of PD management programs, we would observe greater positive or smaller negative effects after the implementation of the PD programs.

3 Data

3.1 GWSS Distribution Data

In 2022, the GWSS fully infested six counties, and it partially infested six counties, as shown in Figure B.8 panel (a) (Appendix B). Most grape-planting counties in northern and central California are at risk of being infested by GWSS. We obtained GIS files on the yearly GWSS distribution between 2001 and 2018 from the Pierce Disease Board[3]. We then merged the

[3] The GWSS distribution in 2018 is shown in Appendix B Figure B.9.

GWSS distribution layer with the county map layer to calculate the yearly GWSS infestation share by dividing the GWSS infested area by the total county area. Figure B.10 in Appendix B summarizes the detailed information on PD and GWSS infestation data for all counties with varying infested shares between 2001 and 2018.

3.2 Grape Acreage Data

We obtained county-year-variety-level grape acreage data from the USDA National Agricultural Statistics Service. We selected 26 main grape varieties that were consistently planted from 1992 to 2021. There are four types of grapes: raisin, table, red wine, and white wine. 52 counties planted at least one acreage of the selected 26 varieties between 1992 and 2021. There is no acreage data available for the years 1994 and 2001-2003, so we excluded these years from the dataset for raisin grapes. Additionally, we dropped all county-variety combinations if the total acreage for the combination consistently remained at 0 from 1992 to 2021[4]. Based on the trends of infested shares by county,[5] several counties—such as Butte and Contra Costa—were only infested during a few isolated years. Since these infestations affected only small areas and were mostly controlled in residential zones, they are unlikely to have impacted agricultural grape production. Therefore, we do not classify these counties as treated [6] .

3.3 Spatial Pattern Data

We utilized GIS maps generated from the State of California Pesticide Use Reports (PUR) data between 1992 and 2021[7] to obtain spatial patterns of citrus and grape production in California. California's pesticide use reporting program is recognized as the most comprehensive pesticide use reporting program in the world. In 1990, California implemented a

[4]The trends of total grape acreage for 5 managed counties and never-infested counties are shown in Appendix C.

[5]The trends in infested shares are shown in Appendix B.

[6]We use alternative model specifications in the robustness checks.

pesticide use reporting program requiring full reporting of agricultural pesticide use. Under this program, all agricultural pesticide use must be reported monthly to county agricultural commissioners, who then report the data to the California Department of Pesticide Regulation (DPR) (CDPR, 2017). We used four columns in the dataset to identify the spatial patterns of citrus and grape production: Date, SITE_NAME, AG_NONAG, and COMTRS.

- YEAR: the year when the pesticide application was completed
- SITE_NAME: the commodity where a pesticide product was applied (i.e., grapes, citrus, strawberries, tomatoes, etc.)
- AG_NONAG: production agricultural or Non-agricultural use identifier.
- COMTRS: Meridian, Township, Range, Section—approximately 1x1 square mile sections defined by the Public Land Survey System.

We dropped all non-agricultural records in the current research and focused only on agricultural records. Each record has an identification code for COMTRS. Since the Pesticide Use Reports (PUR) does not provide the exact addresses or locations of pesticide applications, the COMTRS (County, Meridian, Township, Range, Section) units are the smallest geographic areas for which the PUR provides data. From CPUR, we can determine if each COMTRS has at least one record of pesticide application related to grape or citrus within the year. We define grape COMTRS as COMTRS with at least one pesticide use record for grape production and citrus COMTRS as COMTRS with at least one pesticide use record for citrus production.

Similar to COMTRS, an MTR (Meridian, Township, Range) is approximately a 6x6 square mile section, also defined by the Public Land Survey System grid. It is a geographic unit

[7] One potential alternative data source for analyzing spatial patterns is Crop Sequence Boundary (CSB) data. However, CSB data only started in 2008, which means we would lose variation in spatial pattern changes before 2008 with that dataset.

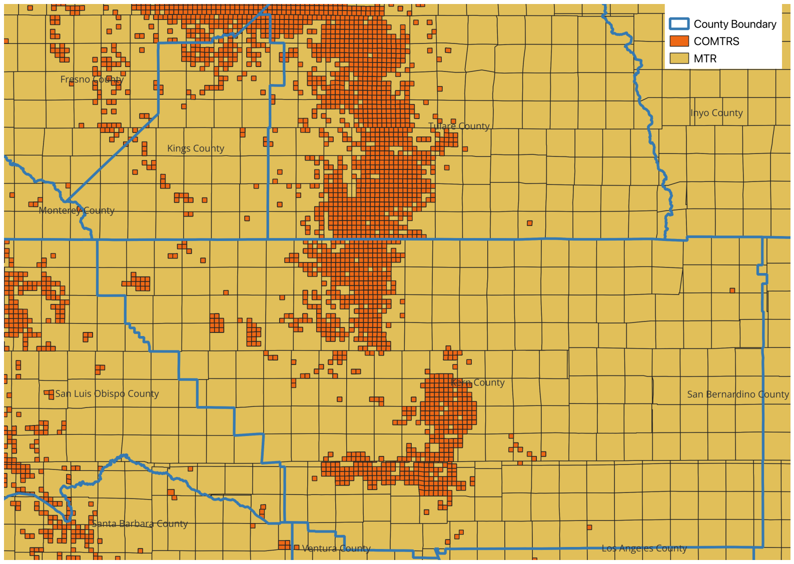


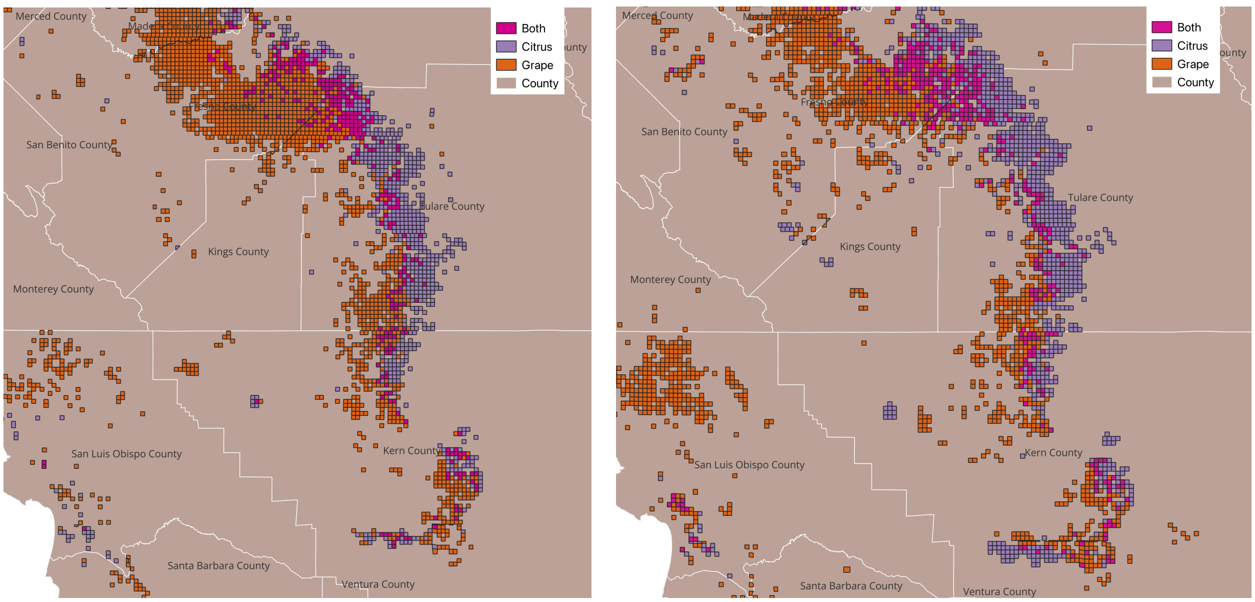
Figure 2: COMTRS, MTR, and County

larger than a COMTRS but smaller than a county. Each MTR contains around 36 COMTRS units. We combined the GIS maps for COMTRS, MTRs, and counties with pesticide use records. Figure 2 shows the geographic relationship between COMTRS, MTR, and county. In Figure 2, the blue boundary represents the county boundary, the yellow squares indicate the MTRs, and the orange squares represent the COMTRS.

3.3.1 COMTRS-level

We can obtain the geographic distribution of grape and citrus COMTRS from the Public Land Survey System. Figure 3 compares the geographic distribution of grape and citrus COMTRS in 1992 and 2021 in Tulare, Fresno, and Madera counties. The orange squares represent grape COMTRS, the purple squares represent citrus COMTRS, and the magenta squares represent COMTRS with both grape and citrus pesticide use records. In Figure 3, there are more grape COMTRS in areas distant from citrus in Panel (b) than in Panel (a).

Using the maps of COMTRS, we calculated the minimum distance between the grape and the nearest citrus COMTRS for each grape COMTRS, which allows us to analyze spatial patterns effectively. In Figure 4, orange squares indicate grape COMTRS, purple squares indicate citrus COMTRS, and magenta squares show COMTRS with both citrus and grape records. The dots inside each square is the geometric centroid of each square. The minimum distance between grape and citrus COMTRS for each grape COMTRS is the distance between the geometric centroid of the grape COMTRS and the nearest citrus COMTRS (as shown by black lines in Figure 4). If a COMTRS has both citrus and grape records, the minimum distance is 0.



(a) 1992 (b) 2021

Figure 3: COMTRS Distribution in Tulare, Fresno, and Madera Counties

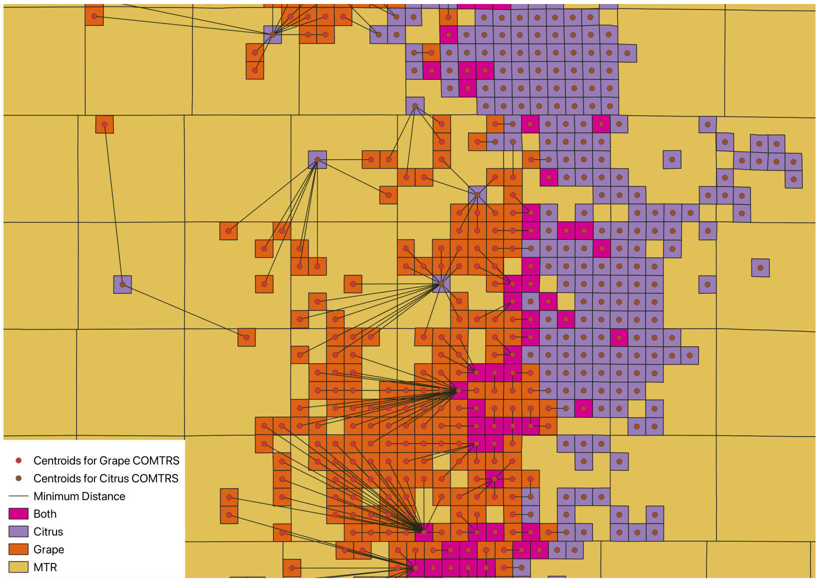


Figure 4: The Minimum Distance of Each Grape COMTRS to the nearest Citrus COMTRS

3.3.2 MTR-level

COMTRS has small areas, approximately 1x1 square mile. GWSS infestation and PD may lead all growers in the infested COMTRS to abandon their production. If this is the case, the grape COMTRS may be converted to other uses and would be dropped from the sample after being infested. Additionally, grape COMTRS may be converted to citrus COMTRS, affecting the minimum distance for nearby grape COMTRS. To address the issue, we aggregated the minimum distance to the MTR level and introduced the average minimum distance for each MTR. The Average Minimal Distance (i.e., observed distance) is calculated as follows:

- find the minimum distance between the center of a grape COMTRS and the nearest citrus COMTRS
- sum the distances of all COMTRS within the MTR
- divide the sum distance by the total number of grape COMTRS within the MTR.

However, Figure 3 shows that the distribution of citrus COMTRS has changed over time.

As a result, the average minimum distance for individual grape parcels might decrease due to the relocation choices of citrus growers, even if grape growers tend to plant grapes in parcels away from citrus production [8]. To estimate the effects of infestation on only grape growers' relocation choices, we need to introduce a new distance variable that provides more information on the distance grape growers intended to achieve rather than the distance they eventually achieved.

To separate the effects of infestation on the average minimum distance observed on the map and the average minimum distance grape growers intended to achieve, we introduced the average minimum lagged distance (lagged distance for grape growers) between the grape parcels in year t and citrus parcels in year $t-1$ as follows:

- find the minimum distance for each grape COMTRS in year t to the nearest citrus COMTRS in year $t-1$
- sum the distances of all grape COMTRS within the MTR
- divide the sum distance by the total number of grape COMTRS within the MTR in year t

Using this lagged average minimum distance as the dependent variable in regressions provides valuable insights into grape growers' willingness to avoid proximity to citrus. Suppose the estimated effect of infestation with the observed average minimum distance is positive but smaller than the estimated effect with the lagged average minimum distance. In that case, it suggests that grape growers intended to plant grapes away from citrus but failed to achieve the distance they expected due to changes in citrus production locations. Thus, in this case, grape growers may suffer more losses than they expected after relocation.

[8]Detailed example can be found in the last section

Since the GWSS cannot transmit harmful diseases to citrus in California, a GWSS infestation would not affect citrus production or the distance that citrus growers intended to achieve. However, the pest management programs may impose implicit costs on citrus growers, motivating them to relocate. To analyze the effects of GWSS infestation on citrus growers' location choices, we can apply the same methods to measure the distance that citrus growers intended to achieve. The lagged average distance (the lagged distance for citrus growers) between the grape parcels in year $t-1$ and citrus parcels in year t is calculated as follows:

- find the minimum distance for each citrus COMTRS in year t to the nearest grape COMTRS in year $t-1$
- sum the distances of all citrus COMTRS within the MTR
- divide the sum distance by the total number of citrus COMTRS within the MTR in year t

Additionally, the number of citrus and grape parcels may have changed over time. The number of citrus productions would affect both the severity of PD and the average minimum distance between citrus and grapes. Thus, it is important to consider the share of citrus production. The citrus and grape shares for each MTR is calculated as follows:

$$\text{citrus (grape) share} = \frac{\text{total area of citrus (grape) COMTRS}}{\text{area of MTR}} \tag{1}$$

Table D.5 in Appendix D presents the summary statistics for the dependent and independent variables used in the regressions. The top part of the table displays statistics for the entire sample, consisting of 1084 MTRs that planted grapes between 2002 and 2019. These statistics were used to generate the estimates shown in Table F.8. The bottom part focuses on the summary statistics for 256 grape-planted MTRs that have ever been infested by GWSS.

These observations were used to generate the estimates in Table F.9.

3.3.3 County-Level

Following the same methods discussed above, we also constructed the average minimum distance, average lagged minimum distance, and average lagged minimum distance for citrus growers at the county level. However, as shown in Appendix B, Figure B.10, there may not be sufficient variation and observations for county-level analysis. Only ten counties have varied infested shares over time. Thus, the county-level analysis is less reliable than the MTR-level analysis. Only MTR-level analysis results are shown in the main body of the paper, and county-level summary statistics and analysis can be found in Appendix E.

Another advantage of MTR-level analysis is the ability to exclude areas that never produced grapes or citrus. In county-level analysis, we overlook the specific locations of infestations. Infestation may occur in areas where grapes are not planted. In such cases, the infestation would not influence the location choices of grape growers. By utilizing MTR-level data, we can exclude MTRs that never planted grapes or citrus from the sample, thereby making better use of the location information of infestation.

4 Empirical Strategy and Results

GWSS infestations and PD can affect the spatial patterns of grape production through two channels: first, they can decrease grape production in infested counties. Second, they may motivate grape growers to plant vineyards further away from citrus trees within infested areas. In this section, we would first estimate the effects of PD and GWSS infestation on grape acreage. Then, we would estimate the effects of PD on the distance between citrus and grape production at both the county and MTR levels. County-level analysis can be found in the appendix.

4.1 The Effects of PD and GWSS Infestation on Grape Acreage

We use event studies to explore whether the outbreak of GWSS significantly led to a shrinkage in grape production in infested counties and if implementing the pest management program has mitigated these effects. We estimate a model of grape acreage at the year, county, and grape variety level.

Counties may not consistently plant all grape varieties at all times, resulting in many zero values in acreage data. Due to the presence of zeros, log transformation cannot be applied. Instead, we use the inverse hyperbolic sine transformation to adjust the data distribution. According to Bellemare and Wichman (2020), when the dependent variable y is sufficiently large, the elasticity of y with respect to independent variables is approximately equal to the product of the independent variable and the estimated coefficients. Therefore, we can still interpret the estimated coefficients as a percentage change. Our estimating equation is

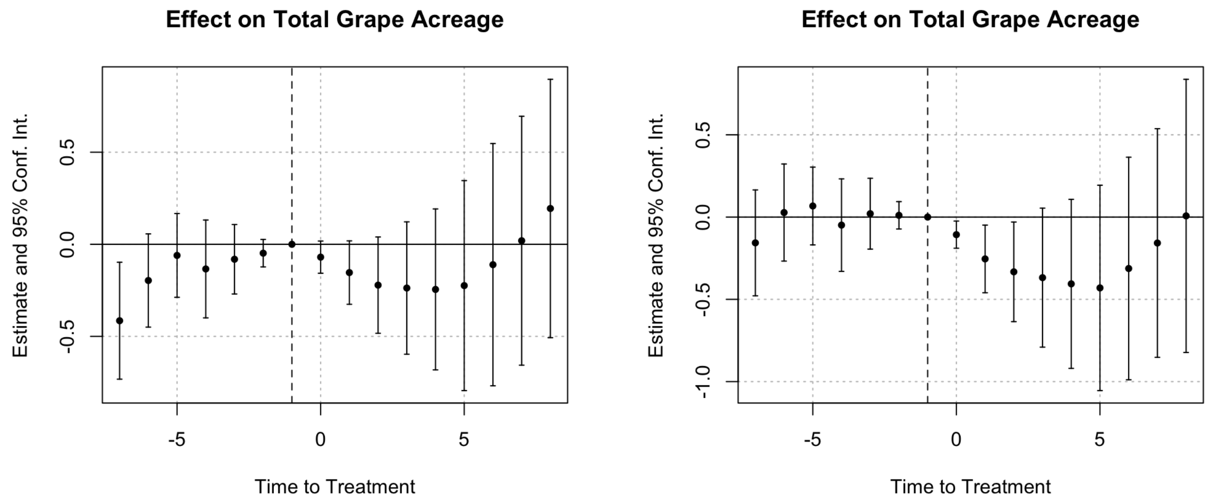
$$ashinh(y)_{vct} = B_c \left[\sum_{j=2}^{J} \beta_j (Lag\_j)_{ct} + \sum_{k=1}^{K} \beta_k (Lead\_k)_{ct} \right] + \mu_{cv} + \gamma_{vt} + \epsilon_{vct} \tag{2}$$

where

$$asinh(y)_{cvt} = ln(y_{cvt} + \sqrt{y_{cvt}^2 + 1}) \ . \tag{3}$$

The dependent variable is the total grape acreage for each county (c), variety (v), and year (t). We group event time into 3-year bins surrounding the year immediately before the treatment. We include dummy variables for whether the treatment (here, the start of the infestation) will take effect in (or have been in effect for) 0-2 years, 4-6 years, and so on. Following the setting in Allcott et al. (2019), B_c is an indicator variable for whether the county has been infested by GWSS, so B_c is 0 for never-infested counties. The interaction with B_c ensures that we only use the infested counties to identify β but still include the full sample to improve the precision on the covariates and fixed effects.

4.1.1 Results



(a) All Sample (b) Never-Infested Counties Excluded

Figure 5: Event Study Results

Panel (a) in Figure 5 displays the regression results with all counties, including control counties that have never been infested by GWSS. The average estimated effect is around -0.15 for the first 9 years after GWSS infestation, implying that GWSS infestation led to approximately a 15% annual loss of grape acreage. The significance increased after treatment, potentially due to the implementation of Area-wide Pest Management Programs. In Panel (a), we observed significantly negative effects in the earliest time-bin, approximately 17 years before the infestation. The violation of the parallel trend assumption implies that treated and control counties differed in unobserved characteristics 17 years before the infestation. Thus, there is a concern that the difference in total grape acreage in the post-treatment period may be driven by unobserved factors instead of GWSS infestation. However, in Figure 5 panel (a), the estimated effects were insignificant between 16 and 1 year before the infestation, suggesting that the difference in observed factors between treated and control counties disappeared near the year of infestation. To address the potential issue caused by the violation of parallel trends, we excluded never-infested counties from the sample, as these counties may differ from ever-infested counties in many aspects, such as location and climate conditions.

Panel (b) in Figure 5 displays the regression results with a sample excluding control counties that have never been infested by GWSS. The average estimated effect is around -0.26 for the first 12 years after GWSS infestation, implying that GWSS infestation led to approximately a 26% annual loss of grape acreage. The estimated effects become insignificant 12 years after treatment, potentially due to the implementation of Area-wide Pest Management Programs. Notably, the estimated effects become more pronounced after excluding control counties.

While the current analysis focuses on the 26 most widely planted and traditional grape varieties that remained consistent between 1992 and 2021, we need to acknowledge the potential impact of newer grape varieties introduced during this period. The new varieties introduced after the outbreak of PD may have enhanced resistance to PD, prompting growers to alter their variety choices accordingly. Consequently, the results presented only capture the effects on the acreage of the most traditional grape varieties.

4.2 The Effects of PD and GWSS Management Programs on Spatial Patterns

We use fixed-effect regressions to explore whether the infestation of GWSS significantly led to an increase in the distance between citrus and grape COMTRS. Our estimating equation is

$$asinh(Distance)_{ct} = \alpha + \beta share_{ct-1} + \delta T_{ct} + \tau share_{ct-1} * T_{ct} + X_{ct} + \mu_c + \gamma_t + \epsilon_{ct} \ . \quad (4)$$

In this model, the dependent variable is the transformed average minimum distance for each location (c) (i.e., county or MTR) and year (t). As discussed above, the observed distance between citrus and grape production may be different from the distance citrus or grape growers intended to achieve. Three types of minimum average distance are analyzed: observed minimum distance, lagged distance for grape growers, and lagged distance for citrus growers. $share_{ct-1}$ represents the share of infested areas in each location from the previous year. To examine the effects of area-wide pest management programs, we introduce a dummy variable indicating the implementation status for the area-wide pest management programs, T_{ct}. $T_{ct} = 1$ if one county has implemented GWSS area-wide management programs. Additionally, we control for location and year fixed effects and the share of total areas of citrus COMTRS over county areas.

4.2.1 Results

Columns (1) and (2) in Appendix F Table F.8 display the regression results using average minimum distance as the dependent variable. The results indicate that a one percentage point increase in the share of infested areas leads to a 0.25% increase in the average minimum distance. For instance, if an MTR converted from never-infested to fully infested, the observed distance between citrus and grape production would be expected to increase by 25%. Column (2) shows the results after adding the interaction of the infested share and an area-wide pest management treatment dummy. The results suggest that a one percentage point increase in the share of infested areas leads to a 0.37% rise in the average minimum distance without implementing area-wide pest management programs. After implementing such programs, the effects of infestation decrease, with a one percentage point increase in the share of infested areas leading to only a 0.25% ($1 \times 0.0037 \times 100\% - 1 \times 0.0012 \times 100\% = 0.25\%$) increase in the average minimum distance.

Columns (3) and (4) in Table F.8 display the results using lagged average distance as the dependent variable. The magnitude of the estimated effects using lagged distance is similar to those using observed distance. The estimates suggest that a 1 percentage point increase in the share of infested areas leads to a 0.35% increase in the average minimum distance that grape growers intended to achieve without the implementation of area-wide pest management programs. After implementing such programs, the effects of infestation decrease, with a one percentage point increase in the share of infested areas leading to a 0.17% ($1 \times 0.0035 \times 100\% - 1 \times 0.0018 \times 100\% = 0.17\%$) increase in the average minimum distance. Additionally, the implementation of area-wide pest management programs has significantly increased the distance by 8%. One potential explanation for this effect could be that grape growers in managed areas are better informed about the risks associated with proximity to citrus productions, thus they are more likely to relocate to areas further away from citrus.

As shown in the example section and Appendix A, the final distance achieved may be smaller or greater than the distance grape growers intended to achieve due to the relocation choices of citrus growers. According to the estimates in (2) and (4), the estimated effects using the observed distance were similar to the estimated effects using the distance grape growers intended to achieve; however, the estimated effects of area-wide pest management programs are significantly smaller in (2) than in (4). The results imply that the GWSS infestation itself did not significantly impact citrus growers' location choices, as we observe insignificant differences in the estimated coefficient for infested share. However, the area-wide pest management programs can impact citrus growers' location choices. Thus, observed distance measures might underestimate the effects of area-wide pest management programs on grape growers' relocation choices.

Columns (5) and (6) show the results using lagged average distance for citrus growers as the dependent variable. Column (5) suggests that a one percentage point increase in the share of infested areas leads to a 0.007% increase in the average minimum distance. We then decomposed the effects in column (6). This analysis suggests that implementing area-wide pest management programs, rather than GWSS infestation, motivated citrus growers to change their locations. Specifically, implementing these programs may have increased citrus production costs, leading citrus growers to plant citrus further away from grapes in managed counties. This finding is consistent with the results obtained from comparing columns (2) and (4). Table F.9 shows the regression results using only ever-infested MTRs. The results in Table F.8 and Table F.9 have the same pattern and similar magnitude.

There is concern that the number of grape COMTRS in each MTR may be affected by GWSS infestation. If this is the case, some MTRs may convert from grape MTRs to non-grape MTRs and be excluded from the sample. Consequently, the estimates in Table F.8 may be biased. To address this concern, we regressed the number of grape COMTRS within each MTR on the infested share. The results in Table F.10 suggest that if one MTR becomes fully infested, the number of grape COMTRS would decrease by around 0.18 on average. Considering that the average number of grape COMTRS in the sample is 7.2, this represents an average decrease of approximately 2.5%. If one non-managed MTR becomes fully infested, the grape COMTRS will decrease by around 0.74. However, the coefficients for the infested share in both models are insignificant, leading us to believe that GWSS infestation does not significantly reduce the number of grape COMTRS within each MTR.

5 Heterogeneity Analysis

5.1 Grower Type

Grower types can influence growers' decision-making processes. For example, diversified growers—those who own both grape parcels and other types of parcels—may find it easier to convert grape land to alternative uses. As a result, diversified growers may be less likely to exit the market in response to changes in infestation rates, whereas grape-only growers may be more likely to do so. Using the PUR dataset, we extract grower ID information to reorganize the data and examine how infestation affects the composition of grower types at the MTR level. We classify a grower in a given MTR-year as a specialized grape grower if they have pesticide application records only for grape production within that MTR and year. We reestimate equation (1.4), using dependent variables: (i) the share of grape growers, (ii) the share of specialized grape growers among all growers, and (iii) the share of diversified growers among all growers.

Table 1: Effect of Infestation and Treatment on Grape Growers' Share

	Total Grape Share	Specialized Share	Diversified Share
Infested Share	−0.001	−0.001*	0.000
	(0.001)	(0.000)	(0.000)
AWMP	−0.054*	−0.055**	0.001
	(0.023)	(0.019)	(0.009)
Infested Share × AWMP	0.001	0.001*	0.000
	(0.000)	(0.000)	(0.000)
Citrus Share	−0.280+	−0.377**	0.096
	(0.151)	(0.098)	(0.088)
Num.Obs.	2793	2793	2793
R2	0.885	0.837	0.578

+ p <0.1, * p <0.05, ** p <0.01, *** p <0.001

Standard errors clustered at the county level.

Columns in Table 1 present the regression results using the share of total grape growers, diversified growers, and grape-only (specialized) growers as dependent variables. Columns (1) and (3) show that infestation has little effect on the overall share of grape growers and the share of diversified growers. This is consistent with the idea that diversified growers have greater flexibility or capacity to adjust their production decisions in response to Pierce's

Disease, as they can more easily convert grape parcels to other uses. It also suggests that diversified growers are more resistant to the risks associated with Pierce's Disease. Column (2) indicates that a one-percentage-point increase in the share of infested areas is associated with a 0.1 percentage point decrease in the average share of specified grape growers. However, after the implementation of control programs, the share of specified grape growers appears to recover.

5.2 Temporal

To explore temporal heterogeneity in the response to pest pressure, we divided the full sample period (2001–2019) into four subperiods: 2001–2005, 2006–2010, 2011–2015, and 2016–2019. We then interacted the lagged infested share with period indicators to estimate time-varying effects. As shown in Table 2, the baseline coefficient on lagged infested share is positive and statistically significant in both specifications, indicating that in the early 2000s when grape growers started to recognize the harm caused by PD, grape growers tended to increase their distance from citrus production in response to greater pest pressure. Specifically, a one percentage point increase in infested share is associated with an increase of approximately 0.0010 to 0.0014 percent in average distance, depending on the model.

However, the interaction terms reveal a temporal decline in this effect. During the second and third periods (2006–2010 and 2011–2015), the interaction terms are small and statistically insignificant, suggesting that the spatial response to infestation did not differ meaningfully from the baseline. In the final period (2016–2019), the coefficient becomes negative, and in Model (2), which includes fixed effects by county, this decline is statistically significant at the 10% level. This pattern indicates that growers became less responsive over time, and in later years, areas with higher infestation rates were no longer associated with greater spatial avoidance. One possible explanation is that pest management programs and local adaptation reduced the importance of infestation risk, diminishing the need for growers to adjust location strategies in response.

Table 2: Temporal Heterogeneity in the Effect of Infested Share on Lagged Distance

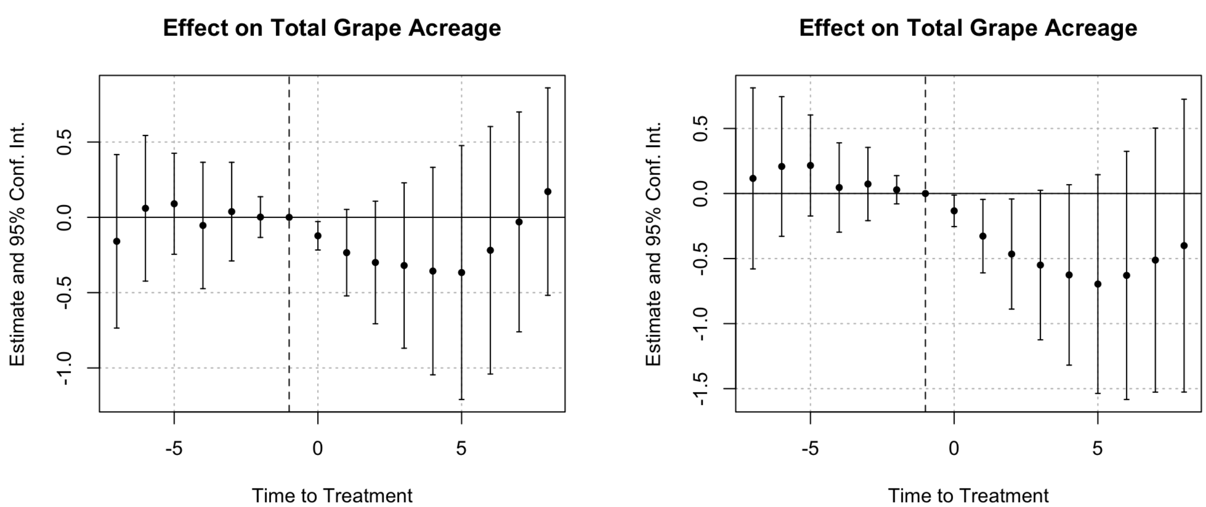
Dependent Variable:	Lagged Distance	
Model:	(1)	(2)
Variables		
Infested Share (%)	0.0014***	0.0010***
	(0.0004)	(0.0003)
Citrus Share	-1.420***	-1.482***
	(0.2213)	(0.2027)
Infested Share × Period 2	0.0014	0.0002
	(0.0012)	(0.0006)
Infested Share × Period 3	-2.5×10^{-7}	-0.0019
	(0.0008)	(0.0014)
Infested Share × Period 4	-9.56×10^{-5}	-0.0018*
	(0.0007)	(0.0009)
Fixed Effects		
MTR	Yes	Yes
Year	Yes	
Year × County		Yes
Fit Statistics		
Observations	2,793	2,793
R^2	0.925	0.950

Clustered (COUNTY) standard errors in parentheses

*Significance: *** p <0.01, ** p <0.05, * p <0.1*

6 Robustness Checks

As noted in the data section, some counties experienced only temporary infestations that were quickly controlled within residential areas. In the main specification, we treat these counties as non-treated. To test the robustness of this assumption, we explore two alternative specifications. In the left panel Figure 6 (a), we exclude all counties with temporary infestations from the sample. In the right panel, we instead classify these counties as treated starting from the first year GWSS was detected. In both cases, the results remain qualitatively consistent with the main specification, supporting the robustness of our findings.



(a) (b)

Figure 6: Robustness Checks of Event Study Results

To ensure the validity of our main findings on distances, we assess the robustness of our results to alternative model specifications. Specifically, we test whether our estimates are sensitive to different fixed effects structures and the inclusion of lagged explanatory variables.

Our baseline specification includes MTR and year fixed effects. To account for unobserved heterogeneity at a finer spatial and temporal level, we re-estimate the model using county-by-year fixed effects. Column (2) in Table 3 uses the full sample, while Column (3) restricts the sample to MTRs that were ever infested. These richer specifications absorb additional sources of variation that might bias the estimates. Across all specifications, the estimated treatment effects remain statistically significant and similar in magnitude, suggesting our results are not driven by specific choices of fixed effects.

To test whether the effect of pest infestation on treated areas operates with a delay, we re-estimate our baseline specification using lagged values of the infested share variable from one to six years prior. Across the first four lag specifications, the coefficient of lagged infestation remains positive and statistically significant, indicating that grape growers respond to historical pest pressure by increasing distance from citrus production. The magnitude of the coefficient declines with longer lags and becomes statistically insignificant after the fourth year, suggesting that most of the behavioral response occurs within a few years of infestation. This finding supports our assumption that grower responses are not immediate but follow pest pressure with a modest delay, consistent with perennial crop adjustment dynamics. The stability of the results under different lag structures adds credibility to our identification strategy and reinforces the interpretation that the treatment effect reflects a behavioral response to pest pressure rather than contemporaneous shocks.

Dependent Variable:	Lagged Distance		
Model:	(1)	(2)	(3)
Variables			
Infested Share (%)	0.0020***	0.0004	0.0007**
	(0.0005)	(0.0007)	(0.0003)
Citrus Share	-2.021***	-1.757***	-1.462***
	(0.3196)	(0.3100)	(0.2022)
Fixed-effects			
MTR	Yes	Yes	Yes
year	Yes		
County-year		Yes	Yes
Fit statistics			
Observations	13,727	13,727	2,793
R^2	0.92708	0.95421	0.94979

Clustered (COUNTY) standard-errors in parentheses

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 3: County-year Fixed Effects

Dependent Variable:	Lagged Distance					
Model:	One-Year	Two-Year	Three-Year	Four-Year	Five-Year	Six-Year
Variables						
Infested Share (%)	0.0029***	0.0030***	0.0016**	0.0011*	-0.0005	-0.0002
	(0.0006)	(0.0006)	(0.0007)	(0.0005)	(0.0012)	(0.0012)
Infested_share× treatment_AWMP	-0.0016***	-0.0015**	-0.0011*	-0.0007	-0.0002	3.8×10^{-5}
	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0006)	(0.0007)
treatment_AWMP	0.1196***	0.1191***	0.0706**	0.0610*	0.0331	0.0308
	(0.0381)	(0.0321)	(0.0327)	(0.0306)	(0.0338)	(0.0353)
Citrus Share	-1.441***	-1.394***	-1.420***	-1.311***	-1.249***	-1.308***
	(0.1818)	(0.1765)	(0.1975)	(0.2434)	(0.2699)	(0.2079)
Fixed-effects						
MTR	Yes	Yes	Yes	Yes	Yes	Yes
year	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	2,793	2,537	2,309	2,100	1,910	1,729
R^2	0.92489	0.92457	0.92832	0.93013	0.93021	0.93020

Clustered (COUNTY) standard-errors in parentheses

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

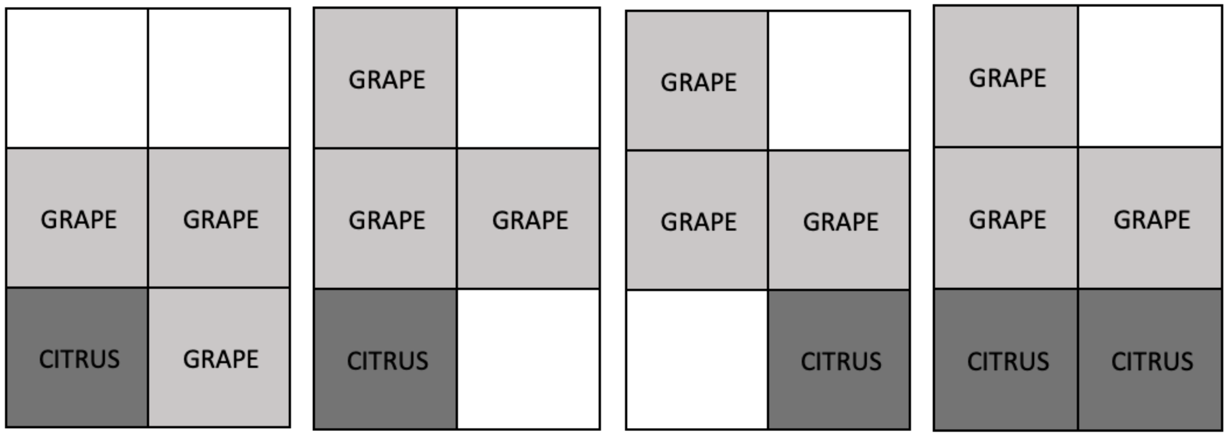
Table 4: Different Year Lags

7 Conclusion

In this study, we empirically analyze the effects of Pierce's Disease (PD) on grape production, focusing on both the acreage and the spatial patterns of grape and citrus cultivation. The results suggest that pest pressure induces spatial avoidance behavior. Specifically, PD and Glassy-Winged Sharpshooter (GWSS) infestation can lead to an estimated 26% annual loss of grape acreage, prompting growers to reduce planting in infested areas to minimize losses. Additionally, a one percentage point increase in GWSS infestation share is associated with a 0.37% increase in the spatial distance between grape and citrus production without the implementation of control programs. Control programs appear to be effective, as their presence mitigates the impact of infestation, highlighting their role in reducing pest pressure.

These findings underscore the importance of dynamic models of agricultural decision-making, particularly regarding spatial responses to pest threats. They also emphasize the need for sustained and coordinated pest control efforts. Although our analysis leverages rich spatial data, future research could benefit from incorporating farm-level management decisions or yield outcomes to better understand the economic consequences of these spatial adjustments. Shifts in grape production locations can involve various costs, including replanting expenses and potential yield losses due to suboptimal soil and climate conditions or delays in grapevine productivity. As a result, spatial changes in response to PD likely entail welfare losses, even if one could expect these to be lower in aggregate than those arising from PD in the absence of behavioral adjustments. Building on this study, future research could link these spatial responses more directly to yield or profitability measures in order to quantify the welfare implications of pest pressure and the effectiveness of control efforts in shaping agricultural land use.

A Another Example of Joint Relocation



(a) Case 2.0 (b) Case 2.1 (c) Case 2.2 (d) Case 2.3

Figure 7: Examples When Intended Distance is Smaller than Actual Distance

Citrus growers might utilize the abandoned grape parcels, leading to an larger increase in the average minimum distance than grape growers intended to achieve.

Panel (a) shows the case (Case 0) when there is no infestation. There are three grape parcels and one citrus parcel, with two grape parcels adjacent to the citrus parcel. Assume that the side length of a square is d. D_0 shows the original distance without any interventions. Thus, the average minimum distance in Case 0 is

$$D_0 = \frac{(\sqrt{2}+1+1)d}{3}$$

Panel (b) illustrates the first case (Case 1) when this area is infested by GWSS. In this scenario, grape growers cease planting in the parcel adjacent to citrus, and a new grape parcel appears in the top-left corner. Citrus growers choose not to change their location. The observed distance, D_1, is equal to the distance that grape growers intended to achieve and greater than the original distance, D_0. Thus, the average minimum distance in case 1 is

$$D_1 = \frac{(2 + \sqrt{2} + 1)d}{3} > D_0$$

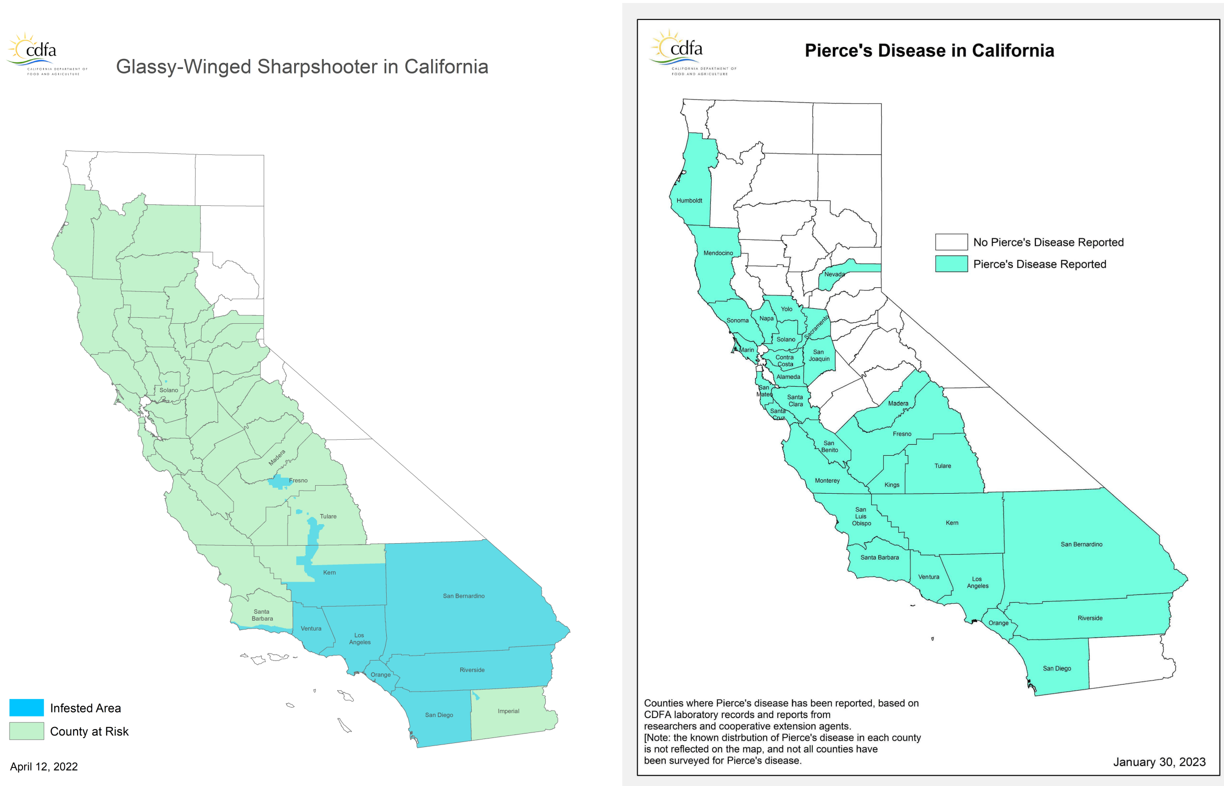
Panel (c) depicts the second case (Case 2) when this area is infested by GWSS. In this scenario, the abandoned grape parcel are more profitable than the original citrus parcel owned by the citrus growers, so citrus growers decided to utilize the abandoned parcel. Thus, now the citrus growers occupy the bottom-right parcel. The distance that grape growers actually achieved is greater than the distance that grape growers intended to achieve, so $D_2 > D_1$. Thus, the average minimum distance in case 2 is

$$D_2 = \frac{(\sqrt{5} + \sqrt{2} + 1)d}{3} > D_1$$

Panel (d) depicts the third case (Case 3) when this area is infested by GWSS. In this scenario, the abandoned grape parcel are more profitable than the original citrus parcel owned by the citrus growers, so citrus growers decided to utilize the abandoned parcel, and there is an expansion of citrus. Thus, now the citrus growers occupy two bottom parcels. The distance that grape growers actually achieved, D_3, is smaller than the distance that grape growers intended to achieve, so $D_3 < D_1$ but greater than the original distance. Thus, the average minimum distance in case 3 is

$$D_0 < D_3 = \frac{(2 + 1 + 1)d}{3} < D_1$$

B Summary Statistics for GWSS Distribution



(a) GWSS (b) Pierce Disease

Figure 8: PD/GWSS Distribution

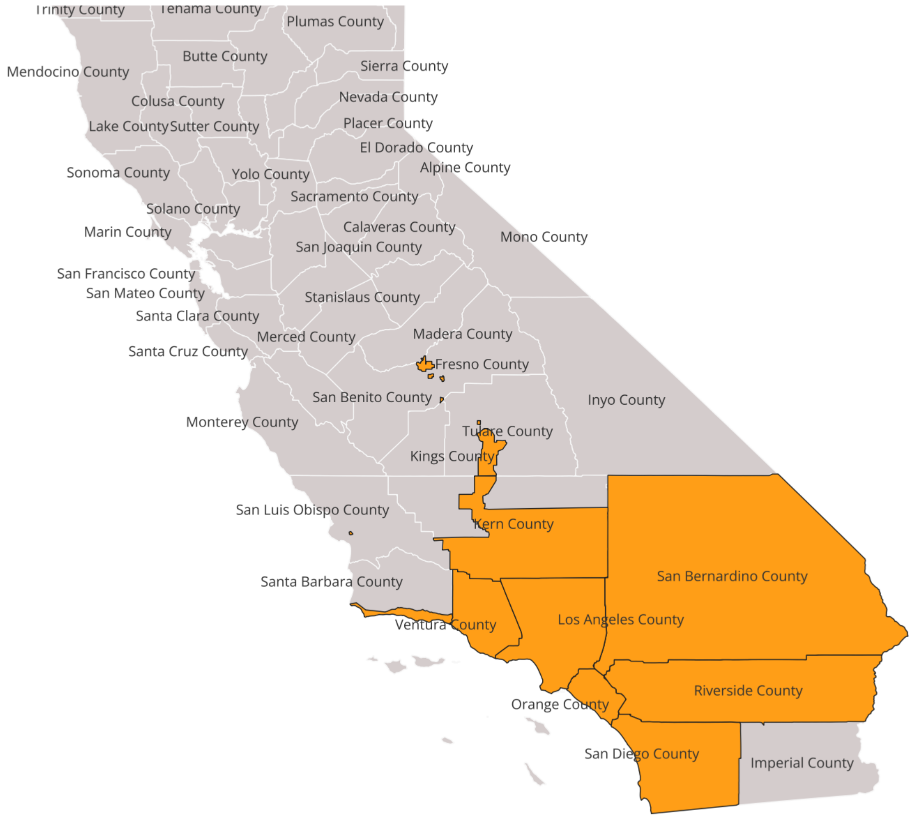


Figure 9: GWSS Distribution in 2018

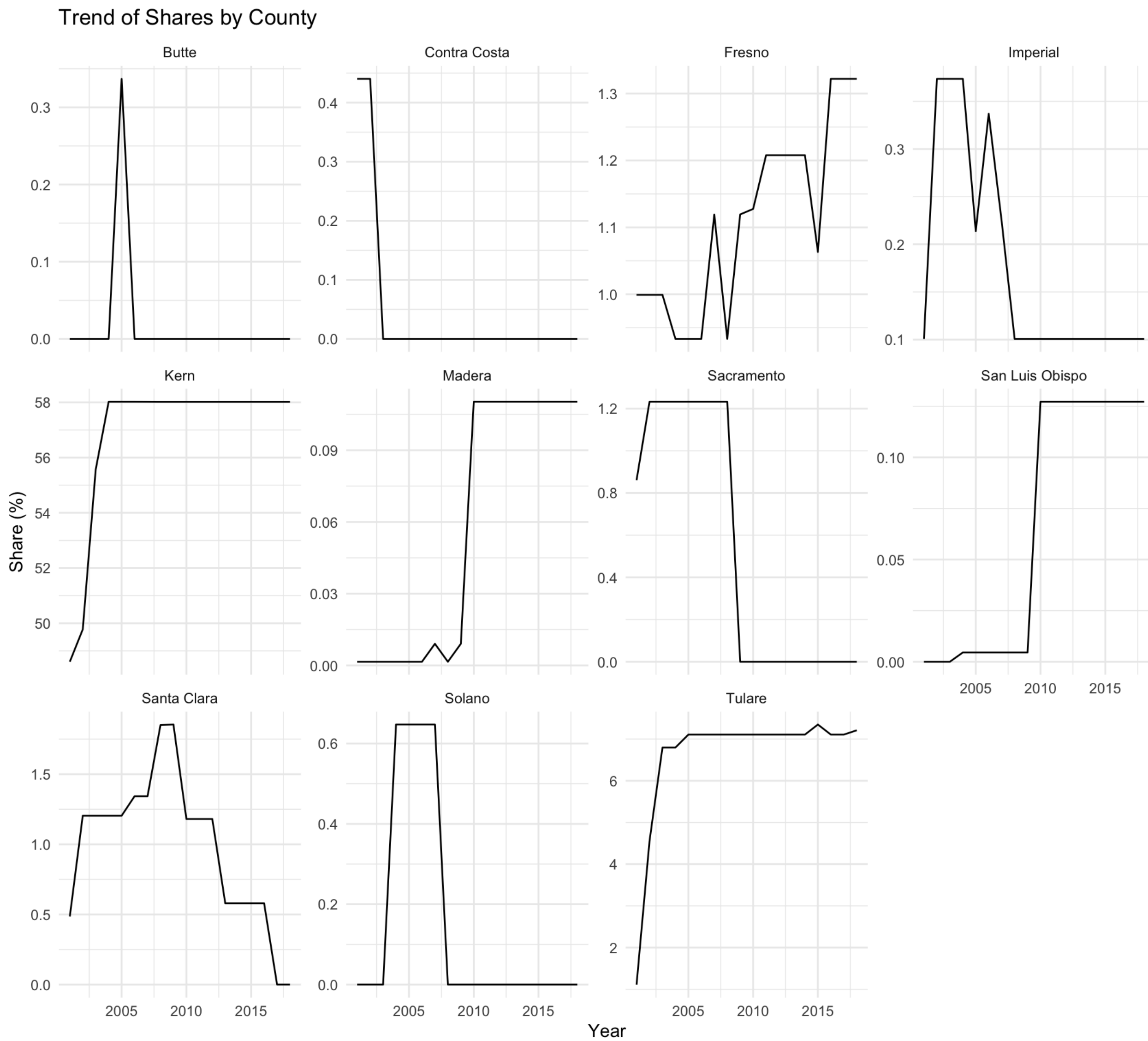


Figure 10: Variations in GWSS Distribution

In Figure B.10, the infested share (%) is calculated by dividing the infested area obtained from GWSS infestation GIS files by the geographic areas of the counties and then multiplying by 100%. The value of the infested share in Figure B.10 is between 0 and 100.

C Trends of Grape Acreage in California

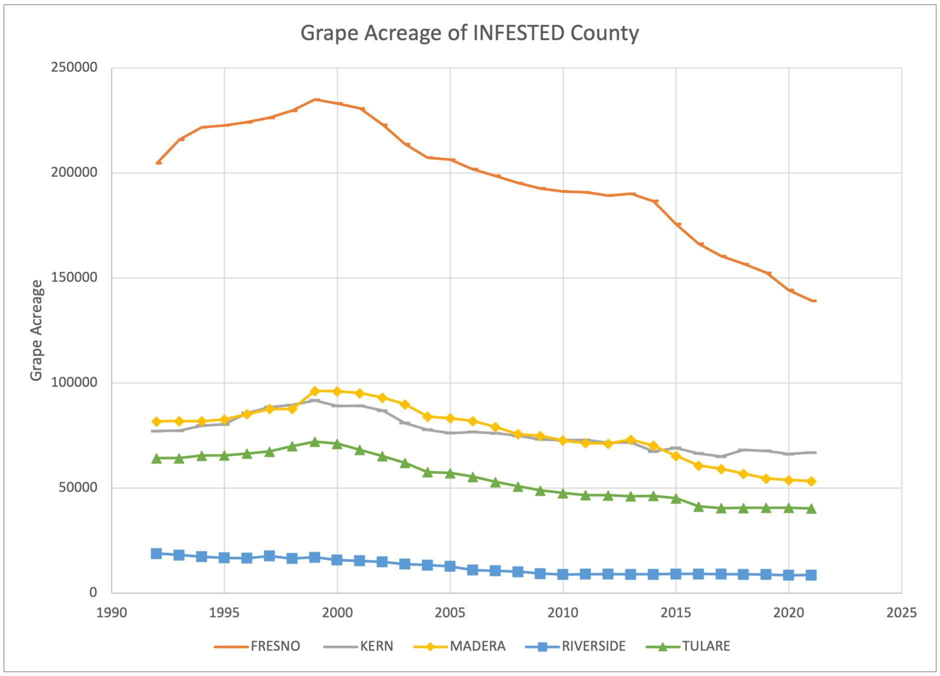


Figure 11: Grape Acreage of Infested Counties

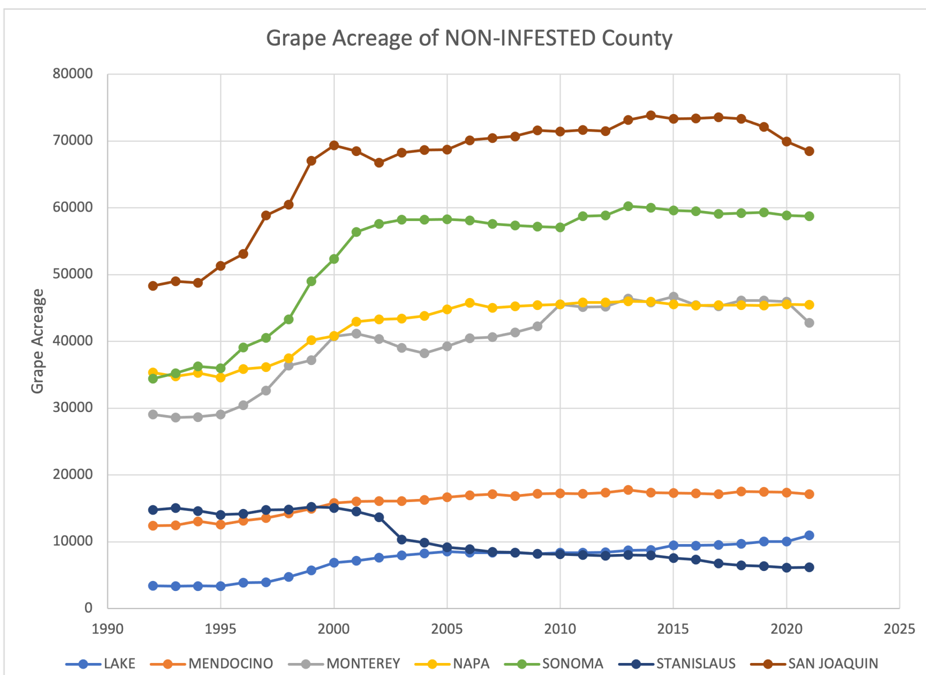


Figure 12: Grape Acreage of Non-infested Counties

Figure C.11 displays the grape acreage of the five main grape-planting counties that were infested by GWSS, while Figure C.12 shows the grape acreage of non-infested counties. The above two figures show that grape acreages in most counties expanded before 2000. However, from 2000 onwards, the grape acreage of infested counties consistently decreased, while the grape acreage of most non-infested counties consistently increased. These acreage trends are consistent with the hypothesis that the outbreak of GWSS in 1999 raises overall concerns about grape production under the risk of PD, ultimately leading to a shrinkage in grape production in infested counties or counties at high risk. However, grape growers in non-infested counties may have benefited from increased prices due to the decreased supply in Southern California, potentially enabling them to steadily expand production.

D MTR Sample Statistics

	variable	minimum	q1	median	mean	q3	maximum	observations
	ALL SAMPLE (Sample Used in Table F.1)							
1	Infested Share (%)	0.00	0.00	0.00	14.47	0.00	100.00	13727
2	Lagged Distance	0.00	2.09	3.13	2.87	3.81	5.58	13727
3	Distance	0.00	2.07	3.12	2.87	3.81	5.58	13727
4	Lagged Distance for Citrus	0.00	0.48	1.09	1.38	1.95	5.27	4159
	EVER-INFESTED MTR (Sample Used in Table F.2)							
1	Infested Share (%)	0.00	33.29	100.00	71.11	100.00	100.00	2793
2	Lagged Distance	0.00	0.62	1.20	1.53	2.48	4.85	2793
3	Distance	0.00	0.61	1.18	1.51	2.45	4.87	2793
4	Lagged Distance for Citrus	0.00	0.52	1.06	1.38	1.96	5.11	2239

Table 5: Summary Statistics

E County-Level Analysis

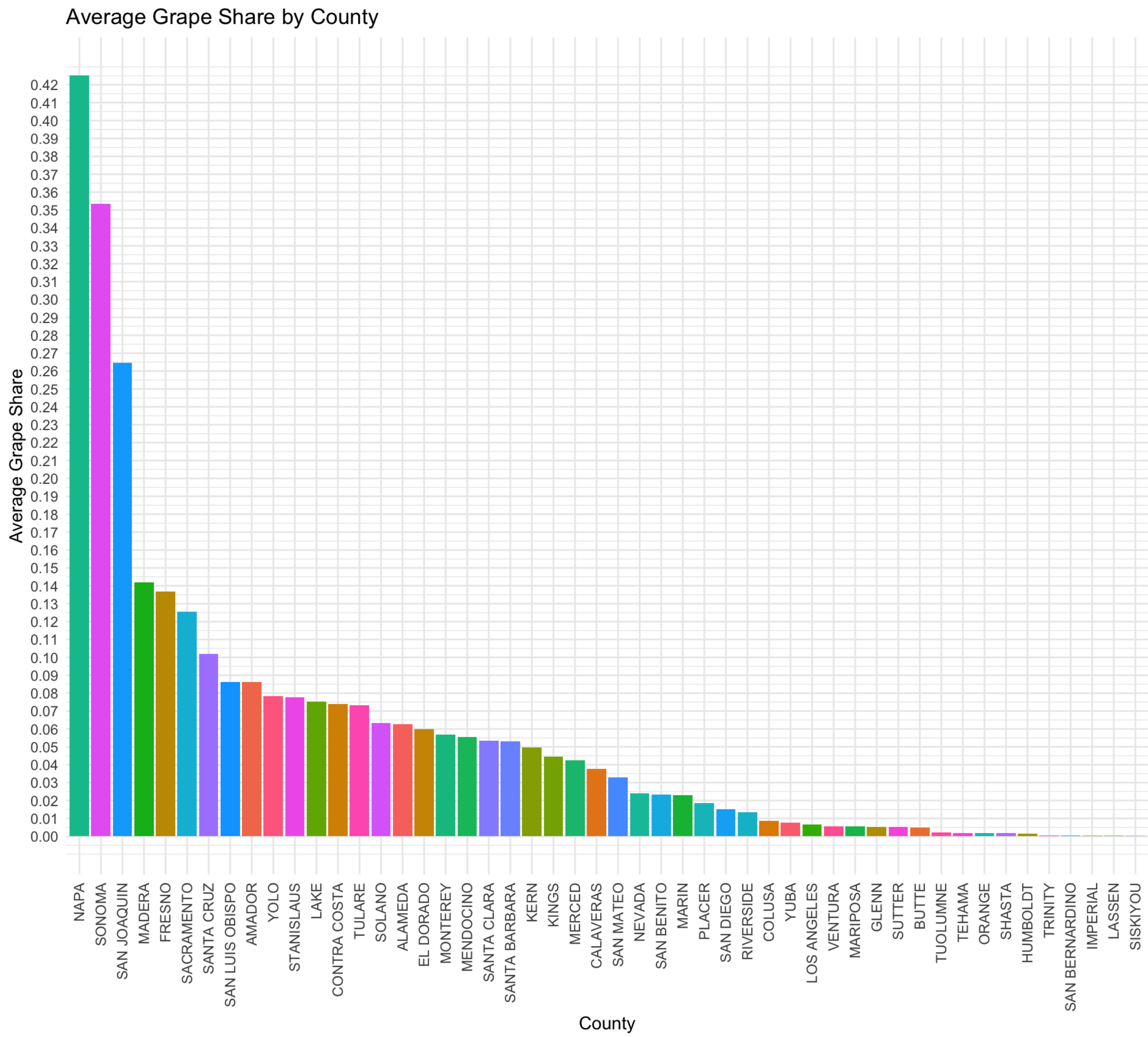


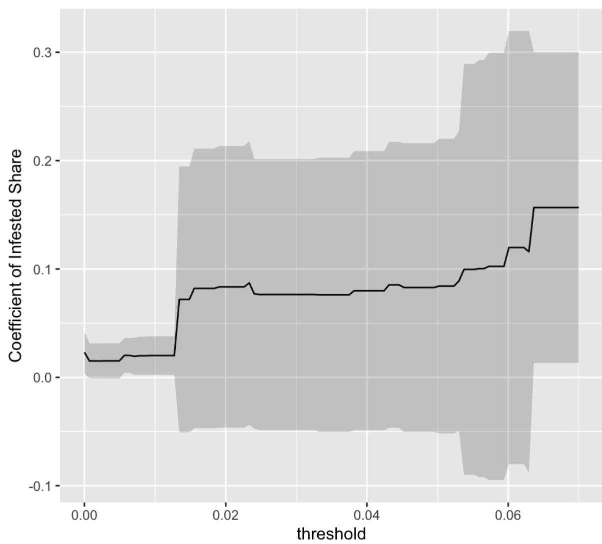
Figure 13: Average Grape Shares by County

	Sample at Threshold of 0.01							
	variable	minimum	q1	median	mean	q3	maximum	observation
1	infested_share (%)	0.00	0.00	0.00	8.67	0.13	99.96	575
2	Lagged Distance	0.57	2.59	3.28	3.12	3.76	4.90	575
3	Distance	0.58	2.55	3.28	3.11	3.76	4.90	575
4	Lagged Distance For Citrus	0.00	0.75	1.17	1.29	1.57	3.13	347
	Sample at Threshold of 0.07							
1	infested_share (%)	0.00	0.00	0.00	0.60	0.11	7.35	252
2	Lagged Distance	1.08	2.68	3.37	3.20	3.90	4.55	252
3	Distance	1.07	2.68	3.37	3.19	3.88	4.54	252
4	Lagged Distance For Citrus	0.00	0.68	1.02	1.11	1.44	2.81	154

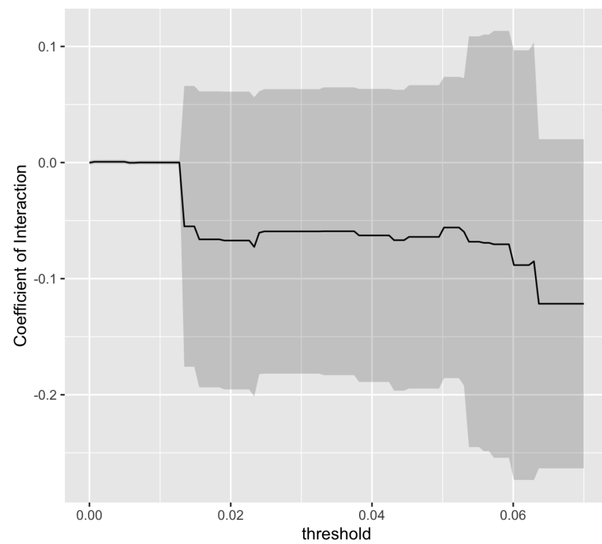
Table 6: Summary Statistics

In some counties, only a few COMTRS had grape production, but the average minimum distance based on these COMTRS could affect the results. To eliminate the potential bias caused by these COMTRS, we set a threshold and excluded all observation of the counties with average grape shares[9] lower than this threshold in county-level analysis. Regression results with a continuous threshold are shown in Figures E.14 and E.15. The maximum threshold in Figures E.14 and E.15 is 0.07. With a threshold of 0.07, the sample includes 252 observations across 14 counties and 18 years. When the threshold is set to 0.02, the sample includes 521 observations. footnote.

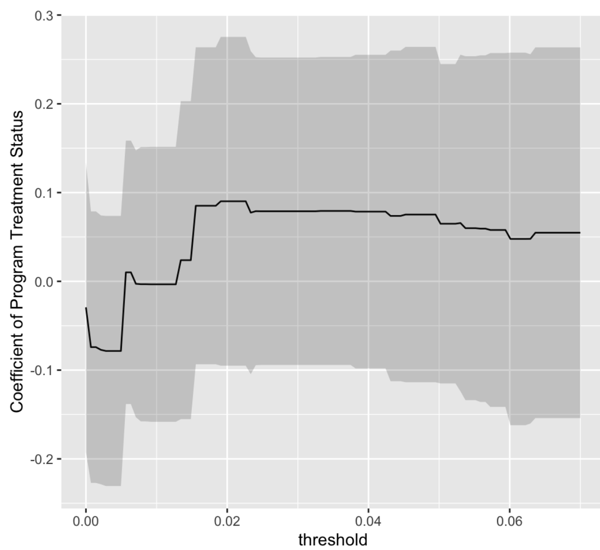
[9] Average grape share for each county is shown in Figure E.13.



(a) $\hat{\beta}$



(b) $\hat{\tau}$



(c) $\hat{\delta}$

Figure 14: Estimates Using Average Minimum Distance As Dependent Variable

Dependent Variables:	Distance		Lagged Distance		Lagged Distance For Citrus	
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
infested_share_map_lag	0.0200**	0.0201**	0.0138	0.0155	0.0219**	0.0180
	(0.0094)	(0.0091)	(0.0114)	(0.0113)	(0.0103)	(0.0107)
citrus_share_3	-46.93***	-46.89**	-25.12**	-24.02**	18.66	17.39
	(16.70)	(17.27)	(10.77)	(11.32)	(11.52)	(12.48)
treatment_AWMP_3		-0.0034		-0.0807		-0.0071
		(0.0790)		(0.0573)		(0.0737)
infested_share_map_lag × treatment_AWMP_3		2.61×10^{-5}		0.0003		0.0032*
		(0.0009)		(0.0008)		(0.0016)
Fixed-effects						
COUNTY_N	Yes	Yes	Yes	Yes	Yes	Yes
YEAR	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	575	575	575	575	347	347
R^2	0.93442	0.93442	0.92821	0.92830	0.81216	0.81425
Within R^2	0.09568	0.09569	0.02730	0.02859	0.01679	0.02768

Clustered (COUNTY_N) standard-errors in parentheses

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

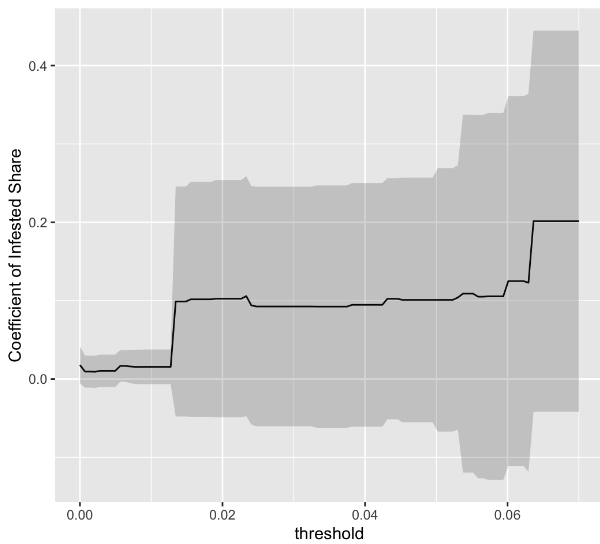
Table 7: Regression Results at Threshold of 0.01

Figure E.14 displays the regression results using average minimum distance as the dependent variable at different threshold levels. In sum, the estimate for β are consistently greatly than 0, while the estimates for τ are consistently negative. The significance of the estimates depends on the threshold and the sample size. However, the estimates for ρ are always insignificant.

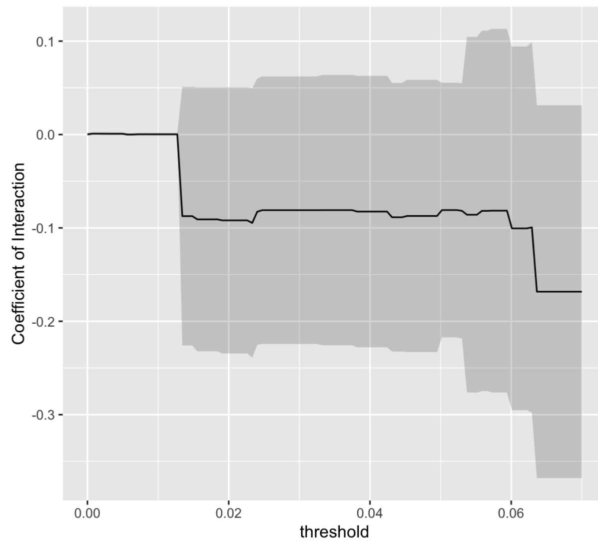
The estimates are significantly different with different thresholds. Larger estimates can be obtained with greater thresholds. For example, the results with a threshold of 0.01 suggest that a 1 percentage point increase in the share of infested areas leads to around a 2% increase in the average minimum distance in counties without area-wide pest management programs, while the results with a threshold of 0.07 suggest that a 1 percentage point increase in the share of infested areas leads to around a 15% increase in the average minimum distance in non-managed counties. The difference in estimates is caused by different counties included in the samples. At the threshold of 0.01, we include 37 counties in the sample, and the average infested share in the sample is around 8.67%, while at the threshold of 0.07, we include only 14 counties in the sample, and the average infested share in the sample is around 0.06%. At the threshold of 0.07, only the variations in GWSS infestation in Fresno and Tulare are used to calculate the estimates.

Panel (b) shows the estimates for the interaction between the infested share and an Area-wide pest management treatment dummy. It suggests that after implementing such programs, the effects of infestation on observed distances decrease. Specifically, a 1 percentage point increase in the share of infested areas leads to a 3.5% increase in the average minimum distance at the threshold of 0.07.

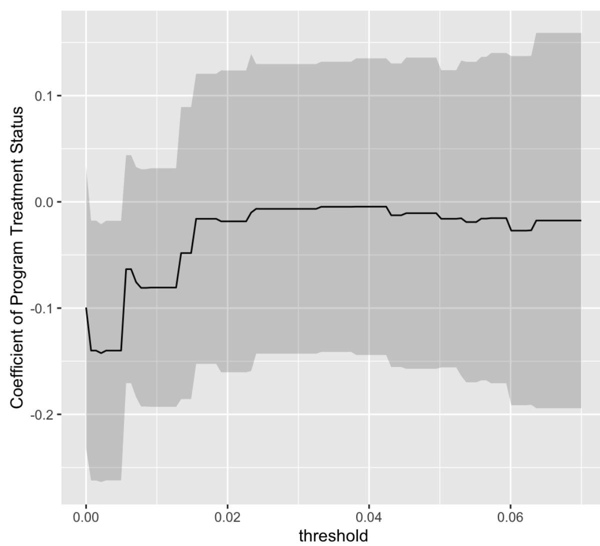
In non-managed counties, where no management programs exist, grape growers would suffer much greater losses if their parcels were adjacent to citrus. The risk of crop damage and losses is heightened in these counties, potentially prompting more grape growers to distance themselves further from citrus cultivation. The results also imply that the management programs effectively decreased the losses caused by the externality, making grape growers less likely to change locations.



(a) $\hat{\beta}$



(b) $\hat{\tau}$



(c) $\hat{\delta}$

Figure 15: Estimates Using Lagged Average Distance As Dependent Variable

Figure E.15 shows the results using lagged average distance as the dependent variable. The magnitude of estimated effects using lagged distance is slightly greater than those using observed distance, suggesting that on average, the increase in observed distance is smaller than the distance grape growers initially intended to achieve. Changes in the location of citrus parcels have mitigated the grape growers' efforts to relocate. The patterns of the estimates in Figure E.15 are consistent with those in Figure E.14.

F Effects on the Distance at MTR-level

Dependent Variables:	Distance		Lagged Distance		Lagged Distance For Citrus	
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
Infested Share (%)	0.0025***	0.0037***	0.0020***	0.0035***	0.0002	0.0007
	(0.0005)	(0.0006)	(0.0005)	(0.0006)	(0.0015)	(0.0020)
citrus_share	-3.769***	-3.795***	-2.021***	-2.070***	0.6174**	0.5990**
	(0.7145)	(0.7300)	(0.3196)	(0.3240)	(0.2493)	(0.2477)
treatment_AWMP		0.0148		0.0869*		0.1145**
		(0.0570)		(0.0475)		(0.0493)
infested_share × treatment_AWMP		-0.0012*		-0.0018***		-0.0011
		(0.0007)		(0.0005)		(0.0009)
Fixed-effects						
MTR	Yes	Yes	Yes	Yes	Yes	Yes
year	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	13,727	13,727	13,727	13,727	4,159	4,159
R^2	0.93066	0.93070	0.92708	0.92716	0.91915	0.91932
Within R^2	0.04557	0.04609	0.01332	0.01433	0.00432	0.00640

Clustered (COUNTY) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 8: Regression Results with ALL Grape-Planted MTRs

Dependent Variables:	Distance		Lagged Distance		Lagged Distance For Citrus	
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
infested_share (%)	0.0018***	0.0030***	0.0016**	0.0029***	0.0022	0.0044
	(0.0005)	(0.0007)	(0.0006)	(0.0006)	(0.0017)	(0.0028)
citrus_share	-2.585***	-2.600***	-1.423***	-1.441***	0.5873*	0.5843*
	(0.3437)	(0.3480)	(0.1884)	(0.1818)	(0.3184)	(0.3202)
treatment_AWMP		0.1157**		0.1196***		0.1461*
		(0.0404)		(0.0381)		(0.0696)
infested_share × treatment_AWMP		-0.0015**		-0.0016***		-0.0026
		(0.0006)		(0.0005)		(0.0016)
Fixed-effects						
OBJECTID	Yes	Yes	Yes	Yes	Yes	Yes
year	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	2,793	2,793	2,793	2,793	2,239	2,239
R^2	0.92604	0.92624	0.92468	0.92489	0.91581	0.91640
Within R^2	0.07216	0.07459	0.02357	0.02640	0.00658	0.01352

Clustered (COUNTY) standard-errors in parentheses

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 9: Regression Results with Ever-Infested MTRs

Dependent Variable:	The Number of Grape COMTRS Within Each MTR	
Model:	(1)	(2)
Variables		
Infested Share (%)	-0.0018	-0.0074
	(0.0078)	(0.0063)
citrus_share	-5.443**	-5.087**
	(2.578)	(2.465)
treatment_AWMP		-1.204***
		(0.2373)
infested_share× treatment_AWMP		0.0104***
		(0.0032)
Fixed-effects		
OBJECTID	Yes	Yes
year	Yes	Yes
Fit statistics		
Observations	13,727	13,727
R^2	0.97393	0.97412
Within R^2	0.00610	0.01362

Clustered (NAME) standard-errors in parentheses

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 10: Effects on the Number of Grape COMTRS

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