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Pesticide Restrictions and Registration Delays: Implications of California's Sustainable Pest Management for the Lettuce Industry

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Effective pest management ensures the safety and quality of California produce, protects producers, and maintains export market access. California launched its new Sustainable Pest Management (SPM) framework that targets removal of certain priority pesticides but also seeks to reduce economic risk to growers and activate new markets to drive SPM. Removing pesticides products from the registered list of allowable pest control agents increases the need for new pesticides. However, pesticides that are federally approved can be delayed for use in California by 1–3 years. We evaluate the economic implications of SPM and California's registration process for lettuce.

Key words: equilibrium displacement model, neonicotinoids, pyrethroids, research and development, specialty crops

Introduction

Effective pest management in California is critical for ensuring the safety and quality of California produce, protecting producers and consumers, and maintaining access to international markets. An increasingly connected global economy and changing climate is highlighting the importance of timely and cost-effective pest management. For example, the state is currently suffering from an historic exotic fruit fly outbreak with widespread quarantines across the state (CDFA, 2024a), Pythium wilt and Impatiens necrotic spot orthotospovirus (INSV) infections have caused substantial crop losses in lettuce (Hasegawa and Del Pozo-Valdivia, 2023), and Asian Citrus Psyllid and Huanglongbing continue to impact the citrus industry (CDFA, 2024b). At the same time there are increasing restrictions on existing registered pesticides, which limits the tools available to manage and prevent costly outbreaks. Effective pest management requires access to a range of existing, registered pest control agents and for companies to continually innovate and bring new products labeled for California's specialty crops to market.

California's new Sustainable Pest Management (SPM) initiative seeks to frame the future of pest management in the state (SPM, 2024). It is a broad framework that includes many elements that are still being defined by multiple state agencies, so the economic analysis and framework presented in this paper is timely and may help define program elements. Among many other

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elements, SPM includes a goal to phase out the use of selected "priority" registered pesticides. It also identifies multiple "leverage points" for implementing agricultural SPM that include "reducing economic risk for growers transitioning to SPM" and "activating markets to drive SPM." In this paper we illustrate the implications of eliminating example priority pesticides, quantify economic risk for growers, and describe research and development (R&D) investment potential to drive SPM. This is, to our knowledge, the first paper to evaluate the economic implications of components of California's new SPM framework.

Limiting access to existing registered pest management products can increase costs for growers, decrease yield, increase risk and production uncertainty, and decrease crop protection (Zilberman et al., 1991; Joseph et al., 2017; Kathage et al., 2017; Scott and Bilsborrow, 2018; Böcker, Möhring, and Finger, 2019; Kudsk and Mathiassen, 2020; Möhring et al., 2020); benefits of banning harmful pesticides can also be offset by risks of substitution with other available active ingredients (Gray and Hammit, 2000; Perry and Moschini, 2020; Gensch et al., 2024). Absent suitable alternatives, pesticide bans and restrictions increase the need to quickly register new, effective products. However, the registration process for new products in California is time consuming, causing pesticides that are federally approved for agricultural use to be delayed for use in California by 1–3 years or more (DPR, 2023). This affects R&D investment decisions by crop protection product companies (registrants), and ultimately increases costs to growers, processors, and consumers. These factors have implications for SPM in California.

Existing statewide programs such as the University of California's Integrated Pest Management (IPM) guidelines and national programs such as the IR-4 Project help specialty crop growers manage pests. These programs provide guidelines for effective and environmentally sustainable pest management practices, as well as conduct scientific research to determine best management practices. The California SPM framework is intended to be the next iteration of IPM, with guidelines and implementation specifics that are still to be developed.

We evaluate the economic impact of changes in access to neonicotinoid and pyrethroid insecticides for California's lettuce industry. We develop an economic model of the California, Arizona, and Mexico lettuce supply chain to evaluate the economic impact of product restrictions and pesticide registration delays. We contribute to the existing literature by: (i) developing an equilibrium displacement model of the full lettuce supply chain, (ii) quantifying economic impacts of eliminating priority pesticides under the SPM framework in California, (iii) evaluating the economic impact of California's registration timeline for new pest management products, and (iv) describing implications for R&D investment decisions for bringing new products to market such as those that are promoted under SPM. Economic impacts are measured in terms of changes in consumer and producer welfare; changes in conventional and organic lettuce production; and changes in the US market share for lettuce from California, Arizona, and Mexico. We describe the implications for R&D and identify several extensions for future research.

Pest Prevention and Pesticide Registration

California has several programs and agencies charged with different aspects of pest prevention and management. The California Department of Food and Agriculture (CDFA) Pest Exclusion Branch focuses on exclusion and prevention of pests. The California Department of Pesticide Regulation (DPR) regulates pesticide sales and use; all new products are subject to the DPR regulatory process. DPR and CDFA are developing the SPM framework, which is a joint effort with the California Environmental Protection Agency. Pest management responsibilities at the farm fall to growers and their certified agricultural pest control advisers (PCA).

The CDFA Pest Exclusion Branch implements exterior and interior pest exclusion strategies and regulates seeds and nursery stock. Exterior pest exclusion is accomplished by inspecting commodities entering the state via commercial and private vehicles. Interior pest exclusion is accomplished by inspecting agricultural products in each county and implementing quarantines to regulate production and limit movement of infested materials. For example, the invasive Tau fruit fly was discovered in Southern California in August 2023 and the Queensland fruit fly was discovered in November 2023, leading to quarantines in parts of Los Angeles and Ventura counties; both quarantines are still in effect as of February 2024. Seeds sold in California are subject to labeling requirements and are inspected to prevent the transmission of noxious weeds. Sellers of nursery stock must be licensed, and plant materials must be certified, to prevent the sale of pest-infested products. CDFA's exclusion and prevention practices help reduce growers' exposure to harmful pests but cannot prevent all pests and do not preclude use of pesticides.

California pesticides are subject to rigorous registration and regulatory programs under DPR that are in addition to federal requirements and are wider in scope than any other state. This registration process—which evaluates products with new active ingredients or new products with existing active ingredients already approved for agricultural use by the US Environmental Protection Agency (EPA)—can lead to the rejection of products if they are deemed to pose a significant risk to human health or the environment. The California pesticide evaluation process is time consuming, causing pesticides that are federally approved for agricultural use to be delayed for use in California by 1–3 years or more (DPR, 2023).

The DPR Pesticide Registration Branch is responsible for the evaluation process. Within this branch there are several groups that evaluate a product's suitability for agricultural use including: the Chemistry Program, the Plants, Pests, and Disease Program, the Microbiology Program, the Ecotoxicology Program, the Human Health Assessment Branch, and the Environmental Monitoring Branch. The time it takes to review a product for registration compounds as each DPR group conducts its evaluation. For example, the average time spent on ecotoxicology evaluation for new product applications submitted in 2020 was more than 500 days (Exponent, unpublished report)[1].

A product deemed safe for agricultural use by the federal EPA may be rejected for use in California by the DPR. For some evaluation criteria (such as ecotoxicology), the EPA and DPR analyze the same data or studies. However, the DPR may identify data deficiencies not noted by the EPA, interpret data differently, or use an alternative evaluation method. In a draft report evaluating the registration timeline and rejection rates of DPR, the 2020 pesticide rejection rates ranged from 5%–30% across branches (Exponent, unpublished report). When an EPA-approved pesticide is rejected for agricultural use in California, growers may turn to more expensive or less effective alternatives, putting them at a competitive disadvantage with growers in other states or other countries growing the same crops that are not subject to such restrictions.

The timeline for products registered in 2022 was 191 days on average for products with a currently registered active ingredient, and 1,191 days for products with a new active ingredient (DPR, 2023). Most other states have minimal or no additional requirements for registering pesticides beyond EPA approval—Arizona requires environmental fate data for new active ingredients, and New York is the only other state to require all data reviewed by the EPA.

The state implements and funds pest prevention and exclusion programs, and regulates pesticides, but it is ultimately the grower and PCA responsibility to manage pests at the farm. The University of California regularly publishes and updates IPM guides for growers to assist pest management efforts. These guides advise growers on effective pest management and monitoring techniques and aim to reduce risks to the environment and human health. For example, the IPM guide for lettuce includes pesticide suggestions from preplant through postharvest, provides management advice for specific insects, weeds, and diseases, details the toxicities of available pesticides, and provides additional crop management tools (UC IPM, 2024). SPM, which is not yet fully defined, is intended to replace IPM.

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[1] Exponent Inc. 2022. Assessment of California DPR Timelines for Product Registration Actions: Trends, Causes, And Remedies. Draft report, unpublished.

Economic Analysis of Registration Delays and SPM Restrictions

SPM aims to eliminate the use of all priority pesticides in California by 2050. Pyrethroids and neonicotinoids are two such pesticides. Currently, these are among the most widely used, effective, and cost-efficient insecticides used on lettuce and many other crops. Without cost effective and efficient pest management alternatives, affected agricultural production would shift towards regions that without restrictions, thereby curbing potential benefits and destabilizing food security efforts made to date by states like California. For lettuce, this would likely result in production shifting to Arizona and Mexico. This imposes costs on California producers, other businesses, and consumers. In addition, depending on pest management practices in Arizona and Mexico, this could result in regulatory leakage out of California.

DPR registration is slow and results in products being delayed by 1–3 years or more in California. This has implications for R&D and investment in new products. California leads the nation in specialty crops that are part of a healthy diet (e.g., lettuce, vegetables, almonds, pistachios, avocados, and olives). However, specialty crop acreage is much less than the acreage of major commodity crops (e.g., corn, cotton, soybeans, wheat) grown in the US. It follows that there is a larger potential market for commodity crop protection products. A burdensome registration process further disincentivizes investment that would benefit California growers. The smaller market for specialty crop pesticides relative to major commodities such as corn and soybeans, combined with the longer timeline for registering products in California, means R&D specifically for use on California specialty crops is a riskier investment option. The 2050 target timeline for SPM does provide some opportunity for continued investment and innovation for alternatives to “priority pesticides” that may be phased out several decades in the future.

Delaying the availability of a pesticide for agricultural use in California has short-run implications for lettuce growers—farmers in other states or countries with access to these products may benefit from increased yields or decreased production costs. Pesticide restrictions have long-run implications for lettuce growers—although banning the use of harmful pesticides has human health and environmental benefits, production may shift to areas without similar restrictions. Delays and restrictions cause economic impacts to California growers, other businesses, registrants, and ultimately consumers. We described California’s pesticide registration process, pest management at the farm, and the SPM strategy for long-term pest prevention above and apply an economic framework to evaluate the impact of SPM and California’s registration process on R&D.

We use lettuce as an example crop to illustrate the economic consequences of pesticide restrictions under California’s new SPM, and registration delays. California produces most of the lettuce consumed in the United States. Arizona and Mexico are the next two largest suppliers. Delayed adoption of new pesticides or restrictions on current pesticides would cause some production in California to shift out of state—lettuce farms in Southern California and the Imperial Valley are most likely to decrease production because of seasonal competition with Mexico and Arizona. We consider restrictions on pyrethroids and neonicotinoids, insecticides used to control a broad spectrum of pests. We develop an equilibrium displacement model (EDM) to assess the long-run economic impacts of restricting these pesticides, and the short-run effects of delayed registration of new pesticides, for use on California lettuce farms. Using industry data including information from large packer-shippers, we determine markups and price transmission throughout the supply chain and estimate welfare implications of California’s pesticide policies for producers, market intermediaries, and consumers. Lastly, California's pesticide policies are likely to deter registrant R&D and the introduction of new products to market; these implications are discussed qualitatively and left for future research and analysis.

California Lettuce Market and Pest Management

Lettuce is the fifth most valuable agricultural commodity produced in California, with a value of $3.15 billion in 2022 (CDFA, 2023). California harvests 73% of US lettuce acreage, and Arizona is in second with 21%. The three main types of lettuce produced are iceberg lettuce (46% of production), romaine lettuce (36%), and leaf lettuce (18%). The United States is also a net importer of lettuce, with 90% of imports coming from Mexico (Weber et al., 2023). However, the United States exports a considerable amount of lettuce as well—excluding Mexico, net exports were nearly 63 million pounds in 2022, with nearly 80% of these shipped to Canada.

Lettuce production shifts seasonally to areas with optimal growing conditions for year-round production in California—this also aids in a consistent supply to meet US and export demand. Central California supplies most US lettuce in spring through fall, and Arizona's Yuma Valley and California Imperial Valley are the largest suppliers of lettuce in the winter. Lettuce is imported year-round from Mexico—imports are typically highest during fall and winter months, and import demand increases when weather or other disruptions affect US lettuce supply.

Growers are mostly insulated from short-run shocks across the supply chain because of vertical integration and fixed-price contracts. Only 10% of leafy greens are sold on cash or spot markets, and these transactions mostly consist of growers' excess supply beyond what is needed to fulfill their contracted sales (Spalding et al., 2022). Vertical integration of farmers and processors commonly occurs in the lettuce industry in the form of grower-packers, packer-shippers, or grower-packer-shippers. Retailers and food service operators typically establish 1- or 2-year contracts with processors. According to feedback from a large packer-shipper that provided data for the study, most contracts have a fixed price with a bump that triggers under specific market conditions; some contracts use a sliding scale system, but this is less common. In general, the data and qualitative information provided by the packer-shipper are consistent with Spalding et al. (2022) who interviewed personnel at a major romaine lettuce processor and other industry experts to develop their characterization of modern fresh produce markets.

Although the data provided by the packer-shipper are specific to iceberg lettuce, romaine lettuce has the same contract structures, is grown in the same regions, and is distributed to retail and food service operators in similar proportions. Therefore, we expect iceberg farm-to-processor and processor-to-retail price transmissions to be similar to those for romaine lettuce. To protect the confidentiality of the source's contract data, approximations of average price transmissions are used and randomly drawn from a normal distribution. These approximations maintain ordinal ranks of price transmission across conventional and organic lettuce to retail and food service operators, but they are intentionally imprecise in terms of the magnitude of these differences.

Pyrethroids and neonicotinoids are common in home and garden pest control products as well as in commercial agriculture. They are popular for agricultural operations because they treat a variety of pests and are generally safe for humans, which allows for a short re-entry interval after application. This is particularly valuable for fresh fruits and vegetables with specific harvest windows that require workers to be in the fields. Because pyrethroids can be used for many pests, and due to concerns about insects developing resistance to common chemicals, pyrethroids are often used with other insecticides. Common lettuce pests managed with pyrethroids in California include various types of worms, lepidoptera, thrips, and beetles. There are specific crops and pests in California for which neonicotinoids (e.g., imidacloprid) are essential. For example, whitefly pest pressure in the desert lettuce growing regions. Prior to the introduction of imidacloprid, whitefly infestations were routinely damaging more than 50% of lettuce fields during the winter growing season (Gianessi, 2009).

Economic Methods Overview

We developed an economic model for the California, Arizona, and Mexico lettuce industries from production through final retail. We use an extension of the EDM framework as originally developed by Muth (1964) to simulate market and welfare effects of regulations or supply and demand shifts for a single output with two factors of production. There is an extensive literature that has since developed this framework to consider broader applications. We highlight some extensions of this modeling approach that contribute to the framework developed for this study.

Sumner and Wohlgenant (1985) incorporate trade and taxes into an EDM; Alston, Norton, and Pardey (1995) expanded the EDM to consider multiple goods with trade across multiple regions; Alston and James (2002) describe how price policies that operate through input or output markets can be represented in a model with two factors and two outputs; Rickard and Sumner (2008) develop a framework to simulate the effect of trade barriers and domestic support on global markets for processing tomatoes; Wohlgenant (2011) describes a general approach for an EDM with multiple outputs, multiple inputs, international trade, and its applications for vertical industries; Hamilton et al. (2020) construct an EDM to simulate the effects of wage rate polices for California and non-California head lettuce markets; Ferrier, Zhen, and Bovay (2023) use an EDM to determine the effects of compliance costs with the Food Safety Modernization Act on fruit and vegetable markets; and Brester, Atwood, and Boland (2023) review a wide range of EDM applications, including the construction of EDMs that incorporate imports, exports, substitutes, and vertically linked market stages.

Our analysis follows the EDM frameworks defined in the cited literature. We contribute to the literature by expanding on those methods and constructing a model that simultaneously considers multiple outputs (conventional lettuce for retail, food service lettuce, and organic lettuce), multiple regions (California, Arizona, and Mexico), trade (exports to Canada and imports from Mexico), and the vertical structure of the lettuce industry (farm, packer-shippers, and retail). In doing so, we have constructed a model that best incorporates the intricacies of the North American lettuce industry.

We describe but do not quantify the impact of changes in registration timelines and process on the R&D decisions by registrants. Even with a reasonable rate of return, agricultural R&D is continuously underinvested absent government intervention. The rate of return from R&D is dependent on the scale of the industry for which the research applies; furthermore, identifying the lag distribution, life-span, and spillover effects of R&D are critical to estimating total benefits of R&D, but these components are difficult to estimate (Alston et al., 2009).

Our analysis provides a potential empirical example to which these methods can be applied. However, we have limited industry data on R&D investments because this is proprietary company confidential data. We describe the likely implications for R&D and bringing new products to market in California, but do not attempt to quantify those effects. We leave this for future work. Doing so would require research to inform the relationship between research benefits and lagged R&D expenditures, as well as research to quantify the spillover of pesticide R&D. For example, pesticide research for chemicals used on major crops may be effective against pests that infest specialty crops in California, with additional adaptive research. This is because the pests and ecology in California differ from other regions, and the applicability of pesticides may therefore also differ (Fuglie, 2018). However, California's pesticide registration process further delays—or entirely blocks—farmers from realizing spillover R&D benefits.

Equilibrium Displacement Model

We developed an EDM to analyze the likely economic effects of two scenarios: (1) limiting California growers' access to pyrethroids and neonicotinoids, and (2) delaying registration of new pesticides in California. The simulation models trace how the market for lettuce adjusts to a new equilibrium following new pesticide restrictions or delayed pesticide registration. The model considers separately the effects the farm, wholesale, retail, and food service, and it also allows for the trade of conventional lettuce with (imports primarily from Mexico and exports primarily to Canada).

When we refer to conventional lettuce, we simply mean nonorganic lettuce. Conventional lettuce is an aggregate category consisting of iceberg and romaine lettuce as defined by NASS (2023). We make a few simplifying assumptions to characterize the US, Mexico, and Canada lettuce markets. Although production is generally vertically integrated with producers operating as grower-shippers or processors operating as processor-shippers, we consider a market structure of farms, wholesalers, and retailers or food service operators. Because of data limitations, we do not separate consumer sales of lettuce in Mexico into retail and food service. We also consider Mexico production of conventional lettuce, and there is no distinct organic retail space in Mexico. Canada is a net importer of lettuce, and nearly all lettuce comes from the United States. Therefore, we do not incorporate trade between Mexico and Canada. Because lettuce only represents a small cost share of products sold by food service operators, and there is limited data availability regarding wholesale shipments of organic lettuce to food service operators, we do not consider a food service market for organic lettuce in our model.

We present supply and demand equations of lettuce and then explain our choice of parameter values. The system of supply and demand equations (1) – (21) characterize the competitive equilibrium for conventional and organic lettuce from California, Arizona, and Mexico.

$$D_{CL}^{US} = D_{CL}^{US}(P_{CL}^{r-US}, P_{OL}^{r-US}), \tag{1}$$

$$D_{OL}^{US} = D_{OL}^{US}(P_{CL}^{r-US}, P_{OL}^{r-US}), \tag{2}$$

$$D_{FSL}^{US} = D_{FSL}^{US}(P_{FSL}^{r-US}), \tag{3}$$

$$D_{CL}^{MX} = D_{CL}^{MX}(P_{CL}^{r-MX}), \tag{4}$$

$$D_{CL}^{X} = D_{CL}^{X}(P_{CL}^{w-US}, P_{OL}^{w-US}), \tag{5}$$

$$D_{OL}^{X} = D_{OL}^{X}(P_{CL}^{w-US}, P_{OL}^{w-US}), \tag{6}$$

$$S_{CL}^{CA} = S_{CL}^{CA}\left(P_{CL}^{f-US}; \theta^{CA}\right), \tag{7}$$

$$S_{CL}^{AZ} = S_{CL}^{AZ}\left(\, P_{CL}^{f-US}; \theta^{AZ}\right), \tag{8}$$

$$S_{OL}^{US} = S_{OL}^{US}\left(P_{OL}^{f-US}\right), \tag{9}$$

$$S_{CL}^{MX} = S_{CL}^{MX}\left(\, P_{CL}^{f-MX}; \theta^{MX}\right) \tag{10}$$

$$P_{CL}^{r-US} = P_{CL}^{r-US}(P_{CL}^{w-US}; \gamma^{r}), \tag{11}$$

$$P_{OL}^{r-US} = P_{OL}^{r-US}(P_{OL}^{w-US}), \tag{12}$$

$$P_{FSL}^{r-US} = P_{FSL}^{r-US}(P_{FSL}^{w-US}), \tag{13}$$

$$P_{CL}^{r-MX} = P_{CL}^{r-MX}(P_{CL}^{w-MX}), \tag{14}$$

$$P_{CL}^{w-US} = P_{CL}^{w-US}(P_{CL}^{f-US}; \gamma^{w}), \tag{15}$$

$$P_{OL}^{w-US} = P_{OL}^{w-US}(P_{OL}^{f-US}), \tag{16}$$

(17) $$P_{FSL}^{w-US} = P_{FSL}^{w-US}(P_{CL}^{f-US}),$$

(18) $$P_{CL}^{w-MX} = P_{CL}^{w-MX}(P_{CL}^{f-MX}),$$

(19) $$P_{CL}^{w-US} = P_{CL}^{w-US}(P_{CL}^{w-MX}),$$

(20) $$D_{CL}^{US} + D_{FSL}^{US} + D_{CL}^{MX} + D_{CL}^{X} = S_{CL}^{CA} + S_{CL}^{AZ} + S_{CL}^{MX},$$

(21) $$D_{OL}^{US} + D_{OL}^{X} = S_{OL}^{US}.$$

Superscript *r* refers to retail, *f* to farm, *w* to wholesale, *US* to United States, *CA* to California, *AZ* to Arizona, *MX* to Mexico, and *X* to export. Subscript *CL* refers to conventional lettuce, *OL* to organic lettuce, and *FSL* to food service lettuce. Equations (1) and (2) represent US demand for conventional and organic lettuce, respectively, as functions of the prices of conventional and organic lettuce at retail in the United States. Equation (3) represents US demand for lettuce at food service locations (e.g., restaurants) as a function of the price of lettuce. We do not actually observe lettuce prices sold by food service operators, as lettuce represents only a small fraction of a composite product sold to consumers—instead the price is estimated based on intermediary and food service margin. Equation (4) is Mexico demand for lettuce as a function of the price of conventional lettuce at retail in Mexico. Equations (5) and (6) represent export demand for conventional and organic lettuce, respectively, as functions of the prices of conventional and organic lettuce at wholesale in the United States

Equation (7) is the supply of conventional lettuce from California as a function of the farm price of conventional lettuce and a cost shift parameter, θ^{CA}; equation (8) is the supply of conventional lettuce from Arizona and technology shift parameter θ^{AZ}. The cost shift parameter θ^{CA} represents a negative supply shock from restricting the use of pesticides in California, and the technology shift parameter θ^{AZ} represents the positive technological shift from using a newly registered pesticide. Similarly, a positive technological shift, θ^{MX}, enters the supply function of conventional lettuce in Mexico in equation (10). Equation (9) is the total supply of organic lettuce, which may be grown in either Arizona or California. Equation (10) is the supply of Mexican lettuce as a function of the farm price of conventional lettuce in Mexico.

Equations (11) – (14) describe the relationships between retail and wholesale prices for conventional, organic, and food service lettuce. US conventional lettuce is subject to a cost shift parameter, γ^{r}, to allow for additional sorting costs at retail to differentiate lettuce grown according to California standards from other conventional lettuce.

Equations (15) – (18) describe the relationships between wholesale and farm prices for conventional, organic, and food service lettuce. Once again, US conventional lettuce is subject to a cost shift parameter, γ^{w}, to allow for additional packaging and labeling costs for lettuce that is compliant with California pesticide restrictions.

Equations (19) – (21) are the market clearing conditions necessary to derive a solution in equilibrium. Equation (19) defines relationship between wholesale prices of conventional lettuce in the United States and Mexico. Equation (20) states that US demand for conventional lettuce at retail and food service plus Mexico and import demand for conventional lettuce is equal to the supply of conventional lettuce from California, Arizona, and Mexico. And equation (21) equates domestic and export demand for organic lettuce to US organic lettuce supply.

We take the total derivatives of our structural model, expressing them in log-differential form, to obtain a solvable system of equations:

(1') $$dlnD_{CL}^{US} = \eta_{CL}^{US} dlnP_{CL}^{r-US} + \eta_{CL,OL}^{US} dlnP_{OL}^{r-US},$$

(2') $$dlnD_{OL}^{US} = \eta_{OL,CL}^{US} dlnP_{CL}^{r-US} + \eta_{OL}^{US} dlnP_{OL}^{r-US},$$

(3') $$dlnD_{FSL}^{US} = \eta_{FSL}^{US} dlnP_{FSL}^{r-US},$$

(4') $$dlnD_{CL}^{MX} = \eta_{CL}^{MX} dlnP_{CL}^{r-MX},$$

(5') $$dlnD_{CL}^{X} = \eta_{CL}^{X} dlnP_{CL}^{w-US} + \eta_{CL,OL}^{X} dlnP_{OL}^{w-US},$$

(6') $$dlnD_{OL}^{X} = \eta_{OL,CL}^{X} dlnP_{CL}^{w-US} + \eta_{OL}^{X} dlnP_{OL}^{w-US},$$

(7') $$dlnS_{CL}^{CA} = \epsilon_{CL}^{US}\left(dlnP_{CL}^{f-US} - \theta^{CA}\right),$$

(8') $$dlnS_{CL}^{AZ} = \epsilon_{CL}^{US}(dlnP_{CL}^{f-US} - \theta^{AZ}),$$

(9') $$dlnS_{OL}^{US} = \epsilon_{OL}^{US} dlnP_{OL}^{f-US},$$

(10') $$dlnS_{CL}^{MX} = \epsilon_{CL}^{MX}(dlnP_{CL}^{f-MX} - \theta^{MX}),$$

(11') $$dlnP_{CL}^{r-US} = \tau_{CL}^{r-US} dlnP_{CL}^{w-US} + \gamma^{r},$$

(12') $$dlnP_{OL}^{r-US} = \tau_{OL}^{r-US} dlnP_{OL}^{w-US},$$

(13') $$dlnP_{FSL}^{r-US} = \tau_{FSL}^{r-US} dlnP_{FSL}^{w-US},$$

(14') $$dlnP_{CL}^{r-MX} = \tau_{CL}^{r-MX} dlnP_{CL}^{w-MX},$$

(15') $$dlnP_{CL}^{w-US} = \tau_{CL}^{w-US} dlnP_{CL}^{f-US} + \gamma^{w},$$

(16') $$dlnP_{OL}^{w-US} = \tau_{OL}^{w-US} dlnP_{OL}^{f-US},$$

(17') $$dlnP_{FSL}^{w-US} = \tau_{FSL}^{w-US} dlnP_{CL}^{f-US},$$

(18') $$dlnP_{CL}^{w-MX} = \tau_{CL}^{w-MX} dlnP_{CL}^{f-MX},$$

(19') $$dlnP_{CL}^{w-MX} = dlnP_{CL}^{w-US},$$

(20') $$\omega_{CL}^{US} dlnD_{CL}^{US} + \omega_{FSL}^{US} dlnD_{FSL}^{US} + \omega_{CL}^{MX} dlnD_{CL}^{MX} + \omega_{CL}^{X} dlnD_{CL}^{X} = \delta_{CL}^{US}(\delta_{CL}^{CA} lnS_{CL}^{CA} +$$

$$(1 - \delta_{CL}^{CA}) dlnS_{CL}^{AZ}) + (1 - \delta_{CL}^{US}) dlnS_{CL}^{MX},$$

(21') $$\omega_{OL}^{US} dlnD_{OL}^{US} + (1 - \omega_{OL}^{US}) dlnD_{OL}^{X} = dlnS_{OL}^{US}.$$

Equations (1') – (21') correspond to equations (1) – (21), expressed in log-differential form. Equations (1') – (3') are the percentage changes in demand for conventional, organic, and food service lettuce in the United States; equation (4') is the percentage change in demand for conventional lettuce in Mexico; and equations (5') – (6') are the percentage changes in export demand for conventional and organic lettuce. The parameters η_{CL}^{US}, $\eta_{CL,OL}^{US}$, $\eta_{OL,CL}^{US}$, η_{OL}^{US}, η_{FSL}^{US}, η_{CL}^{X}, $\eta_{CL,OL}^{X}$, $\eta_{OL,CL}^{X}$, η_{OL}^{X}, and η_{CL}^{MX} are the own- and cross-price elasticities of demand for each type of lettuce in the United States, Mexico, and Canada. We assume there is no substitution between lettuce at food service operations with lettuce at retail.

Assuming homothetic separability, we can represent the own- and cross-price elasticities for conventional and organic lettuce in equations (1'), (2'), (5'), and (6') as functions of their expenditure shares, the own-price elasticity of demand for lettuce, and the elasticity of substitution between the two lettuce types (Edgerton, 1997):

$$\eta_{CL} = \omega_{CL}\eta - (1 - \omega_{CL})\sigma, \tag{22}$$

$$\eta_{OL} = (1 - \omega_{CL})\eta - \omega_{CL}\sigma, \tag{23}$$

$$\eta_{CL,OL} = (1 - \omega_{CL})(\eta + \sigma), \tag{24}$$

$$\eta_{OL,CL} = \omega_{CL}(\eta + \sigma). \tag{25}$$

Here, η is the own-price elasticity of demand for lettuce, and σ is the elasticity of substitution between conventional and organic lettuce.

In equation (3'), the own-price elasticity of demand for lettuce at food service operations, η_{FSL}, is a function of the cost share of lettuce in food service meals, μ_l, and the own-price elasticity of demand for food service meals, η_{meal}.

$$\eta_{FSL} = \mu_l \eta_{meal} \tag{26}$$

Equations (7') – (9') represent the percentage changes in supply of conventional lettuce from California, Arizona, Mexico, and the percentage change in supply of US organic lettuce. Elasticities of supply are represented by ϵ_{CL}^{US}, ϵ_{OL}^{US}, and ϵ_{CL}^{MX}.

Equations (11') – (14') represent the relationships between the percentage changes of wholesale and retail prices of lettuce. The parameters τ_{CL}^{r-US}, τ_{OL}^{r-US}, τ_{FSL}^{r-US}, and τ_{CL}^{r-MX} are wholesale-to-retail price transmission elasticities. Likewise, equations (15') – (18') are the relationships between the percentage changes of farm and wholesale prices of lettuce, with τ_{CL}^{w-US}, τ_{OL}^{w-US}, τ_{FSL}^{w-US}, and τ_{CL}^{w-MX} serving as farm-to-wholesale price transmission elasticities.

Equations (19') – (21') represent the log-differential versions of the market clearing conditions necessary to determine the equilibrium solutions. Equation (19') maintains the law of one price, by equating the percentage change in US conventional lettuce at wholesale to the percentage change in Mexico conventional lettuce at wholesale. In equation (20'), percentage changes in supply and demand are weighted by their respective shares in total supply and demand. The parameter ω_{CL}^{US} is the share of US demand for conventional lettuce at retail in total Mexico and US conventional lettuce demand, ω_{FSL}^{US} is the share of US demand for conventional lettuce at food service operations, ω_{CL}^{MX} is the share of Mexico demand for conventional lettuce, and ω_{CL}^{X} is the share of export demand for conventional lettuce. The parameter δ_{CL}^{US} is the share of US supply of conventional lettuce in the total supply of US and Mexico conventional lettuce, and δ_{CL}^{CA} is the share of California supply of conventional lettuce in the total supply of US conventional lettuce. Equation (21') is the market clearing condition for the quantity of organic lettuce, and states that the percentage change in demand is equal to the percentage change in supply; here ω_{OL}^{US} is the share of US demand for organic lettuce.

We use Monte Carlo simulations for the purpose of sensitivity analyses. Supply, demand, and price transmission elasticities are drawn randomly from normal distributions. We repeat the process of randomly drawing these parameter values and calculating model solutions 10,000 times to obtain a distribution of results. We provide the values, definitions, and sources for all parameters used in the model in Table 1. Parameters are calibrated based on data for US and Mexico lettuce markets in 2022. The model parameters are described in detail in the appendix.

Table 1. Model Parameters, Definitions, and Values

Symbol	Description	Value
D_{CL}^{US}	US demand for conventional lettuce at retail, 2022, cwt	29,702,693[a,b]
D_{OL}^{US}	US demand for organic lettuce, 2022, cwt	3,203,995[a]
D_{FSL}^{US}	US demand for conventional lettuce at food service operations, 2022, cwt	55,162,144[a,b]
D_{CL}^{MX}	Mexico demand for conventional lettuce, 2022, cwt	2,574,121[b]
D_{CL}^{X}	Rest of world export demand for conventional lettuce, 2022, cwt	3,892,313[c]
D_{OL}^{X}	Export demand for organic lettuce, 2022, cwt	599,159[c]
S_{CL}^{CA}	California supply of conventional lettuce, 2022, cwt	62,734,000[a]
S_{CL}^{AZ}	Arizona supply of conventional lettuce, 2022 cwt	17,612,500[a]
S_{CL}^{MX}	Mexico supply of conventional lettuce, 2022, cwt	10,984,771[b]
S_{OL}^{US}	US supply of organic lettuce, 2022, cwt	3,803,154[a]
P_{CL}^{f-US}	US farm price of conventional lettuce, 2022, \$/cwt	49.45[a]
P_{OL}^{f-US}	US farm price of organic lettuce, 2022, \$/cwt	75.82[a]
P_{CL}^{f-MX}	Mexico farm price of conventional lettuce, 2022, \$/cwt	11.65[b]
P_{CL}^{w-US}	US wholesale price of conventional lettuce, \$/cwt	98.91[a]
P_{OL}^{w-US}	US wholesale price of organic lettuce, \$/cwt	166.80[a]
P_{FSL}^{w-US}	US wholesale price of conventional lettuce to food service operations, \$/cwt	93.96[a]
P_{CL}^{w-MX}	Mexico wholesale price of conventional lettuce, \$/cwt	17.48[b]
P_{CL}^{r-US}	US retail price of conventional lettuce, \$/cwt	168.14[a,d]
P_{OL}^{r-US}	US retail price of organic lettuce, \$/cwt	316.93[a]
P_{FSL}^{r-US}	US price of conventional lettuce at food service operations, \$/cwt	281.89[a]
P_{CL}^{r-MX}	Mexico retail price of conventional lettuce, \$/cwt	22.72[b]
τ_{CL}^{w-US}	US farm-to-wholesale price transmission elasticity for conventional lettuce	N(0.55,0.05)[e]
τ_{OL}^{w-US}	US farm-to-wholesale price transmission elasticity for organic lettuce	N(0.60,0.05)[e]
τ_{FSL}^{w-US}	US farm-to-wholesale price transmission elasticity for food service lettuce	N(0.58,0.05)[e]
τ_{CL}^{w-MX}	Mexico farm-to-wholesale price transmission elasticity for conventional lettuce	N(0.50,0.05)[e]
τ_{CL}^{r-US}	US wholesale-to-retail price transmission elasticity for conventional lettuce	N(0.80,0.05)[d,e]
τ_{OL}^{r-US}	US wholesale-to-retail price transmission elasticity for organic lettuce	N(0.90,0.05)[e]
τ_{FSL}^{r-US}	US wholesale-to-retail price transmission elasticity for food service lettuce	N(0.85,0.05)[e]
τ_{CL}^{r-MX}	Mexico wholesale-to-retail price transmission elasticity for conventional lettuce	N(0.75,0.05)[e]
μ_l	Cost share of lettuce in food service meals	0.02[e]

(Continued on next page…)

Table 1. Continued from previous page…

Symbol	Description	Value
ω_{CL}^{US}	Share of US conventional lettuce demand at retail in total conventional lettuce demand	0.33[a,b]
ω_{FSL}^{US}	Share of US conventional lettuce demand at food service operations in total conventional lettuce demand	0.60[a,b]
ω_{CL}^{MX}	Share of Mexico conventional lettuce demand in total conventional lettuce demand	0.03[a,b]
ω_{CL}^{X}	Share of export conventional lettuce demand in total conventional lettuce demand	0.04%[c]
ω_{OL}^{US}	Share of US organic lettuce demand in total organic lettuce demand	0.84[a,c]
ω^{US}	Share of conventional lettuce in total US retail lettuce demand	0.90[a,b]
ω^{X}	Share of conventional lettuce in total export lettuce demand	0.90[a,b]
δ_{CL}^{US}	Share of US conventional lettuce in US and Mexico conventional lettuce supply	0.88[a,b]
δ_{CL}^{CA}	Share of California conventional lettuce in US lettuce supply	0.78[a,b]
θ^{CA}	Percentage change in cost of conventional lettuce production in California caused by policy change	12.25[e]
θ^{AZ}	Percentage change in cost of conventional lettuce production in Arizona caused by use of newly registered pesticide	5.00[f]
θ^{MX}	Percentage change in cost of conventional lettuce production in Mexico caused by use of newly registered pesticide	5.00[f]
γ^{w}	Percent change in wholesale price of conventional lettuce caused by additional packaging and labelling	0.10[f]
γ^{r}	Percent change in retail price of conventional lettuce caused by additional sorting	0.10[f]
σ	Elasticity of substitution between conventional and organic lettuce	1.90[g]
η	Own-price elasticity of demand for lettuce	–0.77 [h]
η_{CL}^{US}	US own-price elasticity of demand for conventional lettuce	–0.88[i]
η_{OL}^{US}	US own-price elasticity of demand for organic lettuce	–1.79[i]
$\eta_{CL,OL}^{US}$	US cross-price elasticity of demand for conventional lettuce with respect to the price of organic lettuce	0.11[i]
$\eta_{OL,CL}^{US}$	US cross-price elasticity of demand for organic lettuce with respect to the price of conventional lettuce	1.02[i]
η_{CL}^{MX}	Mexico own-price elasticity of demand for conventional lettuce	–1.30 [j]
η_{CL}^{X}	Own-price elasticity of export demand for conventional lettuce	–1.12[i]
η_{OL}^{X}	Own-price elasticity of export demand for organic lettuce	–1.81[i]
$\eta_{CL,OL}^{X}$	Cross-price elasticity of export demand for conventional lettuce with respect to the price of organic lettuce	0.09[i]
$\eta_{OL,CL}^{X}$	Cross-price elasticity of export demand for organic lettuce with respect to the price of conventional lettuce	0.78[i]
η_{meal}	Own-price elasticity of demand for meals at food service operations	–1.00 [h]

(Continued on next page…)

Table 1. Continued from previous page…

Symbol	Description	Value
η_{FSL}	Own-price elasticity of demand for lettuce at food service operations	–0.02 [e]
ϵ_{CL}^{US}	US elasticity of supply of conventional lettuce: long-run, short-run	N(1.40,0.35), N(0.70,0.15) [k]
ϵ_{OL}^{US}	Elasticity of supply of organic lettuce: long-run, short-run	N(1.60,0.40), N(0.80,0.20) [k]
ϵ_{CL}^{MX}	Mexico elasticity of supply of conventional lettuce: long-run, short-run	N(2.00,0.50), N(1.00,0.25) [k]

[a] NASS, 2024.
[b] FAO, 2024.
[c] FAS, 2024.
[d] BLS, 2023.
[e] Authors' estimate based on correspondence with growers and large packer-shippers.
[f] Simulated effect.
[g] Xu et al., 2015.
[h] Okrent and Alston, 2011.
[i] Authors' calculation based on Edgerton (1997).
[j] Authors' estimate based on the US own-price elasticity of demand for lettuce of –0.77 from Okrent Alston (2011) and Mhurchu et al. (2013) who estimates the own-price elasticity of demand for vegetables for low-income groups to be 1.7 higher than high-income groups.
[k] Authors' estimates allowing for uncertainty, based on supply elasticities for lettuce from Liu and Yue (2013).

Results

We use the models and parameters described in the previous section to simulate the effects of pesticide restrictions and delays throughout the lettuce supply chain in two separate scenarios. First, we consider the effects of restricting the use of pyrethroids and neonicotinoids on conventional lettuce produced in California. These are two "priority" pesticides designated by the SPM to be eliminated for use in California. The results from this simulation are changes in the long-run equilibrium until a substitute pesticide is available for use in the state, and the welfare effects can be interpreted as average annual changes over this time horizon. Second, we estimate the effects of delayed pesticide adoption in California. Here we allow Arizona and Mexico to utilize a new pesticide product that lowers average costs (this could be achieved either by increasing yield or reducing total factor inputs). Because the DPR chemical registration process in California delays pesticide adoption by roughly 1–3 years, the simulation results are short-run equilibrium market changes. For both scenarios, we briefly describe potential R&D implications.

Restricting pesticide use in California

Table 2 shows the simulation results for 12.25% cost shift for conventional lettuce production in California. Results are shown in terms of average percentages changes in quantities and prices, with standard deviations provided in parentheses. The average change in supply of California lettuce is relatively large (–7.32%) with production shifting primarily to Arizona (9.82%) and Mexico (15.48%), and to lesser extent organic production (1.95%). The overall changes in demand for lettuce are relatively small compared to the production shifts, with US demand for conventional lettuce decreasing by 2.88%, US demand for organic lettuce increasing by 1.95%, and US demand for food service lettuce decreasing by 0.07% on average. Lettuce prices increase throughout the US supply chain; conventional lettuce prices increase by 6.89% at the farm, 3.88%

Table 2. Equilibrium Changes from a Policy Restricting Pesticide Use

Variable	**Symbol**	**Change (%)**
US quantity demanded of conventional lettuce	$dlnD_{CL}^{US}$	–2.88
		(0.35)
US quantity demanded of organic lettuce	$dlnD_{OL}^{US}$	1.95
		(0.32)
US quantity demanded of food service lettuce	$dlnD_{FSL}^{US}$	–0.07
		(0.01)
Mexico quantity demanded of conventional lettuce	$dlnD_{CL}^{MX}$	–3.79
		(0.49)
Export quantity demanded of conventional lettuce	$dlnD_{CL}^{X}$	–4.35
		(0.49)
Export quantity demanded of organic lettuce	$dlnD_{OL}^{X}$	1.62
		(0.31)
Quantity supplied of CA conventional lettuce	$dlnS_{CL}^{CA}$	–7.32
		(1.31)
Quantity supplied of AZ conventional lettuce	$dlnS_{CL}^{AZ}$	9.82
		(3.11)
Quantity supplied of organic lettuce	$dlnS_{OL}^{US}$	1.90
		(0.31)
Quantity supplied of Mexico lettuce	$dlnS_{CL}^{MX}$	15.48
		(3.96)
Retail price of conventional lettuce	$dlnP_{CL}^{r-US}$	3.21
		(0.39)
Retail price of organic lettuce	$dlnP_{OL}^{r-US}$	0.66
		(0.15)
Retail price of food service lettuce	$dlnP_{FSL}^{r-US}$	3.40
		(0.48)
Retail price of Mexico lettuce	$dlnP_{CL}^{r-MX}$	2.91
		(0.38)
Wholesale price of conventional lettuce	$dlnP_{CL}^{w-US}$	3.88
		(0.44)
Wholesale price of organic lettuce	$dlnP_{OL}^{w-US}$	0.74
		(0.16)
Wholesale price of food service lettuce	$dlnP_{FSL}^{w-US}$	4.00
		(0.52)
Wholesale price of Mexico lettuce	$dlnP_{CL}^{w-MX}$	3.88
		(0.44)
Farm price of conventional lettuce	$dlnP_{CL}^{f-US}$	6.89
		(0.66)
Farm price of organic lettuce	$dlnP_{OL}^{f-US}$	1.24
		(0.27)
Farm price of Mexico lettuce	$dlnP_{CL}^{f-MX}$	7.82
		(1.10)

Notes: Numbers in parentheses denote standard deviations. Refer to Table 1 for variable definitions. Outcomes from EDM simulations are in log-differential form, as indicated by the prefix $\boldsymbol{dln}$

Table 3. Welfare Effects and Wholesale Changes from a Policy Restricting Pesticide Use

Variable	**Calculation**	**Change ($1,000,000)**
Consumer surplus, US	$-D_{CL}^{US}P_{CL}^{r-US}dlnP_{CL}^{r-US}(1+0.5dlnD_{CL}^{US})$ $-D_{OL}^{US}P_{OL}^{r-US}dlnP_{OL}^{r-US}(1+0.5dlnD_{OL}^{US})$ $-D_{FSL}^{US}P_{FSL}^{r-US}dlnP_{FSL}^{r-US}(1+0.5dlnD_{FSL}^{US})$	–694.28 (84.00)
Consumer surplus, Mexico	$-D_{CL}^{MX}P_{CL}^{r-MX}dlnP_{CL}^{r-MX}(1+0.5dlnD_{CL}^{MX})$	–1.67 (0.21)
Producer surplus, conventional lettuce, CA	$S_{CL}^{CA}P_{CL}^{f-US}\left(dlnP_{CL}^{f-US}-\theta^{CA}\right)(1+0.5dlnS_{CL}^{CA})$	–160.33 (20.41)
Producer surplus, conventional lettuce, AZ	$S_{CL}^{AZ}P_{CL}^{f-US}dlnP_{CL}^{f-US}(1+0.5dlnS_{CL}^{AZ})$	63.03 (6.79)
Producer surplus, organic	$S_{OL}^{US}P_{OL}^{f-US}dlnP_{OL}^{f-US}(1+0.5dlnS_{OL}^{US})$	3.60 (0.77)
Producer surplus, conventional lettuce, Mexico	$S_{CL}^{MX}P_{CL}^{f-MX}dlnP_{CL}^{f-MX}(1+0.5dlnS_{CL}^{MX})$	10.80 (1.58)
US wholesale revenue	$P_{CL}^{w-US}(1+dlnP_{CL}^{w-US})$ $*\,(D_{CL}^{US}(1+dlnD_{CL}^{US})\ -S_{CL}^{MX}(1+dlnS_{CL}^{MX})$ $+D_{CL}^{MX}(1+dlnD_{CL}^{MX})$ $+D_{CL}^{X}(1+dlnD_{CL}^{X})\ )$ $+P_{FSL}^{w-US}(1+dlnP_{FSL}^{w-US})D_{FSL}^{US}(1+dlnD_{FSL}^{US})$ $+P_{OL}^{w-US}(1+dlnP_{OL}^{w-US})D_{OL}^{US}(1+dlnD_{OL}^{US})$ $-P_{CL}^{w-US}(D_{CL}^{US}-S_{CL}^{MX}+D_{CL}^{MX}+D_{CL}^{X})$ $-P_{FSL}^{w-US}D_{FSL}^{US}$ $-P_{OL}^{w-US}D_{OL}^{US}$	32.16 (55.61)
US wholesale cost of lettuce	$P_{CL}^{f-US}\left(1+dlnP_{CL}^{f-US}+\gamma^{w}\right)S_{CL}^{CA}(1+dlnS_{CL}^{CA})$ $+P_{CL}^{f-US}\left(1+dlnP_{CL}^{f-US}\right)S_{CL}^{AZ}(1+dlnS_{CL}^{AZ})$ $+P_{OL}^{f-US}\left(1+dlnP_{OL}^{f-US}\right)S_{OL}^{US}(1+dlnS_{OL}^{US})$ $-P_{CL}^{f-US}(S_{CL}^{CA}+S_{CL}^{AZ})$ $-P_{OL}^{f-US}D_{OL}^{US}$	137.73 (35.91)
US wholesale profit	US wholesale revenue – US wholesale cost of lettuce	–105.57 (27.55)

Notes: Numbers in parentheses denote standard deviations. Refer to Table 1 for initial endogenous variable values and parameter and variable definitions. Outcomes from EDM simulations are in log-differential form, as indicated by the prefix $\boldsymbol{dln}$.

at wholesale, and 3.21% at retail on average. The price increases for domestic lettuce cause export demand for US lettuce to decrease and import demand for lettuce from Mexico to increase. This in turn causes the price of lettuce to increase in Mexico by 7.82% at the farm and 2.91% at retail on average. The price changes for organic lettuce are relatively small.

The welfare implications, in millions of dollars, of restricting pesticide use in California are provided in Table 3; standard deviations are in parentheses below the average changes. Average welfare effects followed by standard deviations are presented in this paragraph in parentheses in millions of dollars. The most substantial welfare effect is the decrease in US consumer surplus

Table 4. Equilibrium Changes from Delayed Pesticide Adoption

Variable	Symbol	Change (%)
US quantity demanded of conventional lettuce	$dlnD_{CL}^{US}$	0.54 (0.07)
US quantity demanded of organic lettuce	$dlnD_{OL}^{US}$	–0.27 (0.05)
US quantity demanded of food service lettuce	$dlnD_{FSL}^{US}$	0.01 (0.00)
Mexico quantity demanded of conventional lettuce	$dlnD_{CL}^{MX}$	0.74 (0.10)
Export quantity demanded of conventional lettuce	$dlnD_{CL}^{X}$	0.85 (0.09)
Export quantity demanded of organic lettuce	$dlnD_{OL}^{X}$	–0.21 (0.06)
Quantity supplied of CA conventional lettuce	$dlnS_{CL}^{CA}$	–0.96 (0.20)
Quantity supplied of AZ conventional lettuce	$dlnS_{CL}^{AZ}$	2.53 (0.58)
Quantity supplied of organic lettuce	$dlnS_{OL}^{US}$	–0.26 (0.05)
Quantity supplied of Mexico lettuce	$dlnS_{CL}^{MX}$	3.44 (0.76)
Retail price of conventional lettuce	$dlnP_{CL}^{r-US}$	–0.61 (0.08)
Retail price of organic lettuce	$dlnP_{OL}^{r-US}$	–0.18 (0.03)
Retail price of food service lettuce	$dlnP_{FSL}^{r-US}$	–0.69 (0.10)
Retail price of Mexico lettuce	$dlnP_{CL}^{r-MX}$	–0.57 (0.07)
Wholesale price of conventional lettuce	$dlnP_{CL}^{w-US}$	–0.76 (0.08)
Wholesale price of organic lettuce	$dlnP_{OL}^{w-US}$	–0.20 (0.04)
Wholesale price of food service lettuce	$dlnP_{FSL}^{w-US}$	–0.81 (0.10)
Wholesale price of Mexico lettuce	$dlnP_{CL}^{w-MX}$	–0.76 (0.08)
Farm price of conventional lettuce	$dlnP_{CL}^{f-US}$	–1.39 (0.14)
Farm price of organic lettuce	$dlnP_{OL}^{f-US}$	–0.34 (0.06)
Farm price of Mexico lettuce	$dlnP_{CL}^{f-MX}$	–1.54 (0.22)

Notes: Numbers in parentheses denote standard deviations. Refer to Table 1 for variable definitions. Outcomes from EDM simulations are in log-differential form, as indicated by the prefix $\boldsymbol{dln}$.

(–$694.28, $84.00). On the producer side, farmers in Arizona ($63.03, $6.79) and Mexico ($10.80, $1.58) benefit from the shift in production, and to a lesser extent, organic lettuce farmers ($3.60, $0.77). The effect of the supply shock on wholesalers is quantified in terms of the change in revenue ($32.16, $55.61), cost ($137.73, $35.91), and profit (–$105.57, $27.55) from all US lettuce. Revenue increases are offset by an increase in the cost of lettuce purchased from growers, resulting in a net decrease in wholesaler profits. These welfare effects and changes in wholesaler revenues and costs are average annual effects that would persist until a comparable alternative is introduced to replace the restricted chemicals.

Delayed pesticide adoption in California

The short-run equilibrium changes in the lettuce market from delayed pesticide adoption in California are provided in Table 4. Delayed adoption of pesticides in California is simulated by decreasing production costs in Mexico and Arizona by 5%. Once again, results are presented as percentage changes in the equilibrium quantities and prices, and welfare changes are in millions of dollars. The results are interpreted as short-run effects, as the average lag in pesticide adoption in California is roughly 1–3 years.

The short-run effects of delayed adoption are considerably smaller relative to the effects of restricting pesticide use. There is slight shift in production from California to Arizona and Mexico, with average changes of –0.96%, 2.53%, and 3.44%, respectively. Farm-level prices decrease for all lettuce: conventional lettuce prices decrease by 1.39% on average, organic lettuce prices by 0.34%, and Mexico lettuce prices by 1.54%. The prices changes are smaller as lettuce moves through the supply chain, with average price decreases less than 1% at wholesale and retail.

The welfare implications of delayed pesticide adoption in California in Table 5 are smaller in comparison to the changes presented in Table 3, but still substantial. Welfare effects described in this paragraph are provided in parentheses in millions of dollars along with standard deviations. A 5% reduction in production costs from new pesticide adoption in Arizona and Mexico results in a large increase in US consumer surplus ($139.27, $16.87) and a small increase in Mexico consumer surplus ($0.34, $0.04). Growers in Arizona ($31.86, $1.24) and Mexico ($4.51, $0.27) benefit from the pesticide innovation. On the other hand, California conventional lettuce (–$42.84, $4.18) and organic lettuce growers (–$0.98, $0.18) realize a decrease in producer surplus because they are unable to adopt the new technology. Owing to the farm cost decreases and a small increase in demand for Mexico lettuce, wholesalers are expected to realize a small decrease in profits (–$14.98, $5.25).

Recent correspondence with industry representatives suggests that the delay process has lengthened in recent years. They have indicated that the typical delay is now more than 5 years instead of 1–3 years. Supply would be more elastic in this longer window—therefore, our results should be interpreted as conservative (low) estimates. If the delay were longer, then there would be a greater supply shift from California to Arizona and Mexico.

We do not formally quantify the R&D implications of restricting pesticides for use on California lettuce farms. However, a simple back-of-the-envelope calculation suggests R&D investment in response to a pesticide restriction is not economically feasible. The 2022 farmgate value of conventional lettuce in California was $3.1 billion, and pesticide restrictions would reduce this value by $152 million on average. Shifts in production to organic lettuce and farming in Arizona increase the farmgate value of lettuce by $70 million on average, implying a net domestic loss of $82 million at the farm. A survey by Agbio Investor (2024) found that the average cost of developing a new active ingredient and bringing it to market is $301 million, with an average of 12.3 years between first synthesis and first sale of the product. Assuming a 12-year delay from initial investment to reaching the market and 35 years of return after release, then annual average net return of $99 million would be needed to achieve a 10 percent return on investment (ROI). Considering this hypothetical requires returns beyond the net domestic loss from the pesticide restriction, it is highly unlikely private firms would consider R&D investment to be financially viable. Furthermore, if returns were delayed an additional 3 years and net returns remained the same, the return on investment would decrease to negative 15.0 percent. An average net return of $132 million per year would be needed for a 10 percent ROI.

Table 5. Welfare Effects and Wholesale Changes from Delayed Pesticide Adoption

Variable	Calculation	Change ($1,000,000)
Consumer surplus, US	$-D_{CL}^{US}P_{CL}^{r-US}dlnP_{CL}^{r-US} * (1+0.5dlnD_{CL}^{US})$ $-D_{OL}^{US}P_{OL}^{r-US}dlnP_{OL}^{r-US} * (1+0.5dlnD_{OL}^{US})$ $-D_{FSL}^{US}P_{FSL}^{r-US}dlnP_{FSL}^{r-US} * (1+0.5dlnD_{FSL}^{US})$	139.27 (16.87)
Consumer surplus, Mexico	$-D_{CL}^{MX}P_{CL}^{r-MX}dlnP_{CL}^{r-MX} * (1+0.5dlnD_{CL}^{MX})$	0.34 (0.04)
Producer surplus, conventional lettuce, CA	$S_{CL}^{CA}P_{CL}^{f-US}dlnP_{CL}^{f-US}(1+0.5dlnS_{CL}^{CA})$	–42.84 (4.18)
Producer surplus, conventional lettuce, AZ	$S_{CL}^{AZ}P_{CL}^{f-US}\left(dlnP_{CL}^{f-US}-\theta^{AZ}\right) * (1+0.5dlnS_{CL}^{AZ})$	31.86 (1.24)
Producer surplus, organic	$S_{OL}^{US}P_{OL}^{f-US}dlnP_{OL}^{f-US}(1+0.5dlnS_{OL}^{US})$	–0.98 (0.18)
Producer surplus, conventional lettuce, Mexico	$S_{CL}^{MX}P_{CL}^{f-MX}\left(dlnP_{CL}^{f-MX}-\theta^{MX}\right)$ $* (1+0.5dlnS_{CL}^{MX})$	4.51 (0.27)
US wholesale revenue	$P_{CL}^{w-US}(1+dlnP_{CL}^{w-US})$ $* (D_{CL}^{US}(1+dlnD_{CL}^{US}) - S_{CL}^{MX}(1+dlnS_{CL}^{MX})$ $+ D_{CL}^{MX}(1+dlnD_{CL}^{MX}) + D_{CL}^{X}(1$ $+ dlnD_{CL}^{X}))$ $+P_{FSL}^{w-US}(1+dlnP_{FSL}^{w-US})D_{FSL}^{US}(1+dlnD_{FSL}^{US})$ $+P_{OL}^{w-US}(1+dlnP_{OL}^{w-US})D_{OL}^{US}(1+dlnD_{OL}^{US})$ $-P_{CL}^{w-US}(D_{CL}^{US}-S_{CL}^{MX}+D_{CL}^{MX}+D_{CL}^{X})$ $-P_{FSL}^{w-US}D_{FSL}^{US}$ $-P_{OL}^{w-US}D_{OL}^{US}$	–80.23 (12.52)
US wholesale cost of lettuce	$P_{CL}^{f-US}\left(1+dlnP_{CL}^{f-US}\right)S_{CL}^{CA}(1+dlnS_{CL}^{CA})$ $+P_{CL}^{f-US}\left(1+dlnP_{CL}^{f-US}\right)S_{CL}^{AZ}(1+dlnS_{CL}^{AZ})$ $+P_{OL}^{f-US}(1+dlnP_{OL}^{f-US})S_{OL}^{US}(1+dlnS_{OL}^{US})$ $-P_{CL}^{f-US}(S_{CL}^{CA}+S_{CL}^{AZ})$ $-P_{OL}^{f-US}D_{OL}^{US}$	– 65.25 (8.58)
US wholesale profit	US wholesale revenue – US wholesale cost of lettuce	–14.98 (5.25)

Notes: Numbers in parentheses denote standard deviations. Refer to Table 1 for initial endogenous variable values and parameter and variable definitions. Outcomes from EDM simulations are in log-differential form, as indicated by the prefix $\boldsymbol{dln}$.

Conclusions

Motivation for restricting pesticide use is to reduce potential harm to human health and the environment from high-risk pesticides. The SPM initiative, a joint collaboration between DPR, CEPA, and CDFA, outlines an initial road map for California but it is not yet fully and clearly defined. Pyrethroids have already been identified for DPR review as high-risk pesticides, and neonicotinoids are another candidate pesticide may be targeted for phase-out of agricultural use in California. In the separate pesticide registration process, DPR aims to ensure that new products are suitable for agricultural use in California. However, this process delays pesticide adoption in California by 1–3 years relative to other states.

Shifting to organic production practices is one way growers can respond to pesticide restrictions. However, our results demonstrate that the primary effect of California’s pesticide policies is for lettuce production to shift elsewhere (i.e., Arizona and Mexico), with only minimal changes to organic production. California’s market share for conventional lettuce in the United States decreases from the baseline of 67.8% in 2022 to 63.8% in the pesticide restriction scenario and 67.0% in the delayed adoption scenario. These changes coincide with increased market shares for Arizona and Mexico, and negligible organic market share changes. Initial U.S. market shares are 19.0% for Arizona, 9.6% for Mexico, and 3.6% for organic; in the pesticide restriction scenario, shares increase to 21.2%, 11.2%, and 3.8%, respectively; in the delayed adoption scenario, shares are 19.5%, 9.9%, and 3.6%, respectively. Because most lettuce produced in Arizona and Mexico coincides with the grow cycle in Southern California and Imperial Valley, we expect decreased production to primarily occur in these regions.

Because competing lettuce growing regions have lower standards for pesticide registration and fewer anticipated future pesticide restrictions, the goal of California’s pesticide management policy is hindered. This is referred to as regulatory leakage. Results demonstrate the costs to producers and market intermediaries, and the resulting shift in market share, when pesticides are unavailable for use in California. An unintended consequence of stricter pesticide policy is agricultural production moving to less restrictive areas instead of implementing sustainable practices. This limits the potential benefits of SPM to human and environmental health.

Ideally, SPM policy changes would encourage R&D in alternative pest management solutions that are less harmful to human health and the environment. However, R&D in agriculture is generally underinvested (Alston et al., 2009). Because specialty crops are smaller-scale industries, the private and public benefits of specialty crop R&D are small compared to major commodity crops. This causes R&D investments in specialty crops to be especially low (Alston and Pardey, 2008). This is exemplified by R&D efforts for pesticides, which are mostly focused on applications to commodity crops because there needs to be high enough expected returns to encourage private investment. Restricting access to pesticides before development of a suitable alternative could cause decreased yields and higher pest management costs. Furthermore, if a pesticide is restricted for certain crops in California, but those crops can be produced in other regions that do not face such restrictions, there is less incentive for R&D investment. Considering lettuce is a specialty crop accounting for only 1.5% of total national crop cash receipts, and lettuce can be grown in Arizona and Mexico where pesticide restrictions are relatively low, SPM policy changes may not spur private R&D investments and “activating markets to drive SPM” may be difficult. Sexton, Lei, and Zilberman (2007) discuss this issue in their review of the economics of pesticides and pest control, demonstrating that the high cost of introducing and testing new chemicals is a major impediment to pesticide research. Pesticide restrictions may require government investment in R&D as private firms may not invest—this ultimately impacts farm decisions and may cause production of affected crops to leave the state.

SPM could lead to the development of new pesticides. California is home to many specialty crops that are not suitable for production in other states, and demand for safe and effective pesticides may encourage R&D. On the other hand, the chemical registration process is lengthy, and approval is uncertain. This delays registrants from bringing new products to market and discourages investment in R&D. As a result, specialty crop growers in California would have more limited pest management alternatives compared to out-of-state growers unaffected by SPM. Furthermore, chemical registrants and biotechnology firms generally focus on developing products for use on major crops. R&D focused on applications to specialty crops such as lettuce is less common—and because growers do not face similar restrictions in other regions where lettuce can be grown, SPM may not encourage private investment in R&D. Government investment may instead be needed to advance pest management technologies. Creating pesticide restrictions prior to development of alternative pest management practices would have adverse effects on California growers and cause production to shift out of state. A potential next step following this study would be to quantify and compare long-term changes to California agricultural production and pest management R&D.

Future research could also evaluate whether an announcement of a forthcoming pesticide ban, or initiation of a product safety review process, spurs additional investment in R&D for new alternative products or active ingredients prior to implementation of any ban. We expect that the ability of registrants to develop new products in anticipation of a ban, but prior to any a ban being implemented depends on: (i) how long the ban is noticed in advance, (iii) if the ban is applied to California only or all other states, (iii) how quickly new products or active ingredients can be developed, and (iv) the expected return on those alternative products or active ingredients. An empirical analysis of this research question would require data from individual registrants on new products, active ingredients, and the timing and level of investment. In general, we expect that this scenario is unlikely for a ban specific to California because, as described in this paper, the process for bringing a new product to market is typically around 12 years, plus additional time for California's review and approval process.

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Appendix: Pesticide Restrictions and Registration Delays: Implications of California's Sustainable Pest Management for the Lettuce Industry

This appendix contains detailed descriptions of the model parameters used in the EDM analysis.

Quantities and Shares

Quantities of demand for and supply of lettuce are from NASS (2024) for the United States and FAO (2024) for Mexico and trade. Conventional lettuce is aggregated to include iceberg and romaine lettuce. In 2022, California produced $S_{CL}^{CA} = 62{,}734{,}000$ hundredweight of conventional lettuce, Arizona produced $S_{CL}^{AZ} = 17{,}612{,}500$ hundredweight, and Mexico produced $S_{CL}^{MX} = 10{,}984{,}771$ hundredweight. The implied share of U.S. conventional lettuce in U.S. and Mexico supply is therefore $\delta_{CL}^{US} = 88.0\%$, and the California share of conventional lettuce in U.S. supply is $\delta_{CL}^{CA} = 78.1\%$.

Net exports from Mexico to the United States in 2022 are 8,395,267 hundredweight, implying total demand for lettuce in Mexico of $D_{CL}^{MX} = 2{,}574{,}121$ hundredweight. Export demand for U.S. conventional lettuce is $D_{CL}^{X} = 3{,}892{,}313$ hundredweight; total demand in the United States for conventional lettuce, between lettuce at retail and lettuce at food service operations, is therefore 84,864,837 hundredweight. Based on personal correspondences with lettuce wholesalers in California, food service operators account for roughly 65% of lettuce demand in the United States, and retail 35%, therefore $D_{FSL}^{US} = 55{,}162{,}144$ and $D_{CL}^{US} = 29{,}702{,}693$ (assuming for simplicity that imports go to retail). The implied share of U.S. demand for conventional lettuce in total U.S. and Mexico demand is $\omega_{CL}^{US} = 32.5\%$, the share of U.S. demand for food service lettuce is $\omega_{FSL}^{US} = 60.4\%$, Mexico's share of demand is $\omega_{CL}^{MX} = 2.8\%$, and export demand share is $\omega_{CL}^{X} = 4.3\%$.

Total U.S. production of organic lettuce in 2022 is $S_{OL}^{US} = 3{,}803{,}154$ hundredweight. Export demand for organic lettuce is $D_{OL}^{X} = 599{,}159$ hundredweight. Therefore, domestic demand for organic lettuce is D_{OL}^{US} = 3,203,995, and the share of domestic demand for organic lettuce is $\omega_{OL}^{US} = 84.2\%$.

Prices and Supply Chain Markups

Farm-level prices of lettuce are available from NASS (2024) for the United States and FAO (2024) for Mexico. In 2022, the average price of conventional lettuce U.S. farmers receive is $P_{CL}^{f-US} = \$49.45$ per hundredweight (weighted average of iceberg and romaine lettuce), and the average price of organic lettuce is $P_{OL}^{f-US} = \$75.82$ per hundredweight. The average price paid to farmers for lettuce in Mexico is $P_{CL}^{f-MX} = \$11.65$ per hundredweight.

As discussed before, for the purpose of simplicity, we condensed the packer-shipper stages of the supply chain to a single wholesale stage. The wholesaler intermediary processes, packages, and distributes lettuce to retailers and food service operators, capturing rents along the way. Packaging type, costs, and markups differ depending on whether the lettuce is to be distributed to retailers or food service operators. Our estimates of markups and price transmission are based on confidential cost and price data provided by a large packer-shipper. Costs are detailed by inputs to production, package type, freight rate by destination, and market space (i.e. food service or retail); information on product shrinkage, markups, and market space shares are also provided. Lettuce processing is dominated by a few large firms, and technology is mostly standardized across processors, therefore we are confident that these cost data are representative of the industry.

Markups are generally multiplicative, with farm-to-wholesale markups for U.S. conventional lettuce of 2.0, organic lettuce of 2.2, and food service lettuce of 1.9. The implied wholesale prices from these markups are $P_{CL}^{w-US} = \$98.91$ for U.S. conventional lettuce, $P_{OL}^{w-US} = \$166.80$ for organic lettuce, and $P_{FSL}^{w-US} = \$93.96$ for food service lettuce per hundredweight.

The price transmission elasticities are allowed to vary in simulations according to a normal distribution. The distributions of farm-to-wholesale price transmission are τ_{CL}^{w-US} ~ N(0.55, 0.05), τ_{OL}^{w-US} ~ N(0.60, 0.05), and τ_{FSL}^{w-US} ~ N(0.58, 0.05). In lieu of incorporating a quantity transmission elasticity as well, spoilage costs are reflected in the price transmission elasticity. We do not have intermediary data for lettuce at wholesale in Mexico, but produce markups and price transmission are generally lower compared to U.S. produce. We use a markup of 1.5 for Mexico conventional lettuce, implying a wholesale price of $P_{CL}^{w-MX} =$ \$17.48 per hundredweight, and the farm-to-wholesale price transmission is τ_{CL}^{w-MX}~ N(0.50, 0.05).

Retail prices of lettuce are available from the Bureau of Labor Statistics (BLS, 2023). Average retail prices of iceberg lettuce in 2019 were \$118.40 per hundredweight, and farm prices were \$33.98 (NASS, 2024), implying a farm-to-retail markup of 3.3. Based on the farm-to-wholesale markup of 2.0, the implied wholesale-to-retail markup for U.S. conventional lettuce is 1.7, and the price of 2021 U.S. conventional lettuce is $P_{CL}^{r-US} =$ \$168.14 per hundredweight. Annual changes in farm and retails prices imply a median price transmission from farm-to-retail of 0.44; the implied wholesale-to-retail price transmission elasticity is therefore τ_{CL}^{r-US} ~ N(0.80, 0.05). Wholesale-to-retail margins for organic lettuce are expected to be slightly higher for organic lettuce, and a markup of 1.9 implies a retail price of $P_{OL}^{r-US} =$ \$316.93 per hundredweight; wholesale-to-retail price transmission elasticity is τ_{OL}^{w-US} ~ N(0.90, 0.05). Based on other studies that examine restaurant markups, we have determined that a wholesale-to-food service markup of 3.0 is appropriate. The implied price of lettuce at food service operations is therefore $P_{FSL}^{r-US} =$ \$281.89 per hundredweight and wholesale-to-retail price transmission elasticity is τ_{FSL}^{r-US} ~ N(0.85, 0.05). We expect margins to be slimmer in Mexico and set the retail markup to 1.3, giving a retail price of $P_{CL}^{r-MX} =$ \$22.72; price transmission is also expected to be lower, and the elasticity is set to τ_{CL}^{r-MX} ~ N(0.75, 0.05).

Supply Shifts and Cost Increases

In our first scenario, we simulate the effects of prohibiting specific chemicals for use on California crops. Implementing state policies to ban specific pesticides would increase growing costs as farmers resort to alternative crop protection materials. Crop yield, varying by region, would also drop. Focusing specifically on restrictions on the use of pyrethroids and neonicotinoids, products recommended by California's IPM for lettuce crops, we estimate farmers' production costs would increase by $\theta^{CA} = 12.25\%$. This estimate is based on anonymized input prices and yield data provided by California iceberg lettuce growers, including application rates, costs, and expected yields when applying pyrethroids and neonicotinoids compared to next best alternative pesticide management options. Furthermore, California produce would be subject to additional labelling and sorting costs to signify compliance with California pesticide regulations. In general, these costs are expected to be small. We set the cost shift for wholesale conventional lettuce caused by additional packaging and labelling to $\gamma^{w} = 0.1\%$. We assume the retail cost shift for conventional lettuce caused by additional sorting is $\gamma^{r} = 0.1\%$.

In our second scenario, we examine the effect of delayed pesticide adoption in California owing to the lengthier timeline of pesticide registration in the state. We simulate this effect by introducing positive supply shocks for Arizona and Mexico lettuce producers. These supply changes are hypothetical, but we demonstrate how a $\theta^{AZ} = \theta^{MX} = 5\%$ reduction in grower costs in Arizona and Mexico affects the overall market for lettuce.

Demand Elasticities

Our estimate of the own-price elasticity of demand for lettuce is based on Okrent and Alston (2011), who estimate the own-price elasticity of demand for lettuce in the United States to be $\eta =$ –0.77. We use an elasticity of substitution between organic and nonorganic lettuce of $\sigma = 1.90$

from Xu et al. (2015) who estimate the elasticity of substitution of between organic and nonorganic tomatoes. Using these parameters and a conventional lettuce market share of $\omega^{US} =$ 90.3% (NASS, 2024), we calculate own- and cross-price elasticities of demand for conventional and organic lettuce according to equations (22) – (25). The own-price elasticity of conventional lettuce is $\eta_{CL}^{US} =$ –0.88, the own-price elasticity of demand for organic lettuce is $\eta_{OL}^{US} =$ –1.79, and the cross-price elasticities are $\eta_{CL,OL}^{US} =$ 0.11 and $\eta_{OL,CL}^{US} =$ 1.02. Using a value of $\omega^{X} =$ 89.6% for the share of conventional lettuce in export lettuce demand and an own-price elasticity of demand for export lettuce of $\eta =$ –1.03, the implied own- and cross-price elasticities of export demand are: η_{CL}^{X} = –1.12, η_{OL}^{X} = –1.81, $\eta_{CL,OL}^{X} =$ 0.09, and $\eta_{OL,CL}^{X} =$ 0.78.

Estimates of price elasticities in Mexico are not as prevalent in the economic literature compared to U.S. elasticities. We rely on Mhurchu et al. (2013) who estimate the own-price elasticity of demand for vegetables for low-income groups to be 1.7 higher than high-income groups. Using this ratio, we estimate the own-price elasticity of demand in Mexico for lettuce to be $\eta_{CL}^{MX} =$ –1.3.

Okrent and Alston (2012) find that the own-price elasticity of demand for food away from home ranges between –1.50 and –0.69 with a mean of –1.02 across food demand studies. We use this mean value for the own-price elasticity of demand for food service meals, $\eta_{meal} =$ –1.0. In general, we expect the cost share of lettuce in food service meals to be low. We assume $\mu_l =$ 2% and calculate the own-price elasticity of demand for lettuce at food service operations to be $\eta_{FSL} =$ –0.02 using equation (24).

Supply Elasticities

The own-price elasticities of supply used in simulations are based on Liu and Yue (2013), who use a short-run elasticity of supply for lettuce of 0.45 and long-run elasticity of supply of 1.7 in their analysis of the impacts of time delays on lettuce quality and price. However, their estimates are based on studies that that are now more than a quarter century old. Unfortunately, there is little research to inform updated elasticities of supply. We use these short- and long-run elasticities but incorporate uncertainty by allowing them to randomly vary.

For conventional and organic lettuce in the United States, we define the long-run elasticity of supply as normally distributed with a mean of 1.4 and standard deviation of 0.35, $\epsilon_{CL}^{US} \sim$ N(1.4,0.35), when simulating the effects of pesticide restrictions. When considering the short-run effects of delayed pesticide adoption, we define the elasticity of supply having the following distribution: $\epsilon_{CL}^{US} \sim$ N(0.7,0.15). Supply response of organic lettuce is slightly more elastic, with long-run and short-run distributions of $\epsilon_{OL}^{US} \sim$ N(1.6,0.40), and $\epsilon_{OL}^{US} \sim$ N(0.8,0.20), respectively.

Lettuce supply in Mexico is expected to be more elastic relative to the United States, primarily because the more elastic labor supply. We let the long-run elasticity of supply in Mexico randomly vary according to a normal distribution of $\epsilon_{CL}^{MX} \sim$ N(2.0,0.50). The short-run elasticity of supply is normally distributed as $\epsilon_{CL}^{MX} \sim$ N(1.0,0.25).