Chemical Use Trends and Behaviors in Strawberry Production

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Introduction

By value, strawberries are one of the most important fruits produced in the U.S - in 2020, the total domestic production value ranked third among all fruit and accounted for 13 percent of the total production value of fruits produced in the U.S. overall (Yeh et al. 2023). Since the 1960s, strawberry production has relied extensively on a mixture of two fumigants - methyl bromide (MB) and chloropicrin - as a means to control soil-borne pests and disease; in particular, the pathogenic soil-borne fungus, *Verticillium dahliae.* The fungus itself is long-lived and resilient, and the disease known as Verticillium wilt can result in catastrophic damage, potentially as high as 75% plant loss (Olver and Zilberman 2022).

However, the establishment of the Montreal Protocol and the subsequent (though delayed) phaseout of MB has led to a potentially structural shift in strawberry production. The U.S. Environmental Protection Agency (EPA) started phasing out MB following the Montreal Protocol, an international treaty in 1991, identified MB as a Class-1 ozone-depleting agent. EPA completely banned MB fumigation in 2005, while some strawberry producers were granted critical-use exemptions until 2017. MB is now restricted to mostly nursery uses, and thus, strawberry growers adopt alternative chemicals and methods to substitute for the loss of their primary method of damage control.

In this study, we examine the following research questions: (1) Did the MB ban change growers' overall pesticide use, including both fumigants and non-fumigants? (2) How has the MB ban affected strawberry production? (3) What are the environmental impacts associated with chemical use in strawberry production? We focus on the production in California from 1991-2021 in this study, as the state accounts for more than 90 percent of the total domestic strawberry production.

Strawberry production in California

In California, strawberries are usually raised as an annual crop thanks to a system of nurseries and artificial refrigeration: strawberry nurseries cultivate immature plants, refrigerate them to accelerate their development, and then distribute them to strawberry fruit producers. These "frigo plants" facilitate an annual crop system by reducing the time between planting and harvest, increasing yields and mitigating pest damage. This system is further supported by the use of pre-plant soil fumigants, which are typically applied in the fall after harvest or in the spring before

planting to control soil-borne pests prior to transplanting. The process involves injecting the gas with an active ingredient, such as chloropicrin, 1,3-dichloropropene, or MB, into the soil and then covering the site with a plastic tarp to prevent the gas from dispersing and escaping the soil. This also limits it from entering the atmosphere. The fumigants kill most soil-borne pests, including nematodes, weed seeds, and other pathogens, which makes it possible for strawberry growers to cultivate the same field repeatedly without plant damage or yield loss. The widespread adoption of the MB fumigation process also correlates with the drastic yield increases over the same period, as well as the adoption of other production technologies such as plasticulture (Olver and Zilberman 2022).

Data and method

We analyze changes in pesticide use and production over the period from 1991 to 2021 using panel data from the Pesticide Use Reporting (PUR) dataset provided by the California Department of Pesticide Regulation. The PUR dataset contains information on pesticide application and intensity for all California farms. By matching this dataset with county-level production data from California county crop reports, we create a county-level panel dataset for linear estimation. In addition, to assess the environmental impact related to pesticide use, we link the PUR dataset to the Environmental Impact Quotient (EIQ) dataset[1] using CAS Registry Numbers.

Preliminary results

Changes in pesticide use

Figure 1 provides an overview of total pesticide usage per acre in California strawberry production, segmented by major pesticide types. Notably, fungicide usage has exhibited a consistent upward trend since approximately 2005. During the critical exemption periods (spanning from 2005 to 2017), both fungicide and insecticide usage experienced significant spikes. Subsequently, their usage stabilized, while the other pesticide category, which include minor pesticides (such as acaracides and molluscicides), continued to rise in recent years.

[1] https://cals.cornell.edu/new-york-state-integrated-pest-management/risk-assessment/eiq

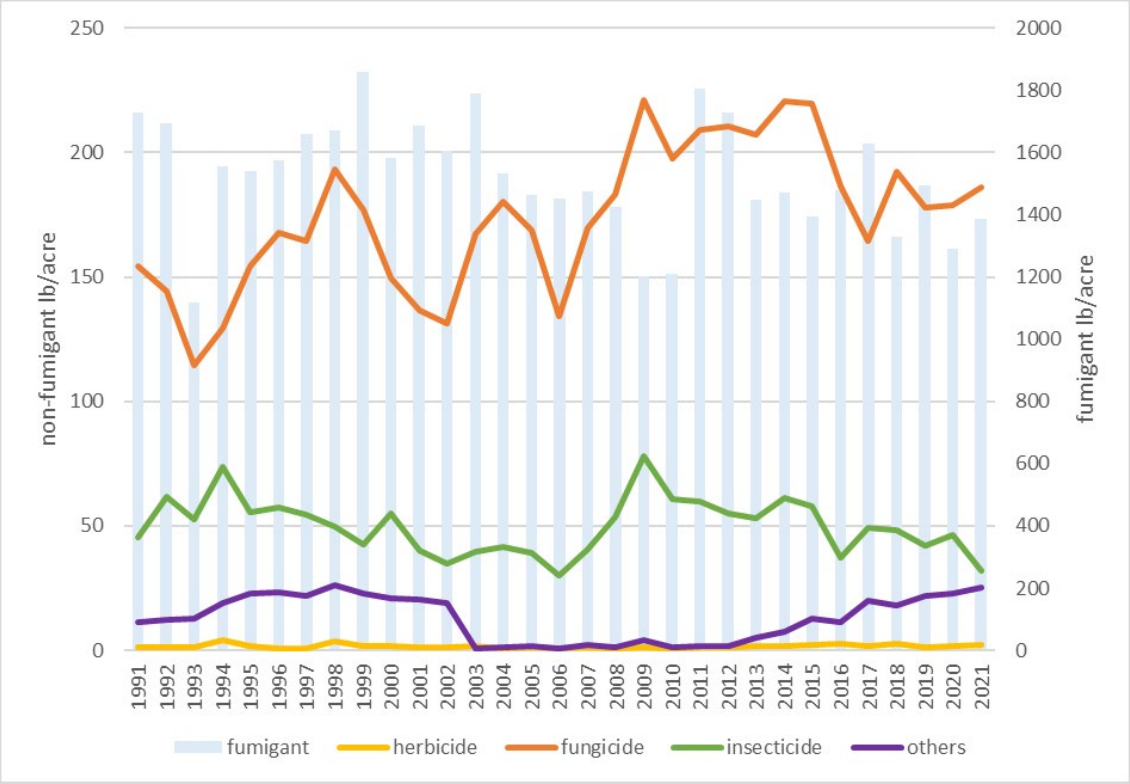

Figure 1. Total pesticide usage per acre in California strawberry production, by pesticide type.

We estimate linear models with different dependent variables of non-fumigant chemical use, including year and county fixed effects. Table 1 presents the regression results for changes in non-fumigant usage, with the unit of analysis at the county level. Considering that fumigants are typically applied in the fall for the subsequent production season starting in spring, we use the prior year's fumigant levels in our model.

The first column in Table 1 aggregates all non-fumigant usage as the dependent variable, while the second-to-last column focuses on individual non-fumigant types. We observe a significant positive correlation between fumigant usage and non-fumigant usage, particularly with regard to fungicides. Additionally, the results reveal an increasing trend in fungicide usage, averaging 0.3 pounds more per acre per year. Furthermore, when compared to Monterey County, most other counties exhibit lower non-fumigant usage. This aligns with intuition, as Monterey stands out as one of the largest strawberry-producing counties and heavily relies on monoculture.

Table 1. Preliminary results for changes in non-fumigants usage

	Total non-fumigants		Fungicide		Herbicide		Insecticide		Others	
Fumigant	0.061	**	0.052	**	0.000		0.009		-0.000	
	(0.016)		(0.011)		(0.000)		(0.005)		(0.002)	
year	0.270	*	0.332	**	0.003		-0.041		-0.021	
	(0.125)		(0.090)		(0.003)		(0.039)		(0.017)	
County [a]:										
Orange	-15.698	**	-10.160	**	-0.046		-3.850	**	-1.545	*
	(4.165)		(2.937)		(0.113)		(1.355)		(0.735)	
San Diego	-20.092	**	-11.607	**	0.073		-5.625	**	-2.821	**
	(4.074)		(2.771)		(0.192)		(1.508)		(0.685)	
San Luis Obispo	-3.393		2.842		0.035		-3.480	*	-2.774	**
	(5.560)		(4.052)		(0.088)		(1.602)		(0.582)	
Santa Barbara	-2.850		2.518		0.043		-3.471	**	-1.945	**
	(3.563)		(2.402)		(0.091)		(1.263)		(0.626)	
Santa Cruz	-10.464	**	-6.348	**	-0.094		-2.904	*	-1.122	
	(3.227)		(2.074)		(0.085)		(1.358)		(0.672)	
Ventura	-8.224	**	-0.958		0.251	*	-6.479	**	-1.042	
	(2.827)		(1.814)		(0.114)		(1.129)		(0.663)	
Intercept	-513.121	*	-649.124	**	-5.441		90.120		44.691	
	(253.807)		(181.164)		(5.918)		(79.525)		(33.484)	
Number of observations	208		208		185		208		207	

** p<.01, * p<.05.

[a] The reference county is Monterey.

To further understand how strawberry growers may have changed their chemical use behavior beyond the quantities, we examine whether the fumigation date has shifted over the study period. We focus on chloropicrin, which is the major fumigant alternative to MB. Figure 2 illustrates the breadth of chloropicrin fumigation dates in Monterey and Santa Barbara counties. Although fumigation date in Monterey has remained temporally stable over the past two decades, Santa Barbara has become increasingly variable around the end of critical use exemption.

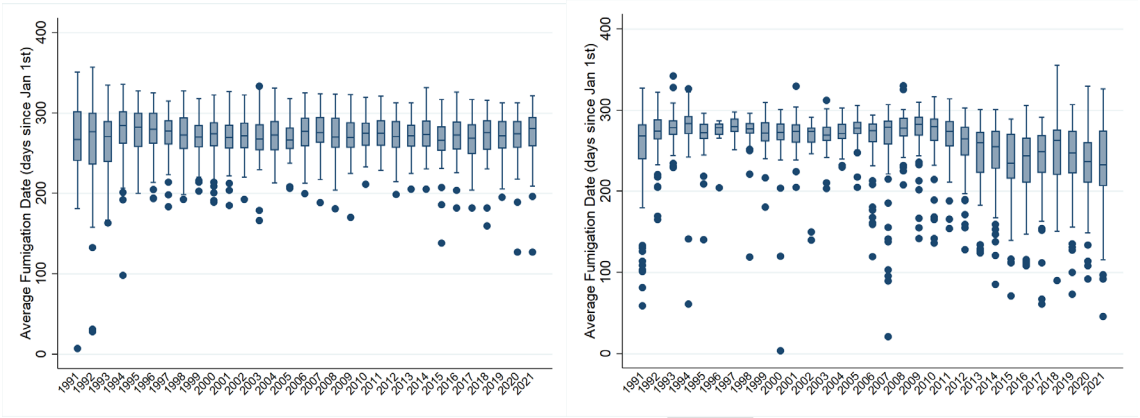

Figure 2 - Fumigation dates of Monterey (left) and Santa Barbara (right)

Production impacts

Figure 3 presents three separate trend lines in strawberry yields per acre over the past three decades. The California trend line is an average across the five major strawberry producing counties - Monterey, Santa Barbara, Santa Cruz, San Luis Obispo, and Ventura. As of 2022, these counties account for virtually all acreage and gross production value of strawberries in the state, at 98 and 99 percent respectively. The maximum and minimum trend lines are the highest and lowest yields per acre drawn from these five counties in a given year.

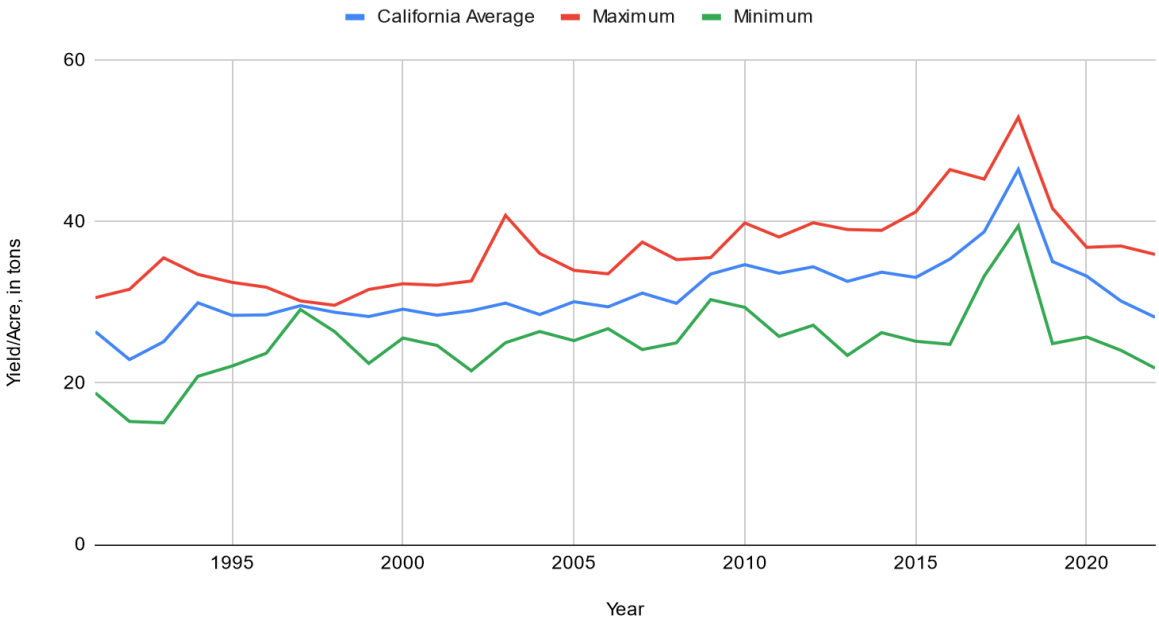

Figure 3. Strawberry yield per acre in California

From the figure, we see that overall productivity in California remained largely static, with yields around 30 tons per acre from the 1990s until the end of the 2000s. Post-2009, yields appear to have achieved a new steady state at 33-35 tons per acre, with two unusually productive years in 2017 and 2018 followed by a (not-unexpected) decline in 2019. We note that this second yield plateau appears to correspond to a widening productivity gap and - as suggested by our earlier figures - an increase in the application of non-fumigant chemicals.

Table 2 summarizes the regression results in yield, presenting the basic specifications in the first column and the additional specification that includes fixed effects of the two post-MB-ban periods in the second column. As anticipated, we observe a significant increasing trend in yield per acre, approximately 0.3 ton per acre per year. The yield is positively associated with fungicide and other pesticide levels, while it exhibits a negative correlation with herbicide levels. However, the model does not indicate a significant relationship between fumigant usage and yield. This could be due to the fact that fumigation is one of the pre-planting field preparation practices which may not directly affect the level of production. In addition, when compared to Monterey County, both Orange and Ventura counties show nearly six tons less in yield per acre.

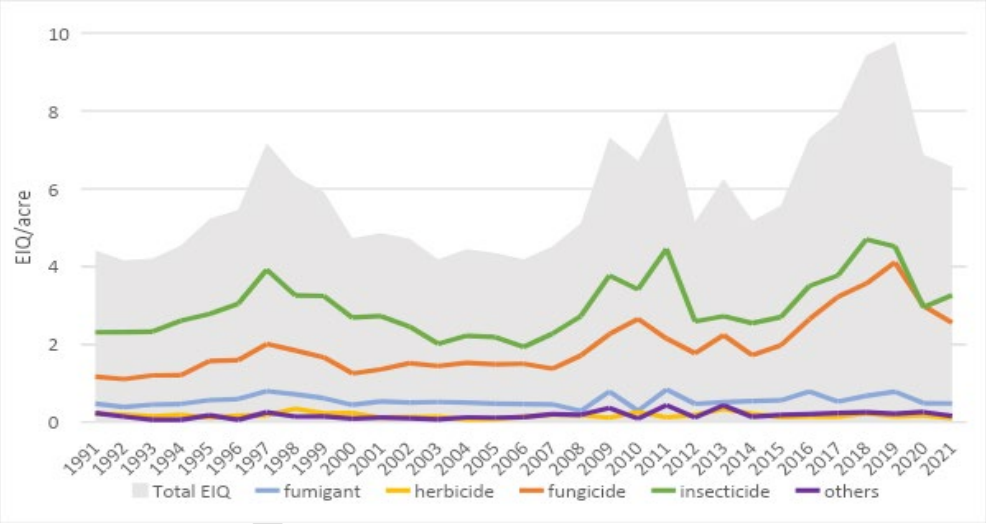

Figure 4. Total Environmental Impact Quotient (EIQ) per acre in California strawberry production, by pesticide type.

We measure the environmental impacts associated with chemical use in strawberry production in Figure 4, total EIQ per acre of strawberry production, categorized by pesticide type. There has

been an increase in the total EIQ per acre since the beginning of the critical exemption use period, with the highest level at 9.78 in 2019. Insecticides account for the largest proportion of the total EIQ, constituting about 50 percent in 2021, followed by fungicides at 39 percent.

Table 2. Preliminary results for changes in yield per acre

	Yield per acre		Yield per acre	
year	0.305	**	0.254	*
	(0.055)		(0.118)	
Pesticide usage per acre:				
fumigant	-0.013		-0.013	
	(0.007)		(0.007)	
fungicide	0.150	**	0.156	**
	(0.056)		(0.057)	
herbicide	-2.292	*	-2.424	*
	(1.028)		(0.993)	
insecticide	0.013		0.010	
	(0.135)		(0.136)	
other pesticide	0.463	*	0.400	
	(0.192)		(0.238)	
County [a]:				
Orange	-5.534	**	-5.551	**
	(1.562)		(1.602)	
San Diego	-1.620		-1.656	
	(1.635)		(1.708)	
San Luis Obispo	-2.627		-2.832	
	(1.757)		(1.791)	
Santa Barbara	-2.808		-2.947	
	(1.600)		(1.632)	
Santa Cruz	-1.653		-1.709	
	(1.379)		(1.379)	
Ventura	-5.953	**	-5.996	**
	(1.680)		(1.687)	
Post MB-ban periods [b]				
2005 < Year < 2017			0.340	
			(1.623)	
Year >= 2017			1.410	
			(2.728)	
Intercept	-579.147	**	-477.096	*
	(110.015)		(235.899)	
Number of observations	184		184	

** p<.01, * p<.05

[a] The reference county is Monterey.

[b] The reference period is pre-MB ban, from 1991 to 2004.

Discussion and next steps

This study aims to provide insights into the impact of pesticide regulations on both production and growers' behaviors. We present information on potential spillover effects, demonstrating that growers may have altered their chemical use behaviors following the MB ban, which subsequently influenced strawberry production.

This avenue of research is of significant importance: not only are fruit and vegetable industries facing progressively greater constraints on pesticides from both domestic and international entities, but these decisions are directly (and perhaps inversely) related to the reliability of agricultural supply chains. The effect of the MB ban on the strawberry industry is a unique case given the high reliance and routine usage of MB in production prior to Montreal Protocol.

Our next steps include expanding the model with a staggered adoption design to account for the varying treatment effects, considering the staggered announcements of regulations related to MB ban (the signing of Montreal protocol in 1995, the partial MB ban starting in 2005, allowances for critical use exemptions from 2005 to 2017, and the total ban for production at 2017). Additionally, we will incorporate market data from USDA Agricultural Marketing Service and enterprise budgets to account for factors such as prices and advancement in chemical use programs. Results of this study contribute to the understanding of pesticide policies and whether there are potential environmental ramifications if production shifts outside of California.

References

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