Agricultural trade policy and water quality: evidence from the Mexican Hass Avocado Import Program

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Abstract: This paper provides empirical evidence that the 2016 Mexican Hass Avocado Import Program amendment led to improved water quality due to Mexican avocado farmers incorporating cleaner production methods and applying less harmful pesticides to their avocados. Two-way fixed effects difference-in-differences analysis shows that the policy improved surface water quality, reducing biochemical oxygen demand (BOD) by approximately 12 percent and chemical oxygen demand (COD) by 11 percent. Further evidence suggests the amendment led to a 2 percent decrease in nitrate pollution and a nearly 1 percent increase in nitrites - likely stemming from cleaner avocado practices and increased avocado production.

Keywords: International Trade, Environment, Development, Agriculture

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1 Introduction

While a growing body of research focuses on international trade's impact on water *consumption* and *scarcity* around the world (Chapagain et al., 2006; Zhong et al., 2023; Zhang et al., 2011), the empirical literature has yet to address the impact of international agriculture trade regulation on water *quality*. Williams and Shumway (2000) come closest on this front, with predictions of how trade policies such as the North American Free Trade Agreement would likely lead to increased agrochemical use and groundwater contamination in the U.S. A related set of literature shows how technology improvements, environmental regulations, and changes in production techniques from trade have led to general ecological improvements across countries (Alam et al., 2011; Lopez, 2017; Strutt and Anderson, 2000; Levinson, 2009; Sunge and Ngepah, 2020; Wang et al., 2023; Antweiler et al., 2001). This paper is the first to show that the 2016 Mexican Hass Avocado Import Program amendment led to improved surface water quality in Mexico. To my knowledge, this paper is the first to provide empirical evidence on how changes in agricultural trade regulation and enforcement in one country (the U.S.) improved the water quality of their trade partner (Mexico).

Even as their incomes rise, the people of Mexico continue to be plagued by water pollution and scarcity issues. Only 58 percent of Mexico's population has daily access to running water, and just 14 percent receive water 24 hours a day. Six million people in Mexico have no access to potable water, and 11 million lack proper sanitation services. Of the available water in the country, 70 percent has some degree of contamination (Copeland, 2023).

Agricultural practices significantly affect water quality. One of the largest sources of water pollution worldwide is the leachate of agrochemicals and pesticides from agricultural areas (Burri et al., 2019; Singh et al., 2019; EPA, 2022). A growing literature emphasizes the significant damage pesticides and agrochemicals have on surface and groundwater

(Singhal et al., 2022; Aydinal and Porca, 2004; Del Rossi et al., 2023; Syafrudin et al., 2021). Agricultural runoff is the leading cause of water pollution in rivers and streams; it is the third leading source for lakes and the second largest source of damage to wetlands (EPA, 2022). Soil erosion, nutrient loss, bacteria from livestock manure, and pesticides are the primary stressors to water quality. Water runoff from agriculture can have a wide range of effects on water quality depending on landscape conditions, soils, climate, and farm management practices.

Agriculture can also dramatically impact water access. Agriculture consumed 76 percent of Mexico's water in 2020; by comparison, agriculture in the U.S. consumed only 40 percent of its freshwater in the same year (FAO, 2020).

Avocado farming, in particular, has important implications for water scarcity and pollution. To produce a single 8-ounce avocado requires 50 gallons of water (Ash, 2021). Sommaruga and Eldridge (2021) describes how avocado production is associated with significant water conflicts, stresses, and hot spots. They urge global avocado producers to consider the potential environmental harms of increasing avocado production. They anticipate the global avocado market to grow at a compound annual rate of 6.2 percent from 2017-2027. In 2018, farmers worldwide used around 6.96 km^2 of water to grow avocados - a volume equivalent to 2.82 million Olympic-sized swimming pools. Mexico accounted for nearly one-third of this water use. Unsurprisingly, water consumption in Mexico doubled in just two decades, and water stress conditions are strongly associated with physical and economic stress (Spring, 2011).

Michoacán, a central state in Mexico, is the world's largest producer of avocados. Indeed, Michoacán is the only state in Mexico that can produce avocados year-round because its unique climate is highly conducive to the fruit's growth. The USDA's 2019/2020 annual report states that 76 percent of Mexican avocado production came exclusively from Michoacán. In 2018, Mexico was the top supplier of avocados to the U.S., with 87 percent of the U.S. market share. The other top-producing states are Jalisco and the State of Mexico, which account for 9.2 percent and 4.5 percent of the country's annual production, respectively. While Michoacán cultivates most of Mexico's avocados, total output elsewhere in the country is also high. The USDA's 2019/2020 annual report shows that outside of Michoacán, Mexico produced 615,002 metric tons of avocado - on par with total production in the second and third largest national producers worldwide (the Dominican Republic produced 665,652 metric tons in 2019, and Peru produced 571,992 metric tons (Elms, 2019)).

Until 2015, Michoacán was the only Mexican state from which the U.S. could accept avocado imports in the history of the two countries' trade relationship. In 2016, the U.S. enacted an amendment to their Mexican Hass Avocado Import Program that allowed all other Mexican states to export their avocados as long as they met strict U.S. Department of Agriculture (USDA) guidelines to reduce the risk of transmitting quarantine pests. One of the policy's primary purposes was to have Mexican avocado farmers use less harmful pesticides in their production. For farmers outside of Michoacán to begin enjoying the lucrative benefits of exporting avocados to the U.S., they would have to significantly alter their harmful pesticide/insecticide practices. The USDA enforces these export standards, and meeting them is challenging. Several Mexican states have taken steps to meet these standards, but Jalisco is the only one to succeed thus far, and they did not satisfy the policy's criteria until 2022.

In this paper, I use a two-way fixed-effects difference-in-differences model to test whether the 2016 Mexican Hass Avocado Import Program amendment impacted water quality in Mexican avocado-producing regions. I find that the policy shift substantially improved surface water quality, with a 12 percent decrease in biochemical oxygen demand and an 11 percent decrease in chemical oxygen demand. Although I cannot test this directly, the most likely channel for these impacts is the regulation's strong incentive to lead farmers to use less harmful pesticides/insecticides. The potential to export avocados resulted in the avocado industry becoming more lucrative, and the new economic opportunity led to an increase in avocado production for regions outside of Michoacán paired with less harmful fertilizer and pesticide practices.

Findings on groundwater are more nuanced. The policy resulted in approximately a 1 percent increase in nitrites (indicating a slight worsening in groundwater quality) but a 2 percent decrease in nitrates (indicating an improvement in groundwater quality). Despite increased avocado production, the negative association between the policy change and nitrates is a unique finding. Berka et al. (2001) finds that agricultural intensification causes *higher* nitrate levels in groundwater. Rao and Puttanna (2000) argues that mitigating nitrate levels for groundwater in developing countries through cleaner agricultural practices is crucial for a nation's water quality. Again, while I can not directly test this, the decrease in nitrates due to the 2016 Mexican Hass Avocado Import Program amendment suggests that avocado farmers likely began using less harmful pesticides/insecticides. The increase of nitrites in the groundwater is similar to the findings of Hendricks et al. (2014).

The USDA regulations on avocado imports are more stringent than Mexico's criteria for avocado farmers to sell locally. The 2016 U.S. policy change increased the value of avocado production in Mexico, incentivizing more farmers to meet USDA regulations to export avocados. This paper contributes to the literature on agriculture's impact on the environment, particularly the literature on how avocado production in Mexico has led to increased soil pollution, deforestation, and water scarcity (Mangiafico et al., 2009; Cho et al., 2021; Bravo-Espinosa et al., 2014; González-Estudillo et al., 2017; Sommaruga and Eldridge, 2021). This article also contributes to the literature on water quality policy and monitoring (Keiser and Shapiro, 2019a,b; Adler et al., 1993; Ebenstein, 2012; Greenstone and Hanna, 2014; Lipscomb and Mobarak, 2016; Kahn et al., 2015; Sigman, 2002; Hill and Ma, 2017; Aklin et al., 2013; Atasoy et al., 2006). Despite the growing literature on water quality monitoring, it remains challenging to measure the economic costs of water pollution (Muller et al., 2011; Peterson and Orden, 2008; Ren and West, 2023; Baerenklau et al., 2014; Wichman, 2014).

The rest of this paper is structured as follows. Section 2 provides background on Mexico's history of water regulation, the 2016 Mexican Hass Avocado Import Program, and USDA avocado trade regulation and enforcement. Section 3 describes the data I use in the analysis. Section 4 lays out the paper's methodology, section 5 discusses results, section 6 covers robustness checks, section 7 explores the effects of the 2016 policy amendment on groundwater, and section 8 concludes.

2 Background on Water Regulation in Mexico and the Mexican Hass Avocado Import Program

2.1 Water Regulation in Mexico

Mexico is running out of available water, and much of its remaining water is toxic (Wolfe, 2018). While the nation may have some of the world's best water laws and regulations, its government does not consistently enforce them. The 1910 Mexican Revolution led to a constitution that mandated the distribution and conservation of water and land for all Mexicans. The constitution places most surface-water resources under federal jurisdiction. The personal business interests of politicians and engineers have hindered Mexico's water quality regulations (Wolfe, 2018).

Mexico's 1992 national water policy reform sought to provide more efficiency, decentralization, and sustainability. However, Mexico has only minimally fulfilled these goals due to changing parties in power and political fragmentation (Wilder, 2010). Some water management methods that city authorities implement increase population exposure to ineffective water management and inadequate sewage discharge practices (Rodriguez, 2010; Madrigal Godinez et al., 2018).

A 2011 survey of Mexico City's households found that families prefer alternative sources of drinking water rather than the city's quality supply services (Rodríguez-Tapia et al., 2017). The study revealed that willingness to pay for other water sources is associated with distrust of town water quality. Chakraborti and Shimshack (2022) finds that industrial facilities in urban Mexico pollute more in poorer neighborhoods. This finding matches much of the literature that indicates pollution disproportionately impacts poorer households compared to more affluent households (Banzhaf et al., 2019).

2.2 The Mexican Hass Avocado Import Program

Carman (2019) provides a rich history of U.S. demand for avocados. The U.S. per capita consumption of avocados averaged 1.51 pounds in the 1990s but dramatically skyrocketed to 8 pounds in 2018. The change in U.S. demand stems from successful marketing and public perception of avocados; the California Avocado Commission (CAC) began to fund diet and nutritional research to proactively inform the public of the health benefits of eating avocados.

Until the early 1990s, California dominated the U.S. avocado market; fresh imports typically accounted for less than 1 percent of total U.S. consumption. In 1994, the North American Free Trade Agreement (NAFTA) was enacted, which opened up trade with the U.S. and Mexico. In 1997, the Mexican Hass Avocado Import Program began. This program only allowed Michoacán to export their avocados to 19 Northeastern and Midwestern states in the U.S. and Washington D.C. In February 2007, the U.S. opened the avocado trade with Mexico to all 50 U.S. states.

In February 2015, the USDA proposed an amendment to the Mexican Hass Avocado Import Program. This amendment allowed all Mexican states to export avocados to the U.S. as long as they met strict guidelines to reduce the risk of transmitting quarantine pests. At the time, the U.S. only allowed avocados from the state of Michoacán to the U.S. This policy required other Mexican states wishing to export their avocados to adhere to phytosanitary guidelines such as requirements for orchard certification, trace back labeling, pre-harvest orchard surveys, orchard sanitation, post-harvest safeguards, fruit cutting and inspection at the packinghouse, port-of-arrival inspection, and clearance activities. A significant concern of the new policy was to ensure fewer pesticide residues on Mexican avocados. The USDA enacted the amendment in June 2016.

Shortly after this amendment, avocado production in Mexico increased. Figure 1 displays Mexico's national avocado production in tons. Avocado production steadily increased from 2010 to 2015, spiked up between 2015 and 2016, and then continued to rise after that. The dramatic growth of production in 2016 is even more apparent in Figure A1 in the appendix, which plots production growth rather than levels. The increased value of avocado production incentivized farmers to enter the lucrative industry.

3 Data

3.1 Water Monitors

The primary analysis in this paper focuses on the impact of the 2016 Mexican Hass Avocado Import Program amendment on surface water quality in Mexico, but I also evaluate impacts on groundwater. Data on water quality comes from the National Water Commission in Mexico (CONAGUA). [1] CONAGUA is a technical advisory commission of Mexico's Ministry of the Environment and Natural Resources (SEMARNAT). It administers national waters, promotes social development, and manages and controls the country's hydrological system. I utilize water quality information from surface and groundwater monitors located throughout the country. The surface water monitors are located in rivers, lakes, dams, streams, and oceans and include measures of key quality indicators such as biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Groundwater monitors are located in wells and provide measures of nitrates, nitrites, and ammonia. All surface and groundwater monitors additionally record ambient temperature.

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[1] CONAGUA published its water quality monitoring data through Gobierno de Mexico and is publicly available: https://www.gob.mx/conagua/articulos/calidad-del-agua

Based on Dube et al. (2016), I restrict the analysis to include monitors in municipalities with a population under 100,000 to ensure a focus on rural municipalities. The surface and groundwater analysis covers water monitor readings during 2013-2019, the period surrounding the U.S. import policy amendment; I include monitors with at least one reading per year. [2] The surface water quality analysis includes 1,257 monitors, and the groundwater analysis includes 1,452 monitors.

The treatment group consists of monitors located in municipalities that ever harvested or sowed avocados from 2003 to 2013. These municipalities are the most likely to try to work toward avocado export certification, because meeting USDA sanitation criteria is difficult and costly and requires farmers to have a well-established avocado farming system. It takes farmers years to develop a well-established avocado farm. The announcement of the 2016 Hass Avocado Import Program amendment took place in February 2015. Only 9 municipalities in the surface water sample began producing avocados in 2015 and/or afterward. 7 of the 9 municipalities only sow and/or harvest 1 to 10 hectares of avocado a year, which is a very small amount. 2 of the 9 municipalities sow and/or harvest approximately 30 to 45 hectares yearly. This is a slightly higher production of avocados, but still not very big. Given that avocado production in these municipalities had not been around before the announcement of the 2016 amendment, it is doubtful that these avocado producers would strive to gain USDA export certification during the sample years.

Figure A2 in the appendix shows the locations of the surface water quality monitors in my sample. I define the treatment group in the analysis as monitors in municipalities that produced avocados in any year from 2003-2013 (i.e., in the decade prior to my analysis). These municipalities have the capacity and practical incentive to change their avocado production capacities more so than municipalities that had not produced avocados

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[2] The original data from CONAGUA consists of an unbalanced panel data set that provides monitor readings from 2012 to 2023. Observations from 2012 are omitted due to the paucity of readings that year. 2019 is the cut-off year because monitor readings become less frequent for the remaining years, and the COVID pandemic may heavily skew the empirical results.

before, or close to, the announcement of the 2016 Mexican Hass Avocado Import Program amendment. The circles represent monitors in municipalities that produced avocados at any point during 2003-2013, and triangles depict the location of monitors inside municipalities that did not grow avocados during that period. In total, 371 of the 1,257 surface water monitors are assigned to the treatment group, and the remaining 886 are assigned to the control group. For the 1,452 groundwater monitors, 429 are assigned to the treatment group and 1,023 are assigned to the control group.

The blackened-out state in Figure A2 in the southwest corner of Mexico is Michoacán. Before the 2016 Mexican Hass Avocado Import Program amendment, Michoacán was the only state the U.S. allowed to export avocados to the U.S. because they met USDA regulations. The analysis does not include data for Michoacán, as the policy change did not incentivize farmers in that state to change their agricultural practices.

The CONAGUA water quality data is bottom-coded. In particular, for almost all the data, BOD readings below 2 mg/L are recorded as " < 2", COD readings below 10 mg/L as " < 10", nitrite readings below 0.005 mg/L as " < 0.005", nitrate readings below 0.031 mg/L as " < 0.031", and some readings of nitrogen ammonia as "< 0.003". Readings below these thresholds indicate high-quality water. To measure the continuous variation of these parameters in the main analysis, I replace the inequality BOD values with 1, the inequality COD values with 5, the inequality nitrite values with 0.0025, the inequality nitrate values with 0.015, and the inequality ammonia values with 0.0015.

3.2 Data for Controls

Measures for total population and percent of the population with at least a high school degree come from the National Institute of Statistics and Geography in Mexico (INEGI) 2010 Censuses and Counts of Population and Housing. [3] Municipal-level data on annual

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[3] From May 31 to June 25, the 2010 Population and Housing Census consisted of more than 106,000 interviewers who traveled throughout the country to visit each home. The micro-data for municipalities is publicly available at https://www.inegi.org.mx/programas/ccpv/2010/microdatos.

agriculture sown and harvested comes from Mexico's Agriculture-Food and Fisheries Information Service (SIAP). [4] I match the census and agriculture data to the water quality data at the municipality level. The census data controls only have municipality variation because they account for data from 2010. Controls for agriculture vary by municipality and year.

In addition, measures for 30 years (1980-2010) of monthly precipitation averages in inches at the municipal level come from Gobierno de Mexico through CONAGUA. [5] This precipitation control accounts for the average of all weather station data in each municipality and month in inches. I match the precipitation and water quality data at the month and municipality levels. [6] Tables A1 and A2 in the appendix provide summary statistics for the surface and groundwater data sets, respectively.

4 Methodology

I employ a two-way fixed effect difference-in-differences model to test whether the 2016 Mexican Hass Avocado Import Program amendment impacted Mexico's water quality. Based on the economic water quality literature, biochemical oxygen demand (BOD) and chemical oxygen demand (COD) are the parameters I use to measure surface water quality (Lipscomb and Mobarak, 2016; Keiser and Shapiro, 2019a; Wang et al., 2018). Using both measures allows the analysis to evaluate the consistency and robustness of its results across different water quality classifications. Equation 1 depicts the difference-in-differences model.

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[4] Annual municipal data for both avocado production and total avocado production in Mexico covers 2003 to the present. The data from SIAP is publicly available through Gobierno de Mexico: https://nube.siap.gob.mx/cierreagricola/.

[5] Data for all weather stations come from CONAGUA and are publicly available through Gobierno de Mexico: https://smn.conagua.gob.mx/es/informacion-climatologica-por-estado?estado.

[6] For municipalities without weather station data, I take the average values of available weather station data from its contiguous municipalities.

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\begin{aligned}
Y_{icmt} = \beta_0 + \beta_1(Post_t \cdot Treat_i) + \beta_2 Temp_{imt} + \beta_3 Prec_{cm} \\
+ \beta_4 Census_{c,2010} + \beta_5 X_{ct} + \alpha_m + \gamma_t + \delta_i + \varepsilon_{icmt}
\end{aligned}
\tag{1}
$$

Y includes water quality measures (logged BOD, logged COD). The model includes measures at the monitor level i, municipal level c, month m, and year t. *Post* is an indicator that equals 1 if the monitor's reading took place during and after January 2016, and 0 otherwise. *Treat* is an indicator that equals 1 if the monitor is in a municipality that grew avocados at any point during the 2003-2013 period, and 0 otherwise. I define the treatment group in this way because municipalities that ever produced avocados during this pre-period are more likely to have the avocado production capacity and incentive to adhere to the 2016 policy amendment than municipalities that have no avocado production capacity or that first begin avocado farming at a later time. Table 1 shows the summary statistics for the surface water data for 2013 and 2014, and it shows no statistical difference in the BOD and COD values between the treatment and control groups during the pre-shock years.

Temp is the logged ambient temperature of a water monitor at the time of the water quality reading, in Celsius. *Prec* controls for monthly average precipitation, in inches, at the municipal level, c, over the period 1980-2010; I use the log(precipitation + 1) value of this measure. *Census* is a vector of controls at the municipality level from INEGI's 2010 census, including the logged total population and the population percentage with at least a high school degree. *X* is a vector of controls at the municipality-year level, including the logged number of hectares of total agriculture sown and harvested, and an indicator for the 2017 earthquake with an 8.2 level magnitude that hit Oaxaca the hardest; this dummy equals 1 if the monitor reading occurred in Oaxaca in 2017 and 0 otherwise. I additionally include fixed effects for month (α_m), year (γ_t), and monitor (δ_i).

For all the regressions, I cluster robust standard errors at the water monitor level following Lipscomb and Mobarak (2016) because the treatment group includes monitors in avocado-producing municipalities. The coefficient of interest is the *Post*Treat* interaction term.

A common restriction for water effluent – and the maximum permitted concentration in surface water – is 10 mg/L of BOD (Qin et al., 2014; Luthy et al., 2015) and 50 mg/L of COD for water reuse according to the EPA (Dresser, 2004). I also evaluate the impact of the 2016 Mexican Hass Avocado Import Program amendment using binary outcomes, where BOD (COD) takes on a value of 1 if the water monitor has a reading above 10 mg/L (50 mg/L) and 0 otherwise. [7]

For the binary outcomes, I employ both OLS and logit models. Equation 2 shows the logit model specification:

$$\begin{aligned}\log\left(\frac{Y_{icmt}}{1-Y_{icmt}}\right) &= \beta_0 + \beta_1(Post_t \cdot Treat_i) + \beta_2 Temp_{imt} + \beta_3 Prec_{cm} \\ &\quad + \beta_4 Census_{c,2010} + \beta_5 X_{ct} + \alpha_m + \gamma_t + \delta_i + \varepsilon_{icmt} \qquad (2)\end{aligned}$$

All logit results in the analysis represent marginal effects. Almost all symbols represent the same thing as equation 2. However, Y represents the binary BOD and COD outcomes, dependent on whether BOD and COD are above or below 10 mg/L and 50 mg/L, respectively.

5 Results

Table 2 displays the two-way fixed effects difference-in-differences analysis results in Equation 1. Columns 1-3 measure the impact of the 2016 Mexican Hass Avocado Import Program amendment on BOD levels in surface water; each column includes progressively more

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[7] BOD and COD effluent regulation can vary from country, locality, and industry. I chose these thresholds for the binary values because they are common effluent limits in the literature.

controls, and the results remain robust and statistically significant regardless of which controls are included in the model. Without controls, the *Post*Treat* coefficient is -0.119. These results suggest that the policy shift resulted in an improvement to surface water quality on the order of a 12 percent decrease in BOD levels. Columns 4 - 6 display the results for COD, and once again, results are robust to the inclusion of various controls. The results suggest that the policy change led to an 11 percent decrease in COD, also an improvement to surface-water quality.

A 12 percent change in BOD is environmentally significant and in line with estimated effect sizes from other studies that explore the water quality impacts of policy change. For instance, Lipscomb and Mobarak (2016) shows that an expansion in administrative municipalities in Brazil led to worse water quality there, on the order of a 9 percent change. When evaluating the impact of the 2016 Mexican Hass Avocado Import Program amendment, based on Table 1, the sample mean of BOD is 21.5 mg/L in the treatment group. The results suggest the 2016 amendment impact is the equivalent of BOD decreasing from 21.5 mg/L to 18.92 mg/L. While BOD exceeding 4 mg/L is not considered acceptable for recreational use (Sigman, 2002), this is still a significant improvement in overall surface water improvement.

Figure 2 depicts the BOD aggregate average each year over time for the treatment group, control group, and the state of Michoacán. The BOD averages are almost identical for the treatment and control groups in 2013, 2014, and 2015. The import policy change was announced in February 2015, and afterward a noticeable gap develops between the treatment and control groups and lasts for the remaining years of the sample. The Michoacán line shows the higher water pollution in Michoacán compared to the rest of Mexico. It intuitively makes sense not to include Michoacán in the empirical sample as it is the only Mexican state that does not need to change its avocado production methods due to the policy. Figure 2 also shows how Michoacán is not a good comparison group for the pre-treatment years of 2013 to 2015.

Figure 3 similarly depicts the COD aggregate average each year over time for the treatment group, control group, and the state of Michoacán. Once again, the COD values among the treatment and control groups are very similar in the pre-treatment years of 2013, 2014, and 2015. After the announcement of the policy change in 2015, a noticeable gap appears between the treatment and control groups that continues through the following years. Figures 2 and 3 both reveal a convex shape among the BOD and COD aggregate values for the treatment and control groups. [8]

Figures 4 and 5 display the event studies for both the BOD and COD results, respectively. Both event studies include point estimates and their 95 percent confidence interval. Year 0 is 2016, which is the year the policy amendment was enacted. Results are normalized to 2015. Both event studies show that the coefficient on the interaction term *Post*Treat* was not statistically significant prior to implementation of the policy shift, for either BOD or COD. These event studies and the statistical tests provided in Table 1 indicate that the results for BOD and COD do not violate the pre-treatment assumption in the difference-in-differences framework.

In Figure 4, the BOD levels show a significant drop from 2016 to 2018; however, the results are not statistically significant by 2019 (denoted 3 on the x-axis of the image). Figure 5 shows that the COD dropped in 2016 among avocado-producing municipalities. The COD results are not significantly different from zero in 2017 (denoted 1 on the x-axis of the image) but remain statistically significant for 2018 and 2019. Together, these event study figures provide strong evidence that the import policy shift had a quick and positive impact on surface water quality in avocado-producing municipalities in Mexico. The timing of the policy's effect on water quality is likely due to the announcement taking place over a year before its enactment, giving farmers time to adjust to the implementation of the new policy.

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[8] The data consists of an unbalanced panel set where monitor readings occur more or less frequently and among different months. This variation of when and how often different monitor readings take place in the data set may explain the convex trend of both the treatment and control groups in Figures 2 and 3.

Table 3 displays the results of the binary methods, where odd columns display binary OLS results, and even columns show Logit average marginal effects. Columns 1 and 2 of Table 3 show the binary method results for BOD, and columns 3 and 4 provide results for COD. For both BOD and COD with binary OLS and logit methods, the findings consistently display a negative relationship between the interaction term and surface water quality. The results all have strong statistical significance, suggesting that the policy decreased the BOD and COD of avocado-producing municipalities compared to non-avocado-producing municipalities.

Gaining avocado certification for exports to the U.S. is a difficult process. The only way for Mexican avocado farmers to become certified is to change their agricultural practices drastically and to consistently use less harmful pesticides. It took Jalisco until 2022 to become certified, and they are the only state to be able to trade Hass avocados with the U.S. other than Michoacán. Several other states are currently working toward avocado certification. When Jalisco gained avocado certification, Jose Gallardo, the head of the Michoacán-Based Association of Mexican Growers, stated, “Today is a day of joy for everyone, knowing that Jalisco is here, but it is going to be happier when the State of Mexico comes, when Nayarit, Colima, Puebla, Morelos come” (Stevenson, 2022).

To my knowledge, there is no available micro-level data set that allows me to test the impact that the 2016 Mexican Hass Avocado Import Program amendment had on pesticide use among Mexican avocado farmers. However, public statements from the Association of Avocado Exporting Producers and Packers of Mexico (APEAM) suggest that Mexican avocado farmers are seeking to use less harmful pesticides; for instance, they are quoted as recently saying “Mexican avocado producers strive every day to reduce the use of chemical pesticides and instead, turn to more sustainable practices in their crops to improve their agricultural practices” (Orduña, 2023).

6 Robustness Checks

The results of this paper stand up to a range of robustness checks. In this section, I detail results of several checks I have performed.

First, several states in the main analysis do not have any rural municipalities that are in the treatment group, including Baja California, Chihuahua, Coahuila, San Luis Potosi, Yucatan, and Quintana Roo. Table A3 in the appendix presents results replicating the analysis in Table 2, but omitting these states. Point estimates and statistical significance do not change substantively.

Next, I evaluate the results of balancing the panel data at the monitor and year level; in my main sample, monitors often have several readings throughout the year during different months. Table A4 in the appendix displays the results of this check. In columns 1 and 2, I average the BOD (COD) records for each monitor-year. The *Post*Treat* coefficient values are -0.115 and -0.099 for BOD and COD, respectively - nearly identical to the values presented in Table 2 - and still strongly statistically significant for both. Columns 3 and 4 present the results of including only the maximum reading for each monitor per year. Here, the *Post*Treat* coefficient is not statistically significant for either BOD or COD, suggesting that heavily polluted surface water bodies remained heavily polluted after the 2016 amendment. Columns 5 and 6 present the results of including only the minimum reading for each monitor-year. This time the coefficient values for BOD and COD are -0.170 and -0.154, respectively – slightly more negative than the results in Table 2 – and both are statistically significant. This suggests that the minimum water quality monitor readings improved after the policy. In short, Table A4 indicates that the most polluted surface water sources did not improve substantially, but the average and less-polluted ones did.

In the appendix, tables A6-A8 display robustness checks of the main surface water results when I replace the BOD inequality values with 1.25, 1.5, and 1.75. Likewise, the tables show the results of replacing the COD inequality values with 1, 3, and 7. These tables show that the results are not sensitive to the original replacement values of BOD and COD being 1 and 5, respectively.

One important factor that can impact a water monitor's BOD and COD readings is whether the monitor is positioned upstream or downstream. Unfortunately, the CONAGUA data does not indicate whether monitor stations are in an upstream or downstream source. To address this issue, I add two-way fixed effects (monitor by month and year fixed effects) to the model in Equation (1). The results are presented in Table A9 of the appendix. They remain robust, regardless of whether I use a two-way fixed effect for monitor by month and monitor fixed effects or just a one-way monitor by month fixed effect. [9]

Following related literature, I also rerun the analysis clustering at the watershed level for both BOD and COD, rather than at the monitor level (Keiser and Shapiro 2019a; Keiser and Shapiro 2019b). Results are available in Table A10 of the appendix. The BOD and COD results remain statistically significant, and similar in magnitude to the main results presented in Table 2. [10]

As a final robustness check, I run placebo tests to address concerns about whether the results of Table 2 are random or if the rest of the country experienced a major shift in water quality due to other reasons/policies. To construct the placebo tests for BOD and COD, I omit all treatment municipalities from the original sample for Table 2. The placebo sample only includes municipalities that were in the original control group. The original sample includes 125 treatment municipalities and 471 control municipalities, so for this test I randomly select 125 municipalities to be in the treatment group. The placebo tests – displayed in Figures A3 and A4 in the appendix – provide evidence that shifts in water quality improvement were not present throughout all of Mexico, and the results

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[9] Table A9 in the appendix also shows that the results are robust when I use monitor by municipality fixed effects or monitor by municipality and year fixed effects.

[10] I do not run a robustness check for clustering at the municipality level because several separate water sources exist in municipalities.

from Table 2 are not random. Both figures show no statistical difference between the random treatment groups and control groups for BOD and COD for pre-treatment and post-treatment years. This test is strongly robust for randomly selecting 125 treatment municipalities numerous times; when I randomly choose different treatment municipalities, the results remain heavily consistent.[11]

7 Ground Water Trends

I next evaluate how the 2016 U.S. Avocado Import Policy amendment impacted Mexico's groundwater pollution. I evaluate nitrate pollutants, following the work of Paudel and Crago (2021). Table 4 reports the summary statistics for nitrites and nitrates, across municipalities assigned to the treatment and control groups. The difference in means between the treatment and control groups for nitrites is not statistically significant during the pre-shock period. However, the difference for nitrates is statistically significant during the pre-shock period ($p \leq 0.05$).

I use Equation 3 to measure the impact of the policy on groundwater pollution:

$$\begin{aligned} Y_{icmt} = \beta_0 + \beta_1(Post_t \cdot Treat_i) + \beta_2 Temp_{imt} + \beta_3 Nitrogen_{imt} \\ + \beta_4 Prec_{cm} + \beta_5 Census_{c,2010} + \beta_6 X_{ct} + \alpha_m + \gamma_t + \delta_i + \varepsilon_{icmt} \end{aligned} \tag{3}$$

This equation is nearly identical to equation (1). The outcome variable is measured as the log(nitrogen+1) values of nitrite and nitrate because most of the variables' data variation is between 0-1. [12] As before, the coefficient of interest is *Post*Treat*. Nitrogen is a vector of controls that include nitrogen controls. [13] Robust standard errors are once

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[11] Results of several randomly selected treatment municipalities available upon request.

[12] The results are robust regardless of whether I use log(nitrogen+1) or the inverse hyperbolic sine function for the nitrogen left-hand variables. The results with the left-hand inverse hyperbolic sine are available upon request.

[13] Many components can impact different nitrogen levels. Concerns of regressing nitrite onto nitrate

again clustered at the monitor level, and the sample includes over 42,000 observations for nitrite and nitrate.

Table 5 shows the results of Equation 3. Columns 1 - 3 regress the policy interactive term on nitrogen in nitrite. The response variable is log(nitrite+1). In the first step of nitrification, ammonia-oxidizing bacteria oxidize ammonia to nitrite (EPA, 2000). In the second step of the nitrification process, nitrite-oxidizing bacteria oxidize nitrite to nitrate (EPA, 2000). Column 1 shows the results of the model with no controls, while column 2 controls for nitrate and ammonia. Column 3 includes controls for nitrate and ammonia, temperature, precipitation, agricultural production, population, and population percentage with at least a high school degree. Point estimates and statistical significance are relatively consistent across columns 1-3, indicating that the 2016 Mexican Hass Avocado Import Program amendment led to approximately a 1 percent increase in nitrites (a slight increase in groundwater pollutants).

The response variable in columns 4-6 is log(nitrate+1). Again, the results are fairly consistent across columns with increasing numbers of controls, but with weaker statistical significance. These results are suggestive of a decrease in groundwater pollutants. The results for nitrates did not satisfy the pretrends assumption; however, the negative association between the interaction term and nitrates is consistent.

Figure 6 displays the event study for the impact of the 2016 Mexican Hass Avocado Import Program amendment on nitrite in groundwater. The figure displays a delayed impact on nitrite pollution, which does not appear until 2017 but remains consistent thereafter. Figure 6 also shows no statistically different level of nitrites between the treatment and control group before 2016. This provides strong evidence that the analysis does not violate the pre-trends assumption.

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and vice versa are reverse causality or simultaneity. When considering the nitrification and denitrification processes, necessary controls for nitrite include ammonia and nitrate. Furthermore, necessary controls for nitrate include nitrite and ammonia. Equations A.1-A.3 in the supplemental appendix display the relationship of the nitrogen indicators through the nitrification and denitrification process.

To test what mechanisms are potentially causing the increased nitrite pollution within avocado-producing regions, I estimate the following association:

$$\begin{aligned} Y_{icmt} = {} & \beta_0 + \beta_1 AvoSown_{cmt} + \beta_2 Avoharvest_{cmt} + \beta_3 NO3_{imt} + \beta_4 NH3_{imt} \\ & + \beta_5 Temp_{imt} + \beta_6 Prec_{cm} + \beta_7 Census_{c,2010} + \beta_8 X_{ct} + \alpha_m + \gamma_t + \delta_i + \varepsilon_{icmt} \end{aligned} \quad (4)$$

For this supplementary analysis, I only include observations from avocado-producing municipalities with avocado harvests. Table 6 displays regression results for Equation 4. The response variable is log(nitrite+1). Column 1 shows the correlation between the logged amount of sown hectares of avocados and logged harvested hectares of avocados on nitrite in groundwater. There is a strong negative correlation between the hectares of sown avocados and nitrite in the groundwater, with a coefficient value of -0.0216. There is a positive relationship between hectares of avocado farmers harvest with a coefficient value of 0.0087. Avocado trees take time to grow. If a farmer sows an avocado seed, it could take up to 13 years before the tree yields fruit. If the farmer plants a tree, it will take 1 to 3 years to produce avocados. The negative relationship between hectares of sown avocado and nitrite may account for municipalities without highly established avocado production. Smaller avocado farmers are likely to sow more than established farmers who have already sown their trees. This parameter may account for how municipalities with less established avocado production have lower levels of nitrite pollutants in the groundwater. The amount of hectares farmers harvest provides a better measure of how more avocado production impacts groundwater quality. Farmers who harvest larger quantities of avocado have more avocado trees and more established avocado farms. This positive relationship indicates that the larger production of avocados in avocado-producing municipalities strongly correlates with nitrite levels in their groundwater sources.

Column 2 of Table 6 reveals a strong and positive correlation between nitrite and nitrates and ammonia. These correlations support the science behind the nitrification and denitrification process and suggest that the nitrates may turn into nitrites in the water. This result is consistent with Table 5. Table 5 may show a negative association between Post*Treat and nitrate because the pollutant turns into nitrite in the water. Columns 3 and 4 show that the results for columns 1 and 2 are robust when adding other control variables such as temperature, precipitation, natural disasters, total agriculture sown and harvested, the percentage of a municipality with at least a high school degree, and the total population.

One concern of the analysis is whether the increase in pollutants is from avocado production instead of other agricultural production. In column four of Table 6, I control the logged total amount of agriculture farmers sowed and harvested in hectares at the municipality level. There is no correlation between the total amount of agriculture farmers sowed or harvested on the nitrite levels in the groundwater. In contrast, there is a strong relationship between how many avocados farmers planted and harvested in a municipality. These results suggest that the increased change in nitrite levels is likely not from general agriculture production and trends. The empirical analysis indicates that avocado production in this region contributes to increased nitrite in groundwater.

The EPA regulates that the maximum contaminant level goals of safe drinking water should not have more than 1 mg/L of nitrite and 10 mg/L of nitrate. The mean nitrite level in the treatment group of the sample, shown in Table 4, is 0.1. A 1 percent increase in nitrite, based on the groundwater sample, would be the equivalent of an increase from 0.1 mg/L to 0.101 mg/L. Thus, the increase in nitrites from the policy is very small and not a major risk to public health. Given the significant increase in avocado production after the announcement of the 2016 Hass Avocado Import Program amendment, the small magnitude of nitrogen change in groundwater may result from the 2016 amendment successfully incentivizing farmers to use less harmful pesticides and adopt cleaner agricultural practices.

8 Conclusion

More work is needed to understand the overall impacts of international trade policy on the environment (Lenzen et al., 2012; Green et al., 2019). To my knowledge, this paper takes the first step in empirically evaluating the impact of agricultural trade regulation on water quality by estimating the effects of the 2016 Mexican Hass Avocado Import Program amendment on Mexico's water quality. I provide evidence that the 2016 amendment incentivized avocado farmers to utilize cleaner avocado production methods, in the form of less harmful pesticides/insecticides, and this led to improved surface water quality. In particular, the analysis shows that the policy shift led to a BOD and COD decrease of approximately 12 percent and 11 percent, respectively. There is also a negative association between the 2016 amendment and nitrate pollution in groundwater. Although the policy change led to a small increase in nitrite pollution in groundwater, this is likely due in part to higher avocado production after the policy. However, the increase in nitrite from the policy is very small and unlikely to cause human health risks on its own.

Mexico has struggled for many years to mitigate its water pollution. The Mexican government must find ways to address its water quality problems. Surface water is expected to have low BOD/COD values to sustain aquatic life (Edokpayi et al., 2017). Higher nitrogen levels in groundwater can lead to adverse human health through exposure (Rezaverdinejad and Rahimi, 2017). High water pollution is also a major equity concern as it disproportionately impacts lower-income communities.

It is often difficult to calculate the direct economic benefits of water quality changes. The EPA states that increased nitrogen levels from fertilizer and manure can stimulate algal blooms in lakes and rivers, producing hypoxic conditions (low oxygen) that greatly damage aquatic life. The algae can further affect recreation uses of local streams, downstream reservoirs, and estuaries. Agricultural operations additionally pollute groundwater and degrade sources of drinking water(EPA, 2023b). While cleaner water quality leads to improved aquatic life, proximity to water resources and the water quality at such sites are positively related to property value and recreational use (Mamun et al., 2023; Phaneuf, 2002; Atasoy et al., 2006). In addition, water pollution can lead to impacts on human health, crop production and other agricultural activities, and impact livestock (Reddy and Behera, 2006). Future research should continue to explore the economic implications of water quality, and there is a need for scholars in the field to design enhanced integration of economic decision-making with biophysical models to improve policies that target climate and land use challenges (Kling et al., 2017).

The story of this paper's findings is straightforward: incentives matter. For decades, Mexico has struggled to improve its water quality. The empirical evidence of this paper is the first to show how policies around international trade of agricultural products can lead to water quality improvements when a developed country monitors a developing country's production. This can be the case when a developing country has a strong enough economic incentive to apply more environmentally safe production methods. There is a strong need for more research on how international agricultural trade policy and regulation among different countries impact water quality. Expanding knowledge regarding trade and water quality can greatly improve policymakers' decisions regarding what laws to enact or amend.

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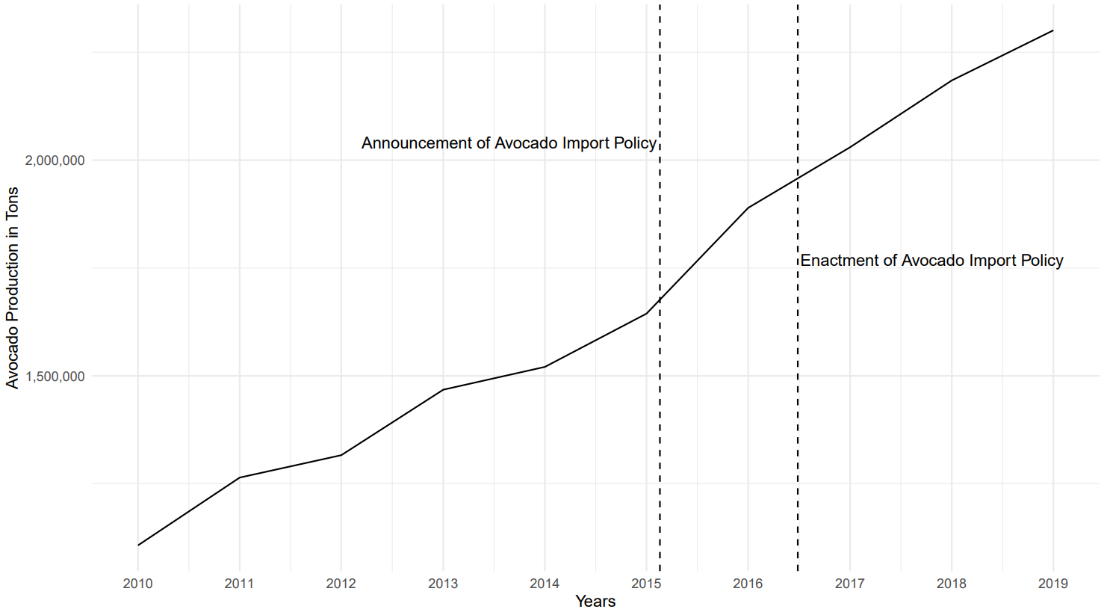
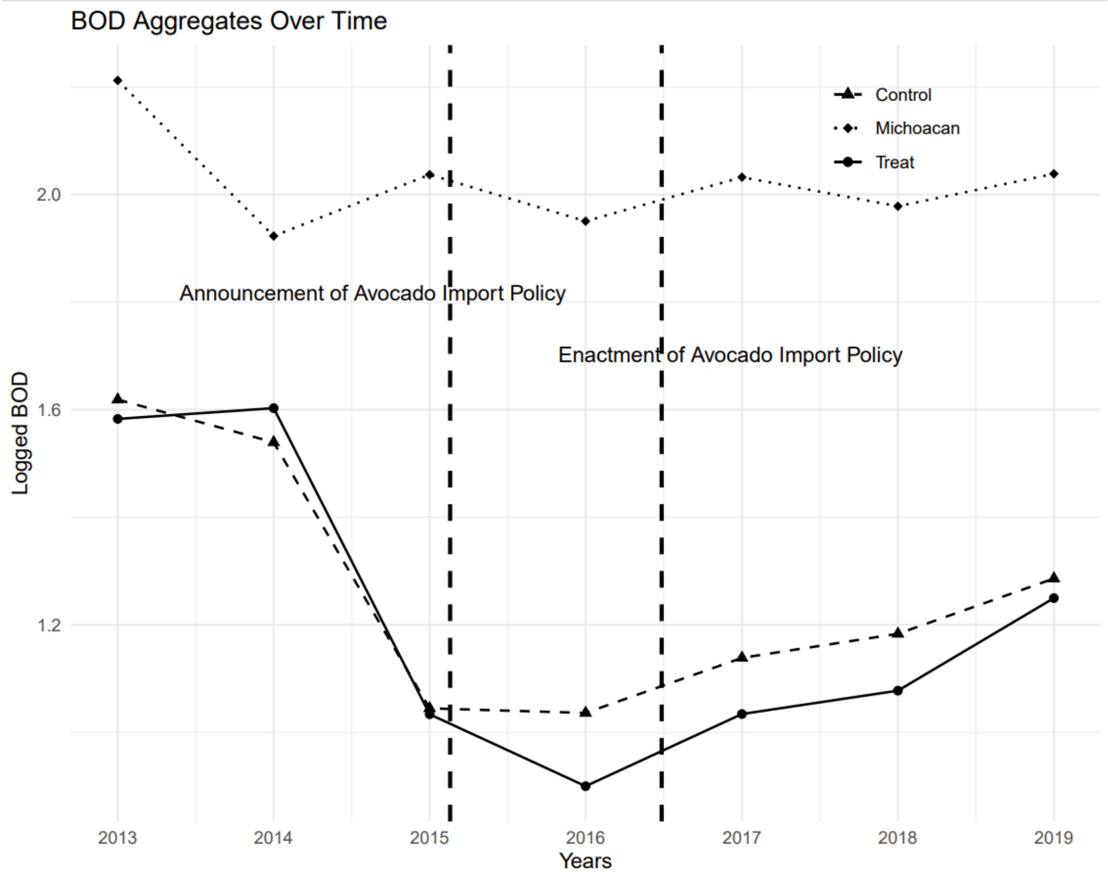
9 Figures and Tables

Figure 1: Mexico's National Avocado Production from 2010 to 2019



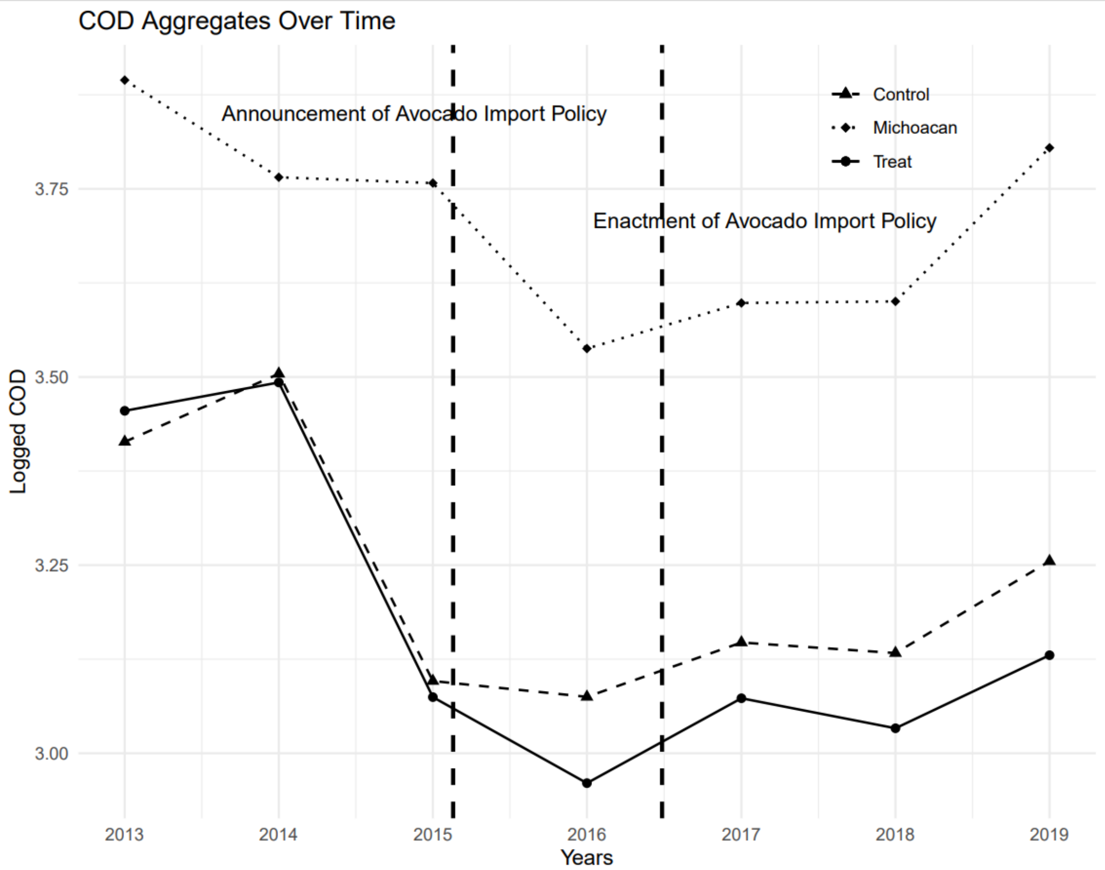
The data for this figure comes from El Gobierno de México's Servicio de Información Agroalimentaria y Pesquera (SIAP). The image displays Mexico's total national avocado production in tons from the years 2010 to 2019. The announcement of the policy and its enactment took place in February 2015 and June 2016, respectively.

Figure 2



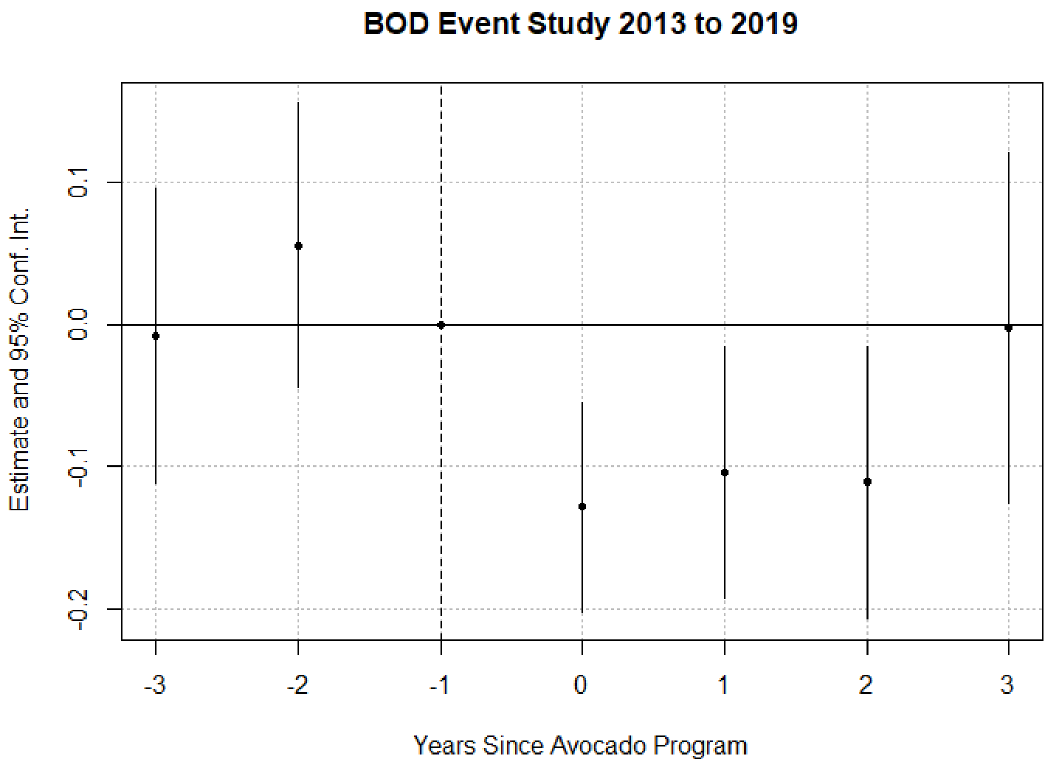
This figure shows the annual aggregate average of logged biochemical oxygen demand for all surface water monitors in the treatment group, control group, and state of Michoacán. The figure covers the years 2013 to 2019. The dashed vertical lines emphasize that the USDA announced the policy to the public in February 2015 and enacted the policy in June 2016.

Figure 3



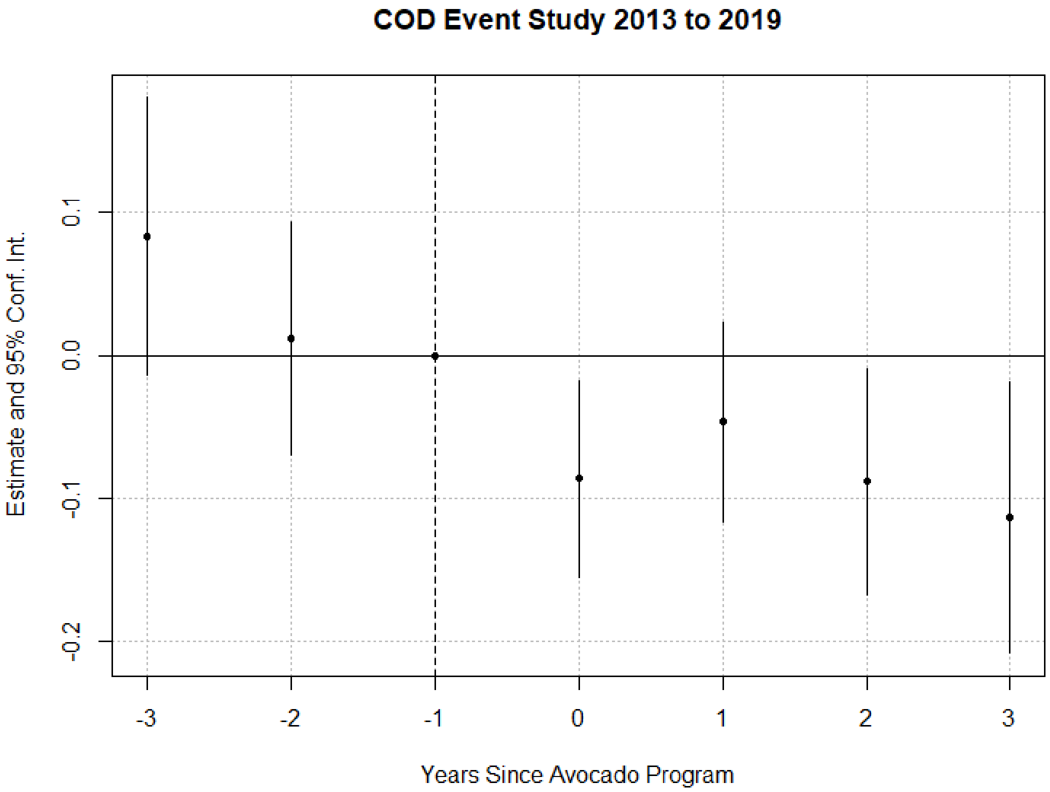
This figure shows the annual aggregate average of logged chemical oxygen demand for all surface water monitors in the treatment group, control group, and state of Michoacán. The figure covers the years 2013 to 2019. The dashed vertical lines emphasize that the USDA announced the policy to the public in February 2015 and enacted the policy in June 2016.

Figure 4



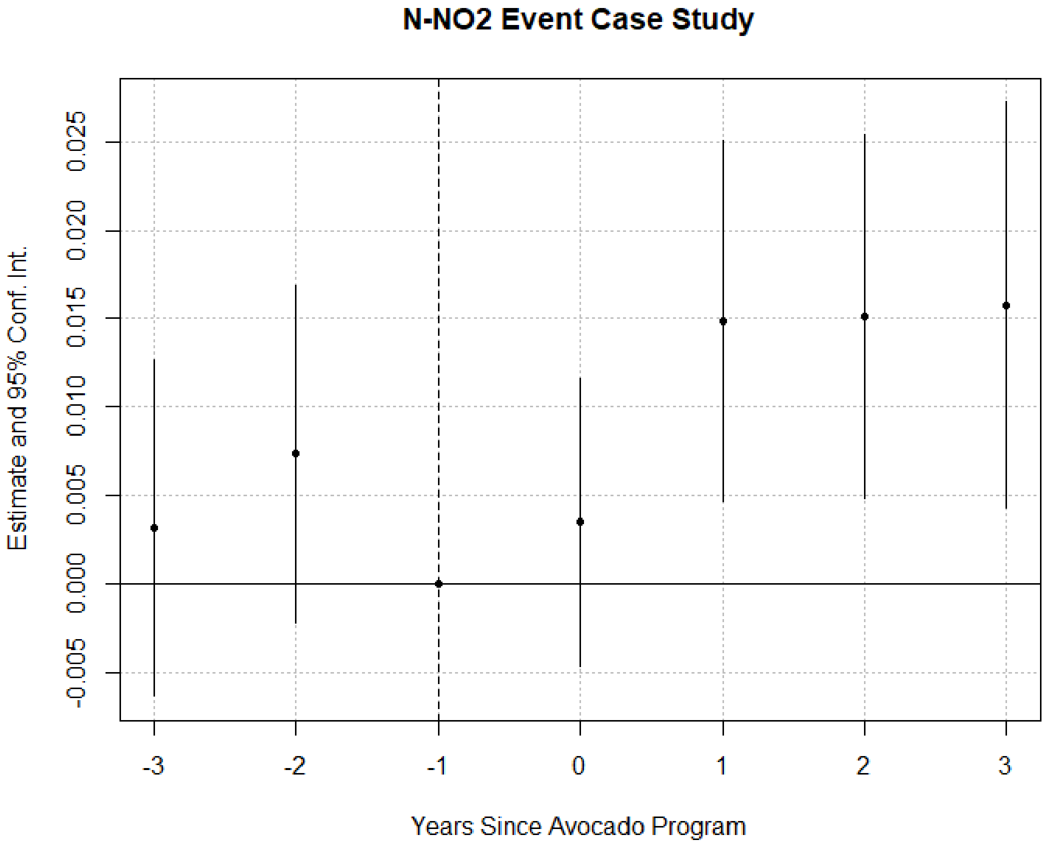
This figure shows the event study for the results from Table 2 for BOD. I measure the estimates with a 95 percent confidence interval. The time period spans from 2013 to 2019. -3 represents the year 2013, 3 is 2019, and 0 is 2016 (the year of the policy's enactment). I normalize the year 2015, which the table displays as -1. The event study includes fixed effects at the month and year level and monitor location. It also includes municipality controls and controls for temperature at the monitor level. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010. All robust standard errors are clustered at the monitor level.

Figure 5



This figure shows the event study for the results from Table 2 for COD. I measure the estimates with a 95 percent confidence interval. The time period spans from 2013 to 2019. -3 represents the year 2013, 3 is 2019, and 0 is 2016 (the year of the policy's enactment). I normalize the year 2015, which the table displays as -1. The event study includes fixed effects at the month and year level and monitor location as well as municipality controls and controls for temperature at the monitor level. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010. All robust standard errors are clustered at the monitor level.

Figure 6



This figure shows the event study for the nitrite results from Table 5. I measure the estimates with a 95 percent confidence interval. The time period spans from 2013 to 2019. -3 represents the year 2013, 3 is 2019, and 0 is 2016 (the year of the policy's enactment). I normalize the year 2015, which the table displays as -1. The event study includes fixed effects at the month and year level and monitor location as well as municipality controls and controls for temperature at the monitor level. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010. All robust standard errors were clustered at the monitor level.

Table 1: Summary Statistics: BOD and COD 2013-2014

	Treatment (N=3,429)		Control (N=8,242)			
Variables	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Diff. in Means**	**P**
BOD (mg/L)	21.5	220.5	19.1	89	2.4	0.545
COD (mg/L)	98.1	1,708.4	72.7	186.4	25.3	0.386
Temperature (Celsius)	27.9	5.0	27.9	5.3	-0.1	0.515
Precipitation (Inches)	104.3	99.1	105.3	106.6	-1.1	0.603
Sown in Thousands (Hectares)	23.0	26.3	14.0	17.5	9.0	< 0.001
Harvest in Thousands (Hectares)	21.3	23.3	13.2	15.8	8.1	< 0.001
Education (2010)	0.2	0.0	0.2	0.1	0.0	< 0.001
Population in Thousands (2010)	44.8	27.7	36.2	27.2	8.6	< 0.001

Note: This table provides summary statistics for the mean and standard deviation of different values among the treatment and control group. In the analysis sample, chemical oxygen demand and biochemical oxygen demand are the variables of interest. The table displays the standard BOD and COD measures in mg/L at the monitor level. Temperature is in Celsius at the monitor level, sown is the amount of hectares of agriculture sown in a municipality, harvest is the amount of hectares of agriculture harvested in a municipality, education represents the percent of a municipality's population that has completed their secondary education in 2010 in decimal form. Population is the total population in a municipality in 2010. Sown, harvest, and population represent their respective values in thousands. Precipitation represents the 1980-2010 monthly average of precipitation in inches at the municipal level.

Table 2: DID Results for BOD and COD

	BOD			COD		
	(1)	(2)	(3)	(4)	(5)	(6)
Post*Treat	-0.119***	-0.118***	-0.120***	-0.110***	-0.110***	-0.110***
	(0.044)	(0.044)	(0.045)	(0.031)	(0.031)	(0.032)
Month and Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Temperature Control	No	Yes	Yes	No	Yes	Yes
Municipal level controls	No	No	Yes	No	No	Yes
N	36,705	36,705	36,705	36,705	36,705	36,705
R^2	0.589	0.589	0.589	0.529	0.529	0.530

Note: All robust standard errors are clustered at the water monitor level. Data for the table spans from 2013 to 2019. The coefficient of interest is Post*Treat. Post equals 1 if the observation took place after 2015, 0 otherwise. Treat equals 1 if a monitor is in a municipality that grew avocados between 2003 to 2013. The response variable in columns 1-3 is the logged value of BOD. For columns 4-6, the response variable is logged COD. Each column includes year and monitor fixed effects and controls for what month the monitor's reading took place. The temperature control is at the monitor station location at the time of the BOD or COD reading. The municipal level controls include the 8.2 magnitude earthquake that hit Oaxaca in 2017, logged hectares of agriculture sown and harvested at the municipal level, the percent of the population that has at least a secondary level of education, and the logged population. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010.

Table 3: Binary OLS and Logit for BOD and COD

	(1) BOD	(2) BOD	(3) COD	(4) COD
Treat*Post	-0.0532***	-0.0407**	-0.0232**	-0.0211**
	(0.0175)	(0.0162)	(0.0093)	(0.0100)
Month and Year FE	Yes	Yes	Yes	Yes
Monitor FE	Yes	Yes	Yes	Yes
Right Hand Controls	Yes	Yes	Yes	Yes
Thresh-Hold	10	10	50	50
Model	OLS	Logit	OLS	Logit
N	36,705	34,056	36,705	33,696
R^2	0.3518	0.2719	0.1436	0.1358

Note: All robust standard errors are clustered at the water monitor level. Data for table 3 spans from 2013 to 2019. The coefficient of interest is Post*Treat. Post equals 1 if the observation took place after 2015, 0 otherwise. Treat equals 1 if a monitor is in a municipality that grew avocados between 2003 to 2013. The response variables in columns 1 and 2 are binary measures where BOD equals 1 if the monitor's reading was above 10 mg/L, 0 otherwise. In columns 3 and 4, COD equals 1 if the monitor's reading was above 50 mg/L, 0 otherwise. All columns include month and year and monitor fixed effects. They also include right hand variables controlling for logged total population, percent of municipality population with at least a secondary education, the 8.2 magnitude Oaxaca earthquake in 2017, logged temperature at the monitor level, and logged agricultural hectares sown and harvested in a municipality. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010. Results for the logit regression represent the average marginal effects.

Table 4: Summary Statistics: Nitrogen 2013-2014

	Treatment (N=3,969)		Control (N=9,356)			
Variables	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Diff. in Means**	**P**
Nitrite (mg/L)	0.1	0.3	0.1	0.4	0.0	0.124
Nitrate (mg/L)	0.7	1.7	0.7	1.5	0.1	0.037
Ammonia (mg/L)	1.7	7.3	2.1	8.4	-0.4	0.002
Temperature (Celsius)	28.0	5.1	28.0	5.2	0.0	0.613
Precipitation (Inches)	3.9	1.5	4.0	1.4	-0.1	0.003
Sown in Thousands (Hectares)	24.5	26.5	14.9	18.7	9.6	< 0.001
Harvest in Thousands (Hectares)	22.7	23.7	14.0	16.7	8.8	< 0.001
Education (2010)	0.2	0.0	0.2	0.0	0.0	< 0.001
Population in Thousands (2010)	48.3	28.5	37.6	26.9	10.7	< 0.001

Note: Above are the summary statistics for the mean and standard deviation of different values among the treatment and control groups. Nitrite and nitrate are the response variables. The table displays the standard nitrite, nitrate, and ammonia measures in mg/L at the water monitor level. Temperature is in Celsius at the monitor level, sown is the amount of hectares of agriculture sown in a municipality in thousands, harvest is the amount of hectares of agriculture harvested in thousands, education represents the percent of a municipality's population that has completed secondary education in 2010 in decimal form. Population is the total population in a municipality in 2010 in thousands. Precipitation represents the log(precipitation+1) value of the 1980-2010 monthly municipality average of precipitation in inches.

Table 5: DID Results for Ground Water Pollution

	(1) Nitrite	(2) Nitrite	(3) Nitrite	(4) Nitrate	(5) Nitrate	(6) Nitrate
Post*Treat	0.0071^{**}	0.0087^{***}	0.0082^{***}	-0.0146	-0.0204^{*}	-0.0207^{*}
	(0.0032)	(0.0028)	(0.0028)	(0.0125)	(0.0116)	(0.0117)
Month and Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Nitrate Control	No	Yes	Yes	No	No	No
Ammonium Control	No	Yes	Yes	No	Yes	Yes
Nitrite Control	No	No	No	No	Yes	Yes
Controls	No	No	Yes	No	No	Yes
N	42,434	42,435	42,434	42,435	42,435	42,434
R^2	0.5013	0.5318	0.5319	0.6341	0.6560	0.6578

Note: All robust standard errors are clustered at the ground water monitor level. Data for this table spans from 2013 to 2019. The coefficient of interest is Post*Treat. Post equals 1 if the observation took place after 2015, 0 otherwise. Treat equals 1 if a monitor is in a municipality that grew avocados between 2003 to 2013. The response variable in columns 1 - 3 is the log(nitrite+1) value of nitrite. For columns 4 - 6, the response variable is the log(nitrate+1) value of nitrate. Columns 1 and 4 do not include any right-hand controls. Columns 2 and 5 control for different nitrogen in groundwater. Columns 3 and 6 control for different nitrogen in groundwater, logged total population, percent of municipality population with at least a secondary education, the 8.2 magnitude Oaxaca earthquake in 2017, logged temperature at the monitor level, and amount of total agriculture sown in hectares at the municipality level. In addition, columns 3 and 6 control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010. Each column includes year and monitor fixed effects and controls for what month the monitor's reading took place.

Table 6: OLS Nitrogen in Nitrite Mechanism

	(1) Nitrite	(2) Nitrite	(3) Nitrite	(4) Nitrite
Log Avocado Sown	-0.0216**		-0.0184**	-0.0180**
	(0.0090)		(0.0074)	(0.0076)
Log Avocado Harvested	0.0087**		0.0082**	0.0076*
	(0.0042)		(0.0040)	(0.0041)
Nitrate		0.0981***	0.0978***	0.0980***
		(0.0141)	(0.0136)	(0.0137)
Ammonia		0.0307***	0.0300***	0.0280***
		(0.0078)	(0.0078)	(0.0065)
Log Temperature			0.0058	0.0057
			(0.0091)	(0.0091)
Precipitation				-0.0011
				(0.0021)
Earthquake				-0.0474
				(0.0367)
Log Agriculture Sown				0.0063
				(0.0250)
Log Agriculture Harvested				0.0063
				(0.0211)
Education				2.9535***
				(0.9220)
Log Population				-0.1305***
				(0.0410)
Year FE	Yes	Yes	Yes	Yes
Monitor FE	Yes	Yes	Yes	Yes
Month Controls	Yes	Yes	Yes	Yes
N	7,623	7,623	7,623	7,623
R^2	0.4789	0.5413	0.5421	0.5425

Note: All robust standard errors are clustered at the ground water monitor level. The data for table 3 spans the years 2013 to 2019. The sample includes monitors that are in the treatment group. The response variable for all columns is the log value of nitrite measured as log(nitrite+1). Log avocado sown is the logged amount of hectares sown in a municipality. Log avocado harvested is the logged amount of hectares harvested in a municipality. I use the log(nitrogen+1) value of both nitrate and ammonia. Log temperature is the logged temperature in Celsius at the monitor level. Earthquake is a dummy variable equal to 1 if the observation is from Oaxaca in 2017, 0 otherwise. Log agriculture sown is the logged total amount of all agriculture sown in a municipality. Log agriculture harvested is the amount of total agriculture sown in a municipality. Education is the percent of the population with at least a high school degree in 2010 at the municipality level in decimal form. Log population is the logged total population in 2010 at the municipality level. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010. Each column includes year and monitor fixed effects and control for what month a monitor's reading took place.

A Appendix

Equations A.1 - A.3 display the nitrification and denitrification process. Tables 5 and 6 in the main paper regress nitrogen right-hand variables onto left-hand variable nitrogen variables. This method raises concerns of simultaneity and reverse causality. Equations A.1 and A.3 show through the chemistry literature that there are natural chemical reactions that result in different nitrogen types forming into other nitrogens. These equations argue that it is important, for better measuring accuracy, to include the nitrogen right-hand controls for the results in Table 5 and 6. Equations A.1 and A.2 depict the nitrification process. The aerobic ammonia oxidations proceed by the following stoichiometry [1] (Ward, 2013) :

$$NH_3 + 1.5O_2 \rightarrow NO_2^- + H_2O + H^+ \tag{A.1}$$

In short, equation A.1 shows the chemical process of how ammonia turns into nitrite. Equation A.2 depicts that through oxidization, nitrite can turn into nitrate [2] (Ward, 2013):

$$NO_2^- + 0.5O_2 \rightarrow NO_3^- \tag{A.2}$$

Denitrification is the dissimilatory reduction of one or both nitrate and nitrite to the gaseous oxides such as nitric oxide and nitrous oxide due to aerobic bacteria. The following is the flow of the denitrification process (Knowles, 1982): $NO_3^- \rightarrow NO_2^- \rightarrow (NO) \rightarrow N_2O \rightarrow N_2$. Equation A.3 shows one of the intermediary steps of denitrification known as nitrate reductase. This is when nitrate forms into nitrite [3] (Marschner, 2011; Bernhard, 2010):

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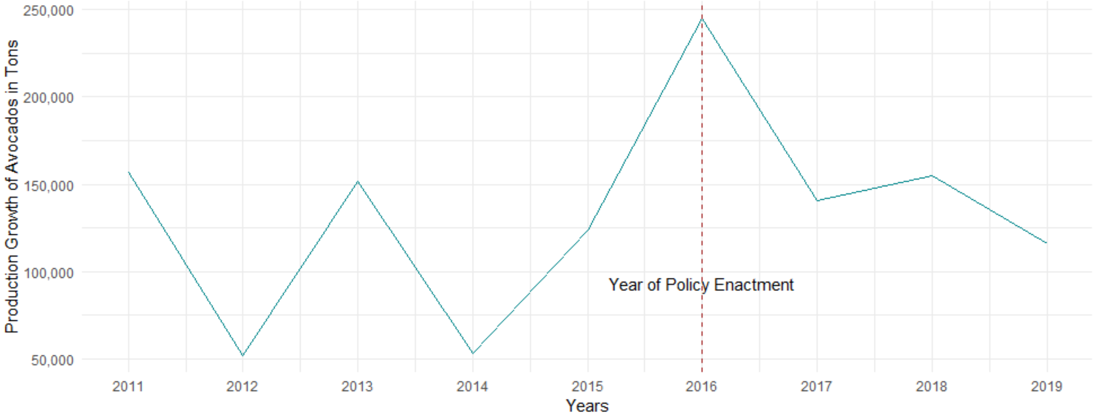
[1] Equations A.1 - A.3 represent standard chemistry symbols. NH_3 and O_2 represent ammonia and oxygen, respectively. Symbols for nitrite, water, and hydrogen ion are NO_2^-, H_2O, and H^+, respectively

[2] NO_3^- stands for nitrate.

[3] e^- is the symbol for an electron.

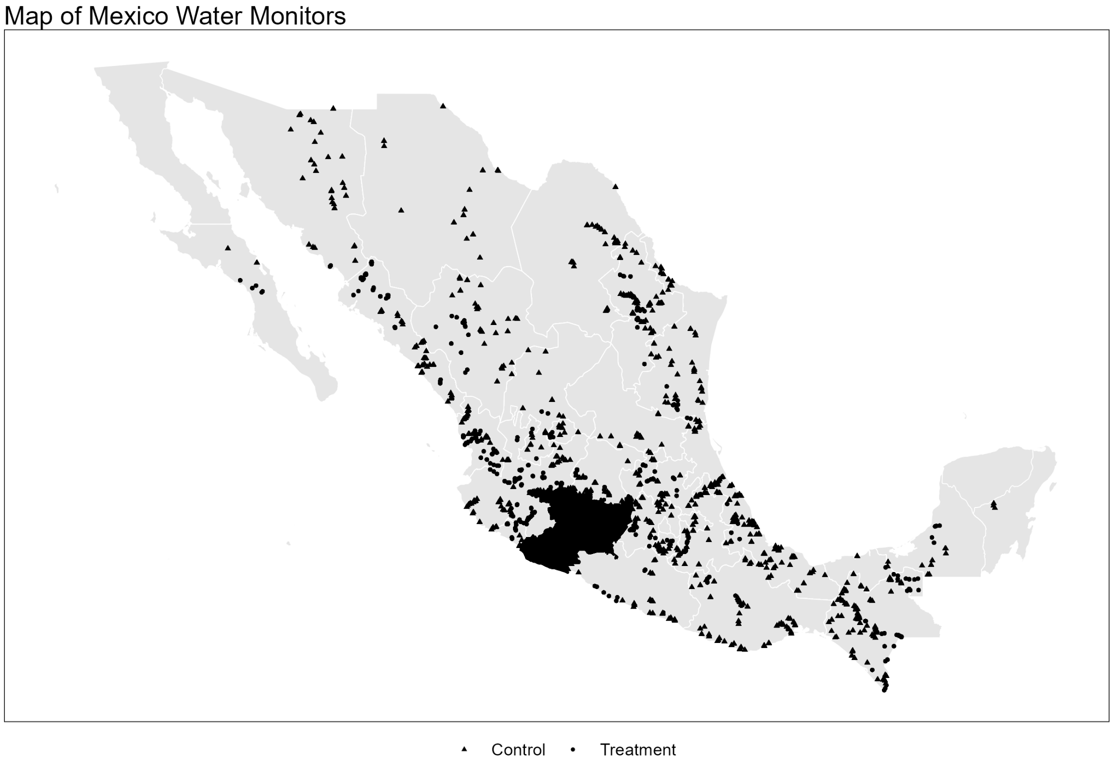
$$NO_3^- + 2H^+ + 2e^- \rightarrow NO_2^- + H_2O \tag{A.3}$$

Figure A1: Mexico's National Avocado Production Growth in Tons



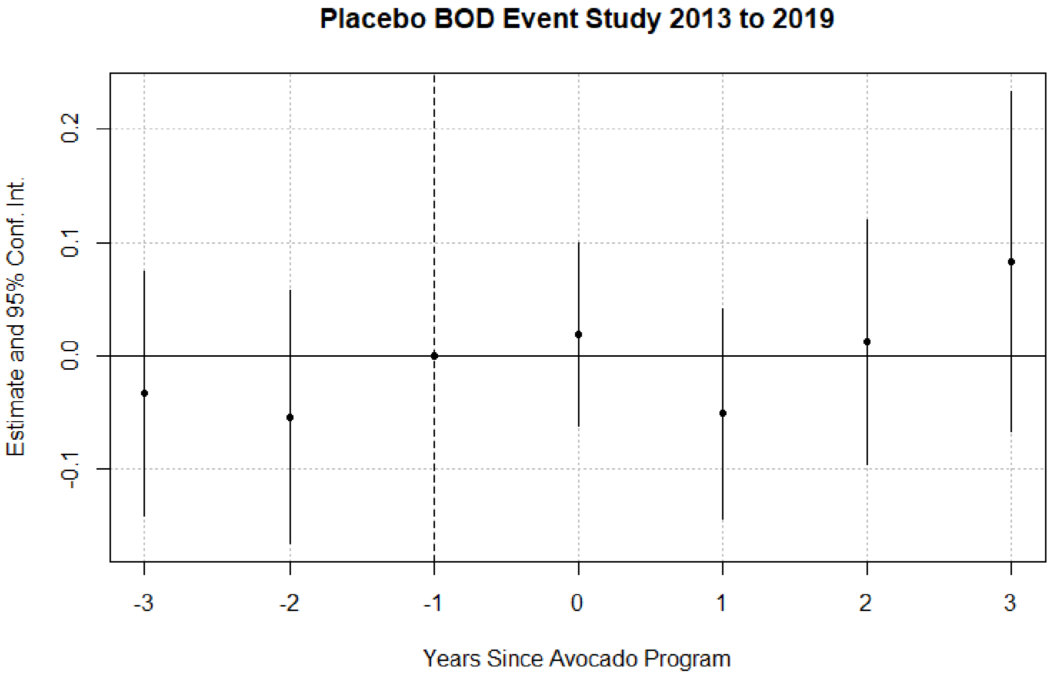
The data for this figure comes from El Gobierno de México's Servicio de Información Agroalimentaria y Pesquera (SIAP). The image shows the difference of the current year's avocado production from the previous year at Mexico's national level. The dashed vertical line on 2016 represents when the 2016 Mexican Hass Avocado Import Program amendment was enacted. The image includes national results for the years 2011 to 2019.

Figure A2



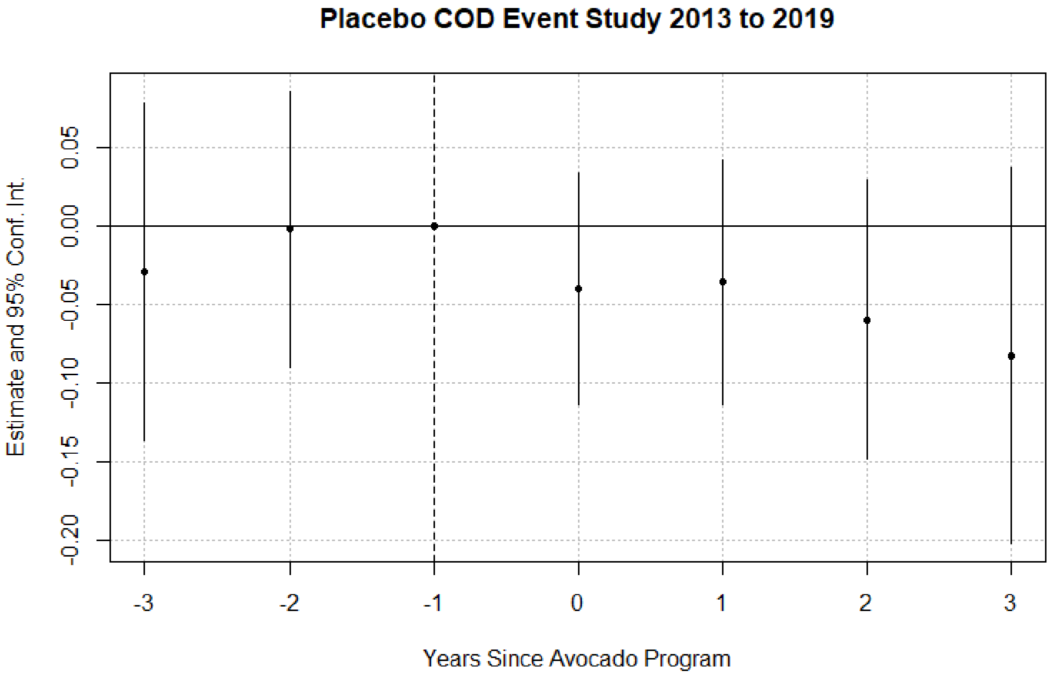
This map shows the geographic locations of the monitors in the surface water monitor sample. The circles represent monitors that are in the treatment group while the triangles symbolize the monitors in the control group. The blackened out state is Michoacán. I do not include monitors from Michoacán in the analysis because it was the one state that could export avocados before the 2016 Mexican Hass Avocado Import Program amendment.

Figure A3



For this figure, I omit the study's original treatment group and only include monitors in control municipalities. 125 out of 471 municipalities are in the treatment group of the original sample. To run a placebo test for BOD, I randomly select 125 municipalities to include in as the new treatment group. The event study includes fixed effects at the month and year level and monitor location as well as municipality controls and controls for temperature at the monitor level. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010. All robust standard errors are clustered at the monitor level.

Figure A4



For this figure, I omit the study's original treatment group and only include monitors in control municipalities. 125 out of 471 municipalities are in the treatment group of the original sample. To run a placebo test for COD, I randomly select 125 municipalities to include in as the new treatment group. The event study includes fixed effects at the month and year level and monitor location as well as municipality controls and controls for temperature at the monitor level. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010. All robust standard errors are clustered at the monitor level.

Table A1: Summary Statistics of BOD and COD Analysis 2013-2019

Variable	**Observations**	**Mean**	**Std. Dev.**
BOD (mg/L)	36,705	16.93	100.85
COD (mg/L)	36,705	65.73	585.81
Temperature (Celsius)	36,705	27.47	5.31
Precipitation (Inches)	3,445	93.99	99.93
Population	1,257	38,557.41	27,600.70
Education (Percent)	1,247	21.68	4.79
Agriculture Sown (Hectares)	471	16,510.85	21,384.59
Agriculture Harvested (Hectares)	471	15,681.63	20,284.45

Note: See data section for definitions of variables.

Table A2: Summary Statistics of Nitrogen Analysis 2013-2019

Variable	**Observations**	**Mean**	**Std. Dev.**
Nitrate (mg/L)	42,435	0.71	1.56
Nitrite (mg/L)	42,435	0.07	0.27
Nitrogen Ammonium (mg/L)	43,435	2.24	8.94
Temperature (Celcius)	42,435	27.64	5.24
Precipitation (Inches)	3,523	93.35	101.26
Population	485	40,655.40	27,736.40
Education (Percent)	485	21.68	4.79
Agriculture Sown (Hectares)	485	17,527.54	22,112.82
Agriculture Harvested (Hectares)	485	16,656.84	20,984.29

Note: See data section for definitions of variables.

Table A3: DID Results for Only States with Monitors in Treatment Group

	BOD			COD		
	(1)	(2)	(3)	(4)	(5)	(6)
Post*Treat	-0.121***	-0.118**	-0.121***	-0.115***	-0.115***	-0.114***
	(0.047)	(0.047)	(0.033)	(0.031)	(0.033)	(0.033)
Month and Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Temperature Control	No	Yes	Yes	No	Yes	Yes
Municipal level controls	No	No	Yes	No	No	Yes
N	33,423	33,423	33,423	33,423	33,423	33,423
R^2	0.5614	0.5616	0.5618	0.4987	0.4987	0.5002

Note: This table is the same as Table 2, but I omit monitors from the states of Chihuahua, Coahuila, San Luis Potosi, Yucatan, and Quintana Roo. These states did not have any monitors in the treatment group among the sample. All robust standard errors are clustered at the surface water monitor level. Data for the table spans from 2013 to 2019. The coefficient of interest is Post*Treat. Post equals 1 if the observation took place after 2015, 0 otherwise. Treat equals 1 if a monitor is in a municipality that grew avocados between 2003 to 2013. The response variable in columns 1-3 is the logged value of BOD. For columns 4-6, the response variable is logged COD. Each column includes year and monitor fixed effects and controls for what month the monitor's reading took place. The temperature control is at the monitor station location at the time of the BOD or COD reading. The municipal level controls include the 8.2 magnitude earthquake that hit Oaxaca in 2017, logged hectares of agriculture sown and harvested at the municipal level, the percent of the population that has at least a secondary level of education, and the logged population. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010.

Table A4: DID Results for Balanced Panel of Mean, Max, and Min

	(1) BOD Mean	(2) COD Mean	(3) BOD Max	(4) COD Max	(5) BOD Min	(6) COD Min
Treat*Post	-0.115**	-0.099**	-0.045	-0.008	-0.170***	-0.154***
	(0.049)	(0.033)	(0.060)	(0.040)	(0.048)	(0.039)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Temperature Control	Yes	Yes	No	No	No	No
N	8,799	8,799	8,799	8,799	8,799	8,799
R^2	0.749	0.761	0.699	0.699	0.63	0.61

Note: All robust standard errors are clustered at the water monitor level. Data for this table spans from 2013 to 2019. The coefficient of interest is Post*Treat. Post equals 1 if the observation took place after 2015, 0 otherwise. Treat equals 1 if a monitor is in a municipality that grew avocados between 2003 to 2013. The sample consists of an even panel at the monitor and year level. Values for BOD and COD are logged. Each column includes year and monitor fixed effects. Columns 1 and 2 measure the average reading of a monitor in a year, columns 3 and 4 measure the highest reading of a monitor in a year, and columns 5 and 6 measure the lowest reading of a monitor in a year. The analysis includes 8,799 observations.

Table A5: Summary Statistics of Nitrogen Mechanism Analysis 2013-2019

Variable	**Observations**	**Mean**	**Std. Dev.**
Nitrate (mg/L)	7,623	0.90	1.69
Nitrite (mg/L)	7,623	0.08	1.69
Nitrogen Ammonium (mg/L)	7,623	1.84	7.10
Temperature (Celsius)	7,623	27.00	4.88
Precipitation (Inches)	805	92.50	97.97
Sown Avocado (Hectares)	195	202.06	347.71
Harvested Avocado (Hectares)	195	168.74	292.91
Total Ag. Sown (Hectares)	195	17,472.58	13,377.64
Total Ag. Harvested (Hectares)	195	16,805.99	12,989.16
Population	90	42,269.01	25,288.87
Education (Percent)	90	0.22	0.04

Note: See data section for definitions of variables.

Table A6: DID Results for BOD and COD When Inequality Values Equal 1.5 and 7, Respectively

	BOD			COD		
	(1)	(2)	(3)	(4)	(5)	(6)
Post*Treat	-0.097**	-0.095**	-0.097**	-0.092***	-0.092***	-0.091***
	(0.038)	(0.038)	(0.038)	(0.028)	(0.028)	(0.028)
Month and Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Temperature Control	No	Yes	Yes	No	Yes	Yes
Municipal level controls	No	No	Yes	No	No	Yes
N	36,705	36,705	36,705	36,705	36,705	36,705
R^2	0.610	0.610	0.610	0.544	0.544	0.545

Note: All robust standard errors are clustered at the surface water monitor level. Data for the table spans from 2013 to 2019. The coefficient of interest is Post*Treat. Post equals 1 if the observation took place after 2015, 0 otherwise. Treat equals 1 if a monitor is in a municipality that grew avocados between 2003 to 2013. The response variable in columns 1-3 is the logged value of BOD. For columns 4-6, the response variable is logged COD. Each column includes year and monitor fixed effects and controls for what month the monitor's reading took place. The temperature control is at the monitor station location at the time of the BOD or COD reading. The municipal level controls include the 8.2 magnitude earthquake that hit Oaxaca in 2017, logged hectares of agriculture sown and harvested at the municipal level, the percent of the population that has at least a secondary level of education, and the logged population. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010.

Table A7: DID Results for BOD and COD When Inequality Values Equal 1.25 and 3, Respectively

	BOD			COD		
	(1)	(2)	(3)	(4)	(5)	(6)
Post*Treat	-0.107***	-0.105***	-0.108***	-0.138***	-0.138***	-0.138***
	(0.041)	(0.041)	(0.041)	(0.037)	(0.037)	(0.037)
Month and Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Temperature Control	No	Yes	Yes	No	Yes	Yes
Municipal level controls	No	No	Yes	No	No	Yes
N	36,705	36,705	36,705	36,705	36,705	36,705
R^2	0.601	0.601	0.601	0.505	0.505	0.506

Note: All robust standard errors are clustered at the surface water monitor level. Data for the table spans from 2013 to 2019. The coefficient of interest is Post*Treat. Post equals 1 if the observation took place after 2015, 0 otherwise. Treat equals 1 if a monitor is in a municipality that grew avocados between 2003 to 2013. The response variable in columns 1-3 is the logged value of BOD. For columns 4-6, the response variable is logged COD. Each column includes year and monitor fixed effects and controls for what month the monitor's reading took place. The temperature control is at the monitor station location at the time of the BOD or COD reading. The municipal level controls include the 8.2 magnitude earthquake that hit Oaxaca in 2017, logged hectares of agriculture sown and harvested at the municipal level, the percent of the population that has at least a secondary level of education, and the logged population. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010.

Table A8: DID Results for BOD and COD When Inequality Values Equal 1.75 and 1, Respectively

	BOD			COD		
	(1)	(2)	(3)	(4)	(5)	(6)
Post*Treat	-0.088**	-0.087**	-0.089**	-0.198***	-0.198***	-0.198***
	(0.036)	(0.036)	(0.036)	(0.050)	(0.050)	(0.050)
Month and Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Temperature Control	No	Yes	Yes	No	Yes	Yes
Municipal level controls	No	No	Yes	No	No	Yes
N	36,705	36,705	36,705	36,705	36,705	36,705
R^2	0.617	0.617	0.617	0.460	0.460	0.462

Note: All robust standard errors are clustered at the surface water monitor level. Data for the table spans from 2013 to 2019. The coefficient of interest is Post*Treat. Post equals 1 if the observation took place after 2015, 0 otherwise. Treat equals 1 if a monitor is in a municipality that grew avocados between 2003 to 2013. The response variable in columns 1-3 is the logged value of BOD. For columns 4-6, the response variable is logged COD. Each column includes year and monitor fixed effects and controls for what month the monitor's reading took place. The temperature control is at the monitor station location at the time of the BOD or COD reading. The municipal level controls include the 8.2 magnitude earthquake that hit Oaxaca in 2017, logged hectares of agriculture sown and harvested at the municipal level, the percent of the population that has at least a secondary level of education, and the logged population. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010.

Table A9: Robustness Results with Varying Fixed Effects

	BOD				COD			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Post*Treat	-0.375***	-0.129**	-0.369***	-0.122***	-0.293***	-0.124**	-0.285**	-0.111***
	(0.047)	(0.055)	(0.038)	(0.044)	(0.035)	(0.040)	(0.027)	(0.032)
Month by Monitor FE	Yes	Yes	No	No	Yes	Yes	No	No
Year FE	No	Yes	No	Yes	No	Yes	No	Yes
Monitor by Municipality FE	No	No	Yes	Yes	No	No	Yes	Yes
Temperature Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	36,705	36,705	36,705	36,705	36,705	36,705	36,705	36,705
R^2	0.547	0.577	0.566	0.589	0.523	0.523	0.515	0.530

Note: All robust standard errors are clustered at the surface water monitor level. Data for the table spans from 2013 to 2019. The coefficient of interest is Post*Treat. Post equals 1 if the observation took place after 2015, 0 otherwise. Treat equals 1 if a monitor is in a municipality that grew avocados between 2003 to 2013. The response variable in columns 1-3 is the logged value of BOD. For columns 4-6, the response variable is logged COD. Each column includes year and monitor fixed effects and controls for what month the monitor's reading took place. The temperature control is at the monitor station location at the time of the BOD or COD reading. The municipal level controls include the 8.2 magnitude earthquake that hit Oaxaca in 2017, logged hectares of agriculture sown and harvested at the municipal level, the percent of the population that has at least a secondary level of education, and the logged population. In addition, I control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010.

Table A10: Main Results with Clustering at the Water Shed Level

	(1) BOD	(2) COD
Post*Treat	-0.122*	-0.111**
	(0.073)	(0.048)
Month and Year FE	Yes	Yes
Monitor FE	Yes	Yes
Controls	Yes	Yes
N	36,705	36,705
R^2	0.589	0.530

Note: All robust standard errors are clustered at the watershed level. Data for this table spans from 2013 to 2019. The left-hand variables are logged BOD and COD for columns 1 and 2, respectively. The coefficient of interest is Post*Treat. Post equals 1 if the observation took place after 2015, 0 otherwise. Treat equals 1 if a monitor is in a municipality that grew avocados between 2003 to 2013. All columns include logged total population, percent of municipality population with at least a secondary education, the 8.2 magnitude Oaxaca earthquake in 2017, logged temperature at the monitor level, and amount of total agriculture sown and harvested in hectares at the municipality level. In addition, both columns control for municipal precipitation by taking the log(precipitation+1) value of the monthly average precipitation from 1980-2010. Each column includes year and monitor fixed effects and controls for what month the monitor's reading took place.