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RESEARCH ARTICLE

Evaluating Large Exogenous Shocks Using an Almost Nonlinear Equilibrium Displacement Model: Food Safety Regulations and Leafy Greens Production

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Abstract

The Food and Drug Administration (FDA) recently published a final rule regarding preharvest irrigation requirements for leafy greens production. We use an equilibrium displacement model (EDM) to quantify the effects of this policy. The model is modified to allow for nonlinear equilibrium trajectories. The results show that the FDA rule will cause North American leafy greens production to decline by 0.99% and farmgate prices to increase by 0.59%. A proposal to increase land buffer areas around confined animal feeding operations (CAFOs) and large composting sites would further increase leafy greens prices and reduce consumption.

Keywords: Equilibrium displacement model; food safety certifications; leafy greens

JEL Codes: Q18; D51; L51

1. Introduction

Leafy greens are a healthy component of consumer diets because they contain calcium, fiber, folate, and other vitamins and minerals.[1] The industry, however, has recently experienced several foodborne illness outbreaks, particularly in the fall and spring growing seasons when most production occurs in Southern California, Arizona, and Mexico. Of the more than 40 outbreaks studied by Marshall et al. (2020), the source of contamination appears to have been cattle or feral pig fecal waste fouling irrigation water. In addition to direct health implications, food safety outbreaks reduce leafy greens consumer and producer surplus because of related declines in consumption. It can take months to rebuild consumer confidence following an outbreak (Spalding et al., 2023). Hence, those involved in the food supply chain have strong incentives to maintain food safety reputations (Bovay, 2023).

In response to food safety issues, the California Leafy Greens Marketing Agreement (LGMA) was developed in 2007 by leafy greens supply chain participants to identify and implement food safety practices using science and data to guide production requirements. The California LGMA and its sister program in Arizona provide non-governmental regulatory guidelines that require

[1]Leafy greens crops include iceberg lettuce, romaine lettuce, green leaf lettuce, red leaf lettuce, butter lettuce, baby leaf lettuce (i.e., immature lettuce or leafy greens), escarole, endive, spring mix, spinach, cabbage, kale, arugula, and chard. In 2023, U.S. production totaled 5.19 million tons of which iceberg lettuce (43%) and romaine lettuce (40%) represented the largest components.

participating producers to follow safety protocols and best management practices to reduce foodborne disease. Members of the California and Arizona LGMAs produce approximately 90% of all U.S. leafy greens (LGMA, 2020). LGMA production and handling practices are updated as new scientific information is developed. The latest update occurred in August 2020. In 2016, the Standards for Growing, Harvesting, Packing, and Holding of Produce for Human Consumption (Produce Safety rule) of the Food Safety Modernization Act (FSMA) was initiated to cover all produce grown for human consumption. LGMA has traditionally included standards set by the Produce Safety rule for leafy greens producers, but the U.S. Food and Drug Administration (FDA) is requiring additional food safety protocols beyond those established by the LGMA. On May 6, 2024, the FDA approved a final rule that revised preharvest water requirements in Subpart E of the FSMA (FDA, 2024). The revisions require the adoption of various mitigation strategies when water systems are deemed to have "increases [in] the likelihood that a known or reasonably foreseeable hazard will be introduced."

In addition to the FDA's new rule, other food safety mitigation strategies have been proposed. Animal activity on adjacent and nearby land is known to have a substantial influence on the probability of produce contamination. Although several mitigation strategies have been suggested to reduce these risks (e.g., fencing, earthen diversion berms, etc.), produce farmers generally have little influence on adjacent landowner's decisions. Therefore, increased physical distance using buffer zones have been suggested as a means for reducing pathogen risks. Since the inception of LGMA, buffer zones around confined animal feeding operations (CAFOs) have increased from 400-feet in 2016 to 1,200 feet.[2] Given that minimum buffer distances are routinely considered when FSMA/LGMA practices are evaluated and that most pathogen contamination has been caused by animal waste, it is likely that extensions of buffer zones will be considered in the future. One proposal calls for expanding leafy greens production buffer areas surrounding CAFOs and composting facilities from the current 1,200 feet to 1-mile radius (depending upon CAFO size and composting location) to a 2-mile radius. We use a modified equilibrium displacement model (EDM) that allows for nonlinear equilibrium trajectories to evaluate the impact of the new FDA irrigation water rule and potential future expansion of buffer areas.

Most California leafy green acreage is currently in compliance with the FDA final rule. However, we estimate that the rule will increase irrigation costs by 39% in California's Imperial Valley and non-California leafy green production areas. Furthermore, potential increased buffer zones would reduce leafy greens acreage in the Imperial Valley by 45%. EDMs have commonly been used to quantify price and quantity responses associated with these types of exogenous shocks (Lim, Gallardo, and Brady, 2023; Samper, Koziol, and Williams, 2025; Staples et al., 2025). They are, however, generally most accurate when estimating the effects of small proportional shocks (Zhao, Mullen, and Griffiths, 1997). EDMs (whether implemented with price/quantity/cost data in levels or after natural logarithm transformations) approximate policy effects by moving along linear hyperplanes that are tangent to an underlying, and possibly nonlinear system of demand and supply equations (Wohlgenant, 2011). The accuracy of conventional EDM approximations decrease with the distance from the original tangency point and depends on the curvature of the underlying system and own-price elasticities of supply and demand.

However, linear equilibrium trajectories are less accurate approximations for large exogenous shocks as they are unable to approximate changes along nonlinear supply and demand functions. Furthermore, if the own-price elasticity of supply for an input is relatively inelastic and a large restriction is imposed, the linear equilibrium trajectory can terminate in the fourth Euclidean quadrant resulting in estimates of negative input prices (Harrington and Dubman, 2008). This occurs because a linear projection is being made using the slope obtained at an initial inelastic point on the supply function.

[2]CAFOs are animal feeding operations that consist of at least 1,000 head of cattle or its equivalent for other species, a commercial dairy, or a feedlot of any size.

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Given the relatively sizable increases in irrigation costs and proposed buffer areas, we modify the EDM solution process so that changes in endogenous variables result from piecewise linear equilibrium trajectories that closely approximate nonlinear curves. The approach is more consistent with EDM assumptions of constant elasticities of demand and supply for outputs and inputs, and constant cross-elasticities of input substitution. We break the two large exogenous shocks into smaller equal increments. After each small exogenous shock, we use the resulting percentage changes in the endogenous variables to calculate new price and quantity values for inputs and output and iteratively solve the EDM. The novel approach mitigates the problem of obtaining negative input prices that can occur when coupling relatively inelastic supply elasticities with large exogenous shocks (Zhao, Mullen, and Griffith, 1997).

Growers, shippers, processors, retailers, and consumers benefit from safer produce. However, additional food safety practices increase production costs and affect the leafy greens market. It is important to consider, and potentially balance, the benefits of reduced foodborne illness outbreaks with the additional costs of new food safety practices. We evaluate the latter using cost of production studies and both a traditional and almost nonlinear EDM.

2. Leafy greens food safety and previous research

Leafy greens consumed in the United States are produced in California's Imperial Valley (9.9% in 2023), other California regions such as the Central Coast (62.7%), and other non-California locations such as Arizona's Yuma Valley and northern Mexico (27.4%) (USDA NASS, 2025). The Federal 2011 Food Safety Modernization Act (FSMA), administered by the FDA, provides production requirements for many products including leafy greens. These regulations address most aspects of fresh produce supplies from production practices to postharvest handling and traceability.

Food safety practices benefit consumers but impose direct and indirect costs on producers (Ferrier, Zhen, and Bovay, 2023; Staples et al., 2022). The FDA (2024) estimates that the cost of their newest rule regarding preharvest irrigation water will be between \$17.5–17.7 million, and benefits will be \$10.3 million. The direct costs include expenses for complying with requirements including water testing, equipment, food safety audits, and production and handling labor. Indirect costs include the opportunity cost of management time for activities such as reviewing and interpreting changing requirements and specifications, and monitoring and enforcing general food safety compliance (Hamilton and McCullough, 2018; 2025).

Additional requirements that increase the costs of producing leafy greens will reduce returns and increase farm business risk unless offset by increased consumer demand for safer produce. *Ceteris paribus*, increased production costs reduce the supply of leafy greens which increases market prices and reduces consumption. These effects are ultimately capitalized into lower land rental rates (or, equivalently, land values). Both the FDA rule and potential larger buffer areas will affect production regions differently. For example, the Imperial Valley and non-California regions generally use surface water for irrigation. Hence, the FDA rule will primarily affect those regions while the "other California" region (which generally uses well water for irrigation) will not be negatively affected. In addition, CAFO and composting businesses that create point-source pollution are primarily located in California's Imperial Valley. Leafy greens production in other California regions (e.g., the Central Coast) are generally not close to CAFOs or large composting sites.

Several studies have evaluated the costs of various components of FSMA and LGMA requirements. For example, Calvin et al., (2017) evaluated seven grower-shipper's costs associated with food safety practices under LGMA and the FSMA's Produce Safety rule even though the latter generally causes the same or lower costs than LGMA requirements. Their case study concluded that additional costs per firm ranged from \$0 to over \$300,000 per year, slightly more than 1% of

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total production costs, while acknowledging the difficulty of separating food safety-specific costs from general operational costs by product.

A more recent study by Olimpi et al. (2019) evaluated food safety requirements on agricultural production in California's Central Coast. Their study provided a quantitative assessment of changing food safety requirements following a 2018 *E. coli* outbreak. They highlight contradictions in the grower-specific approach to food safety metrics and conclude that a more "integrated perspective on regional risk, vulnerability, and resilience" would provide lower costs and better outcomes for the industry. A producer survey found that compliance costs per acre were typically larger for smaller farming operations because of associated increases in fixed costs (Hardesty and Kusunose, 2009).

Other studies have reached similar conclusions regarding the costs of food safety compliance in the leafy greens industry. Hardesty and Kusunose (2009) surveyed California handlers to assess LGMA compliance costs. They found average compliance costs represented about 1% of gross revenues, with higher percentages for smaller operations. Bovay, Ferrier, and Chen (2018) reviewed compliance costs of the FSMA Produce Safety rule across a range of fruit and vegetable industries. They concluded that costs vary by farm size – ranging from 0.3% of annual produce sales for the largest farms to nearly 7% for smaller operations.

Using initial cost estimates from Bovay, Ferrier, and Zhen (2018) across farm sizes and commodities, Ferrier, Zhen, and Bovay (2023) use an EDM to evaluate the price and welfare effects of the FSMA Produce Safety rule. Their study spans 38 fruit and vegetable commodities and estimates changes in equilibrium prices and quantities as well as pass-through effects. They find prices for various leafy greens will increase by only small amounts.

Our research also uses an EDM to examine the impacts of new FSMA requirements. However, we deviate in 3 main areas. First, we focus on farm level prices and quantities and assume leafy greens produced in different regions are perfect consumption substitutes. Second, we develop production and new irrigation protocol costs using local cost of production studies rather than farm averages. Third, we examine changes to FSMA preharvest water treatment practices that were not included in the original ruling.

The recent revision to Subpart E of the Produce Safety rule suggested multiple strategies for mitigating leafy greens contamination from animal waste (FDA, 2021). The final FDA (2024) rule could be interpreted as prohibiting the use of sprinkler irrigation. However, it is more likely that water obtained from a surface source must, at a minimum, be treated if the delivery process causes it to contact an edible portion of a leafy greens crop. Other suggestions included increasing production buffer areas around CAFOs. Therefore, we consider an increase in buffer areas for leafy greens production from the current 1,200 feet to 1-mile radius (depending on CAFO size) to a 2-mile radius. In addition, production could not occur within a 2-mile radius of a composting operation that produces more than 5,000 cubic yards per year, and within a 1-mile radius from all other composting operations.

3. Costs of mitigation strategies

The new FDA irrigation water rule and potential increase in buffer areas surrounding CAFOs and composting facilities will add costs to leafy greens production. We use cost of production budgets developed for iceberg lettuce in the Imperial Valley as a proxy for the costs of producing all leafy greens.[3] Production costs were developed using two University of California Cooperative Extension (UCCE) iceberg lettuce crop budgets – one from 2004 related to Imperial County and a more recent 2017 report related to Monterey/San Benito/Santa Cruz Counties that updates costs

[3]Iceberg lettuce is the largest component of greens production (43%) and has the most recent and complete production cost data. Therefore, we use the costs of producing iceberg lettuce as a proxy for the costs of producing all leafy greens.

given recent changes in technology (Meister, 2004; Tourte et al., 2017). In addition, production costs were further refined using a recent case study of a lettuce grower in Monterey County (Hamilton and McCullough, 2025).

A baseline sample crop budget was constructed. Production costs were adjusted using local data and practices common in the Imperial Valley and other regions (Davids Engineering, 2007; Hamilton and McCullough, 2025). The crop budgets reflect a representative farm in the area. Although per unit fixed costs vary by farm size, per unit variable costs are likely similar. Prices for specific inputs were updated, when possible, from available price lists and discussions with local vendors.

The baseline crop budget assumed furrow irrigation on 40-inch beds. Expected yield in the 2004 UCCE report was 700 cartons per acre, with each carton including 24 wrapped lettuce heads with a gross weight of 40 pounds. Yields were increased to 800 cartons based on Imperial County crop reports (USDA NASS, 2025). The sample budget assumed no use of compost, and fertilizer applications were adjusted to reflect Imperial Valley practices and costs. Herbicide, insecticide, and fungicide costs were obtained from the 2017 UCCE report with some adjustments made based on informal grower feedback.

Custom/contract budget line items are based on the 2017 UCCE report and Hamilton and McCullough (2025). These included costs for harvesting, cooling/palletizing, PCA/CCA, chemical applications, laser leveling, marketing, and sales activities. Costs to mark/disc borders, make cross checks, and break borders (for preseason flooding) were added from the 2004 UCCE report, as was the mechanized process of creating furrows. Costs for irrigation equipment and plant thinning were developed through grower and local supplier interviews. Seed costs were provided by the 2017 UCCE report.

Land rent ($350 per acre) is based on USDA NASS (2025) reports for irrigated land in Imperial County, California for 2024. Irrigation applications (including leaching) and irrigation labor requirements were obtained from the Davids Engineering (2007) report, with current water rates being supplied by the Imperial Irrigation District (2020). Total irrigation costs consider labor costs based on a wage rate of $17.80 per hour with an additional 41% for overhead costs and additional adjustments made for SB 3 (California's 2022 minimum wage increase) and AB 1066 (California's 2022 overtime wage rates). The combination of non-labor and labor irrigation costs total $1,000 per acre (Table 1).

Initial equipment operator and non-machine labor requirements were obtained from the 2017 UCCE report as were fuel, lube, and machinery repair costs. Other cash overhead costs, including property insurance and taxes, food safety and regulatory program assessments, liability insurance, office expenses, and field sanitation costs were from the 2017 UCCE report. Non-cash overhead costs including buildings, fuel tanks, shop tools, and other equipment also came from the 2017 UCCE report. All of these costs as well as cash overhead costs (including office expenses, insurance, and regulatory compliance costs associated with recordkeeping) were adjusted following Hamilton and McCullough (2025). The sum of all other input costs (i.e., other than land and irrigation costs) totaled $9,825 per acre with total costs equaling $11,175 per acre (Table 1).

3.1. Costs of water testing and treatment

All irrigation water obtained from a surface source must have increased testing and treatment if the delivery process causes it to contact an edible portion of a leafy greens crop (FDA, 2024). This will increase the number of peroxyacetic acid treatments from 1 to 6 per growing season. Given an average cost of $77.80 per treatment, the additional 5 treatments would increase irrigation costs from $1,000 per acre to $1,389 per acre. Thus, at a minimum, the new protocols for water treatment would increase irrigation costs by 38.9%.

Table 1. Leafy greens production data

Item	Notation	Value
Land costs (rent)		\$350/acre
Irrigation costs		\$1,000/acre
All other input costs		\$9,825/acre
Total costs		\$11,175/acre
Land cost share	K_g^L	0.0313
Irrigation cost share	K_g^I	0.0895
All other inputs cost share	K_g^O	0.8792
Initial price of leafy greens	P	\$0.47/pound
Initial quantity of leafy greens	Q	11,129 million pounds
Initial total farmgate value of leafy greens		\$5,192 million
Quantity of Imperial Valley leafy greens production	Q_{IV}	1,102 million pounds
Quantity of other California leafy greens production	Q_{OC}	6,978 million pounds
Quantity of non-California leafy greens production	Q_{NC}	3,048 million pounds
Imperial Valley production share of leafy greens	$\mathscr{R}_{IV}$	0.099
Other California production share of leafy greens	$\mathscr{R}_{OC}$	0.627
Non-California production share of leafy greens	$\mathscr{R}_{NC}$	0.274

3.2. CAFO buffer areas

An additional strategy for mitigating animal waste contamination would involve increasing current production buffer areas from the current standard of 1,200 feet to 1-mile radius to a 2-mile radius depending on CAFO size. A geospatial analysis of the Imperial Valley was used to evaluate the impact of a 2-mile buffer restriction. CAFO locations were identified using the California Open Data Portal on Water Quality Regulated Facilities (CAODP, 2023). Crop production regions were developed from several geospatial layers over a six-year period to differentiate leafy greens from other crops. Additional data were obtained from the California Department of Pesticide Regulation Pesticide Use Report (2023). Imperial Valley totals may differ from county and state reports due to the specific regions established for the geospatial analysis. Double-cropped fields are accounted for in the reports.

Figure 1 illustrates Imperial Valley crop production for the 2016 season. Crop types are aggregated into various categories. The leafy greens category includes all leafy greens, and the GIS data consider seasonal rotations. Leafy greens are indicated for fields on which they were produced at any point in annual rotation cycles. Data for other years were reviewed and support the 2016 data. That is, leafy greens are generally grown in the same areas over time. A total of 35 CAFOs within this expanded radius were identified in the Imperial Valley. These CAFOs consist of approximately 1,850 acres. The 2-mile buffer region consists of 177,600 acres.

3.3. Compost buffer areas

If buffer areas around CAFOs were increased, it is reasonable to assume that leafy greens production buffer areas around composting operations would also increase. We consider the effects of expanding buffer areas within a 2-mile radius of a composting operation that produces more than 5,000 cubic yards per year and a 1-mile radius from all other composting operations.

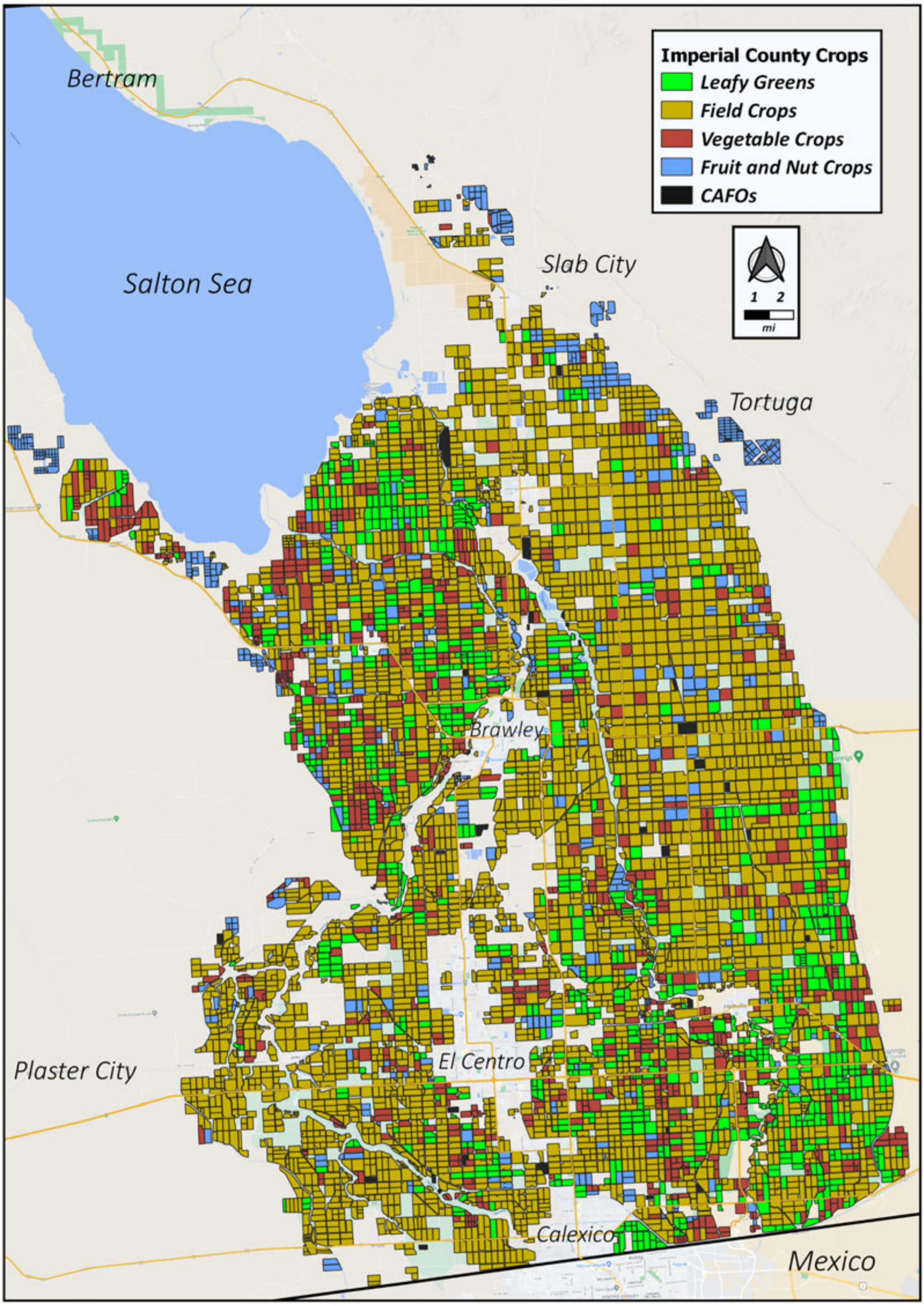

Figure 1. Imperial Valley crop types, 2016 growing season.

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A total of nine active compost sites were identified using the California Department of Resources Recycling and Recovery's Solid Waste Information System (SWIS) database and validated through Google Earth image analysis. However, seven of those sites are associated with CAFOs and are included within the buffer range discussed above.

The total increased buffer range for composting operations and CAFOs encompasses 190,060 acres of the 420,000 cropland acres in the Imperial Valley. Of this acreage, 25,080 acres were planted to leafy greens. This represents approximately 45% of leafy green acreage in the Imperial Valley.

4. An equilibrium displacement model

Many studies have used EDMs to evaluate various regulatory policies on supply chains (e.g., Okrent and Alston, 2012; Rutledge and Mérel, 2023; Zhang, 2021). The impacts of irrigation water treatment and buffer area costs on the leafy greens supply chain is evaluated using an EDM constructed for three leafy greens production regions following Brester, Atwood, and Boland (2023, p. 55) as

$$E(Q) = \eta E(P) \tag{1}$$

$$E(Q) = \mathcal{R}_{IV}E(Q_{IV}) + \mathcal{R}_{OC}E(Q_{OC}) + \mathcal{R}_{NC}E(Q_{NC}) \tag{2}$$

$$E(P) = K_g^L E(w_g^L) + K_g^I E(w_g^I) + K_g^O E(w_g^O); g = IV, OC, NC \tag{3}$$

$$E(x_g^L) = E(Q_g) + K_g^L \sigma_g^{LL} E(w_g^L) + K_g^I \sigma_g^{LI} E(w_g^I) + K_g^O \sigma_g^{LO} E(w_g^O); g = IV, OC, NC \tag{4}$$

$$E(x_g^I) = E(Q_g) + K_g^I \sigma_g^{IL} E(w_g^L) + K_g^I \sigma_g^{II} E(w_g^I) + K_g^O \sigma_g^{IO} E(w_g^O); g = IV, OC, NC \tag{5}$$

$$E(x_g^O) = E(Q_g) + K_g^L \sigma_g^{OL} E(w_g^L) + K_g^I \sigma_g^{OI} E(w_g^I) + K_g^O \sigma_g^{OO} E(w_g^O); g = IV, OC, NC \tag{6}$$

$$E(w_{IV}^{LS}) = 1/\varepsilon_{IV}^L \; E(x_{IV}^L) \tag{7}$$

$$E(w_g^L) = 1/\varepsilon_g^L \; E(x_g^L); g = OC, NC \tag{8}$$

$$E(w_g^I) = 1/\varepsilon_g^I \; E(x_g^I) + E(\theta_g^I); g = IV, NC \tag{9}$$

$$E(w_{OC}^I) = 1/\varepsilon_{OC}^I \; E(x_{OC}^I) \tag{10}$$

$$E(w_g^O) = 1/\varepsilon_g^O \; E(x_g^O); g = IV, OC, NC \tag{11}$$

$$E(w_{IV}^L) = E(w_{IV}^{LS}) \tag{12}$$

The subscript g represents the Imperial Valley (IV), other California (OC), and non-California (NC) production regions. Superscripts represent the three input categories of land (L), irrigation (I), and other inputs (O). For all sectors, Q is the quantity demanded (and supplied) of leafy greens at the farm level, P is the farm level price of leafy greens, and $\mathcal{R}_g$ is the production share of leafy greens produced in each of the three regions. Q_{IV} is the quantity of leafy greens produced in the Imperial Valley, Q_{OC} is the quantity of leafy greens produced in other California regions, and Q_{NC} is the quantity of leafy greens produced in other non-California regions (predominantly Arizona and Mexico). The quantities demanded and supplied of land, irrigation, and other inputs used to produce leafy greens are represented by x_g^L, x_g^I, and x_g^O, while input prices are represented by w_g^L, w_g^I, and w_g^O.

Several elasticity values are specified: η is the own-price elasticity of demand for leafy greens; ε_g^L is the own-price elasticity of supply of land inputs, ε_g^I is the own-price elasticity of supply of irrigation inputs, and ε_g^O is the own-price elasticity of supply of all other inputs. Hicks-Allen elasticities of substitution between inputs i and j are represented by σ_g^{ij}. The symbol K_g^j represents

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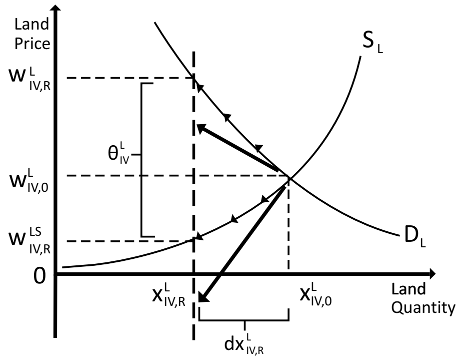

Figure 2. A restriciton on land use.

input cost shares ($K_g^j = \frac{w_g^j x_g^j}{\Sigma_i w_g^i x_g^i}$) such that $\sum_j K_g^j = 1$. Silberberg (1990) notes that $\sum_j K_g^j \sigma_g^{ij} = 0$ is necessary to make the system of equations "add-up" or, more precisely, be homogeneous of degree 0 in input and output prices. This logical condition is analogous to the concept of a lack of "money illusion" in consumer theory. That is, the homogeneity condition implies that no output response should occur if all input prices were, say doubled, along with the output price. Hence, only relative input and output prices influence production behavior as opposed to price levels. In the absence of this condition, EDM outcomes are not consistent with economic theory. The homogeneity conditions are imposed on each production region. For all price and quantity variables, the expression $E(\cdot)$ represents percentage changes such that $E(\cdot) = \frac{d(\cdot)}{(\cdot)}$. The Imperial Valley and the non-California regions will incur additional irrigation costs (θ_g^I) caused by the FDA final rule. The symbol $E(\theta_g^I) = \frac{\theta_g^I}{w_g^I}$ represents proportional exogenous increases in irrigation costs in the Imperial Valley and non-California production regions.

Equation (1) represents the farm-level demand for leafy greens. Equation (2) indicates that the total production of leafy greens is the sum of production occurring in the Imperial Valley, the other California region, and the non-California region. Equations (3)–(6) represent the output supply of leafy greens and associated input demand functions implied by the dual form of Muth's (1964) model for each of the three production regions. Equation (7) is the inverse supply function for land in the Imperial Valley. An increase in buffer zones in the Imperial Valley requires that both a demand price (w_{IV}^L) and a supply price (w_{IV}^{LS}) for land in that region be specified. Equation (8) represents the inverse supply of land in the other California and non-California production regions. Equation (9) represents the inverse supply of irrigation in the Imperial Valley and non-California regions. Equation (10) is the inverse irrigation supply function for the other California region. Equation (11) represents the inverse supply function for all other inputs used to produce leafy greens in each of the three production regions. Equation (12) specifies the relationship between the Imperial Valley land demand and supply prices in the absence of an increase in the buffer zone.

Adding the increased buffer zone restriction to the above system generates a price wedge between the demand and supply prices of land in the Imperial Valley and necessitates the inclusion of an additional variable (θ_{IV}^L) that endogenously computes the difference between the two prices (Figure 2). Hence, when the land restriction is included, $w_{IV}^L = w_{IV}^{LS} + \theta_{IV}^L$ and the proportional difference between changes in the two prices is modeled by replacing equation (12) with

$$E\left(w_{IV}^L\right) = \frac{w_{IV}^{LS}}{w_{IV}^L}\left(\frac{dw_{IV}^{LS}}{w_{IV}^{LS}}\right) + \left(\frac{d\theta_{IV}^L}{w_{IV}^L}\right) = \frac{w_{IV}^{LS}}{w_{IV}^L}E\left(w_{IV}^{LS}\right) + E\left(\theta_{IV}^L\right) \qquad (12')$$

Table 2. Initial EDM parameter values

Parameter	Value
η	−1.69
$\mathscr{R}_{IV}$	0.099
$\mathscr{R}_{OC}$	0.627
$\mathscr{R}_{NC}$	0.274
K_g^L	0.0313
K_g^I	0.0895
K_g^O	0.8792
$\sigma_g^{LI} = \sigma_g^{IL}$	0.50
$\sigma_g^{LO} = \sigma_g^{OL}$	0.10
$\sigma_g^{IO} = \sigma_g^{OI}$	0.30
ε_g^L	0.23
ε_g^I	0.68
ε_g^O	5.00
$E(\theta_g^I) = \frac{d\theta_G^I}{w_{g,0}^I}$	0.389
$E(x_{IV}^L) = \frac{dx_{IV,R}^L}{x_{IV,0}^L}$	−0.45

At the initial equilibrium we assume that $w_{IV}^L = w_{IV}^{LS}$ and the land price ratio $\frac{w_{IV}^L}{w_{IV}^{LS}} = 1$. In the multistage EDM process discussed below, the beginning of stage derived demand price (w_{IV}^L) and supply price (w_{IV}^{LS}) are iteratively updated as is the land price ratio ($\frac{w_{IV}^L}{w_{IV}^{LS}}$) and $E(\theta_{IV}^L) = \left(\frac{d\theta_{IV}^L}{w_{IV}^L}\right)$. The inclusion of the additional endogenous variable, $E(\theta_{IV}^L)$, requires that an additional equation be added to the model. The equation represents the reduction in the quantity of land that can be used in the Imperial Valley for leafy greens production from its initial level, $x_{IV,0}^L$, to its restricted (or reduced) level, $x_{IV,R}^L$,

$$E(x_{IV}^L) = \frac{x_{IV,R}^L - x_{IV,0}^L}{x_{IV,0}^L} = \frac{dx_{IV,R}^L}{x_{IV,0}^L} = -0.45 \quad (13)$$

4.1. Data used to parameterize the EDM

Table 2 presents the values used to parameterize the EDM presented in equations (1)–(13). The own-price elasticity of demand for leafy greens (−1.69) represents a production share weighted average of own-price elasticities of demand for head, leaf, and romaine lettuces (Ferrier, Zhen, and Bovay, 2023). In addition, we require estimates of the own-price elasticities of supply for each of our defined input categories. The elasticity of supply for all agricultural land has been estimated to be relatively inelastic as most land suitable for agricultural production is already being used for that purpose (Tabeau, Helming, and Philippidis, 2017). They estimate that the own-price elasticity of supply for agricultural land in the United States (ε_g^L) is 0.23.

A second input is defined as irrigation costs which includes both labor and capital equipment as well as water and water treatment equipment. Hill, Ornelas, and Taylor (2021) report estimates of the own-price elasticity of agricultural labor that vary widely, but a summary of estimates center around 0.40. Gallaway, McDaniel, and Rivera (2003) estimate Armington supply elasticities for

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309 SIC-code manufacturing industries including many inputs used for irrigation. Although Armington elasticities represent import supply responses to changes in domestic prices, they should be reasonable approximations for inputs used by U.S. production agriculture given the global manufacturing environment. Gallaway, McDaniel, and Rivera (2003) report short-run own-price supply elasticities ranging from 0.74 for valves and pipe fittings to 0.96 for pumps. Hence, we use the midpoint of the range of labor and equipment elasticities (0.68) as an estimate of the own-price elasticity of supply of irrigation inputs (ε^I).

The third input represents all other inputs used to produce leafy greens. This category includes cash overhead costs (e.g., property insurance, taxes, food safety and regulatory program assessments, liability insurance, office expenses, field sanitation costs, and owners' equity). In addition, the category includes cash input costs (e.g., fertilizer, pesticides, and fuel) and non-cash overhead costs including buildings, fuel tanks, shop tools, and other equipment. Most of these inputs are not unique to leafy greens production and are used to produce most U.S. crops. Hence, a reduction in the use of these inputs will likely have a *de minimis* effect on their regional and national prices. Therefore, we assume the own-price elasticity of supply of all other inputs is relatively elastic ($\varepsilon_g^O = 5.0$).

The initial values for the input cost shares $K_g^L = 0.0313$, $K_g^I = 0.0895$, and $K_g^O = 0.8792$ are developed from cost of production studies and are assumed equal across all regions (Table 1). In addition, the EDM requires estimates of the elasticities of substitution among the three inputs. Such estimates are often impossible to estimate because of a lack of data. Therefore, we assume that elasticities of substitution are identical for all regions and use information provided by growers from field interviews in which we asked, "What pairs of inputs are relatively substitutable for each other, and which are less so?" Growers indicated that land and irrigation inputs had some degree of substitutability, so we set this elasticity of substitution equal to 0.50 (i.e., $\sigma_g^{LI} = \sigma_g^{IL} = 0.50$). Land and other inputs were deemed to be the least substitutable, so we set that elasticity to 0.10 (i.e., $\sigma_g^{LO} = \sigma_g^{OL} = 0.10$). Irrigation inputs and other inputs were somewhat substitutable, so we assume $\sigma_g^{IO} = \sigma_g^{OI} = 0.30$. The terms σ_g^{LL}, σ_g^{II}, and σ_g^{OO} must be calculated and included in the model if the economic system is to be homogeneous of degree zero in all prices and allow the system to add up (Silberberg, 1990).[4]

The price of leafy greens was calculated as a weighted average price per head for leaf and romaine lettuce (USDA ERS 2024). Import shares and leafy green production were obtained for California and Arizona from the USDA NASS Agricultural Survey (2025). Leafy greens regional production shares were calculated by multiplying state production totals by county acreages for leafy greens obtained from the 2022 Census of Agriculture (USDA NASS, 2022).

5. Operationalizing the EDM

Leafy greens producers in the Imperial Valley and other non-California regions (i.e., Arizona and Mexico) will incur increased irrigation costs because of the FDA (2024) rule. Most leafy green irrigation in other California regions (e.g., the Central Coast) involves well water rather than surface water. Hence, additional water treatment costs will not be incurred in the other California production region.

5.1. Increased irrigation costs in the Imperial Valley and non-California production regions

The FDA (2024) protocol will increase the costs of irrigation in the Imperial Valley and the non-California production regions for every level of irrigation input. Consequently, the values of $E(\theta_g^I)$ in equation (9) are set to 38.9% which represents the proportional increase in irrigation costs caused by the new FDA protocols.

[4] $\sigma_g^{LL} = -\frac{(K_g^I \sigma_g^{LI}) + (K_g^O \sigma_g^{LO})}{K_g^L} = -\frac{(0.089)(0.50)+(0.879)(0.10)}{0.031} = -4.24$; $\sigma_g^{II} = -\frac{(K_g^L \sigma_g^{IL}) + (K_g^O \sigma_g^{IO})}{K_g^I} = -\frac{(0.031)(0.50)+(0.879)(0.30)}{0.089} = -3.12$; and $\sigma_g^{OO} = -\frac{(K_g^L \sigma^{OL}) + (K_g^I \sigma^{OI})}{K_g^O} = -\frac{(0.031)(0.10)+(0.089)(0.30)}{0.879} = -0.03$.

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5.2. Solving the linear EDM

The EDM presented in equations (1)–(11) is used to evaluate the effects of an exogenous increase in irrigation costs in the Imperial Valley and non-California production regions. It is operationalized by moving the endogenous variables for each equation to the left hand-side and using linear algebra to obtain

$$\boldsymbol{A}\boldsymbol{y} = \boldsymbol{b} \tag{14}$$

where $\boldsymbol{A}$ is a 23 × 23 matrix of parameters, $\boldsymbol{y}$ is a 23 × 1 vector of endogenous variables, and $\boldsymbol{b}$ is a 23 × 1 vector of exogenous shocks. The solution for any exogenous shock is obtained by solving equation (14) as

$$\boldsymbol{y} = \boldsymbol{A}^{-1}\boldsymbol{b} \tag{15}$$

5.3. Solving for nonlinear equilibrium trajectories

EDM estimates are typically obtained by moving along linear equilibrium trajectories. Figure 2 illustrates the process of including the Imperial Valley land use restriction in the EDM. Traditional EDMs estimate changes in endogenous variable caused by input restrictions (such as a reduction in land use) by moving from an initial equilibrium ($x^L_{IV,0}$, $w^L_{IV,0}$) along linear trajectories to a new equilibrium as indicated by the bold arrows. That is, EDMs linearly project changes in endogenous variables caused by exogenous shocks. If relatively small exogenous shocks are being considered (or if demand and supply functions are either linear or only slightly nonlinear), changes in endogenous variables obtained from linear equilibrium trajectories will closely approximate movements along actual demand and supply functions (Zhao, Mullen, and Griffiths, 1997).

Linear equilibrium trajectories, however, are less accurate approximations for large exogenous shocks as they are unable to approximate changes along nonlinear supply and demand functions. EDMs inherently maintain constant elasticities when moving from one equilibrium to another as depicted in Figure 2. If the restricted quantity, $x^L_{IV,R}$, illustrated in Figure 2 is far enough to the left of the original equilibrium, $x^L_{IV,0}$, the lower linear equilibrium trajectory can terminate in the lower right quadrant resulting in positive input use but a negative input price. This occurs because a linear projection is being made using the slope obtained from an initial inelastic point ($x^L_{IV,0}$, $w^L_{IV,0}$) on the supply function (Harrington and Dubman, 2008). That is, the combination of starting at an initial point on an inelastic supply function and exogenously imposing a large negative quantity shock can result in a negative supply price as the linear land supply price (w^{LS}_{IV}) equilibrium trajectory can terminate in the fourth Euclidean quadrant.

Given the relatively sizable increases in irrigation costs and proposed buffer areas, we modify the EDM solution process so that changes in endogenous variables result from piecewise linear equilibrium trajectories that closely approximate the arrow segments on the nonlinear curves in Figure 2. We use the usual EDM approach of assuming constant elasticities of demand and supply for outputs and inputs, and constant cross-elasticities of input substitution. We then break the large exogenous shocks (the increase in irrigation costs $\theta^I_{IV}, \theta^I_{NC}$, and the decrease in land use $dx^L_{IV,R}$) into smaller equal increments. After each small exogenous shock, we use the resulting percentage changes in the endogenous variables to calculate new price and quantity values for inputs and output. Because prices, input levels, and regional leafy greens production change after each incremental shock, the Imperial Valley land price ratio $\left(\frac{w^{LS}_{IV}}{w^L_{IV}}\right)$ and regional production shares ($\mathscr{R}_{IV}$, $\mathscr{R}_{OC}$ and $\mathscr{R}_{NC}$) are recalculated after each iteration. In addition, input cost shares (K^L_g, K^I_g, and K^O_g) change after each step which subsequently requires that new values for $\sigma^{LL}_g, \sigma^{II}_g$, and σ^{OO}_g also be calculated.

Finally, because the exogenous shocks are computed as proportions of quantity levels at the beginning of each step, the exogenous proportional irrigation cost shocks in equation (9)

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$E\left(\theta_{IV}^{I}\right) = \frac{\theta_{IV}^{I}}{w_{IV}^{I}}$, $E\left(\theta_{NC}^{I}\right) = \frac{\theta_{NC}^{I}}{w_{NC}^{I}}$, and the proportional land restriction in equation (13) ($\frac{dx_{IV,R}^{L}}{x_{IV}^{L}}$) are recomputed at each iteration.[5] After re-parameterizing the $\boldsymbol{A}$ matrix in equation (14) with these new values, the model is again solved for another small shock. This approach does not change the linearity of each step of the equilibrium trajectory. However, the recalculation of starting points for each successive step allows for the next linear portion of the trajectory to have a different slope. This results in piecewise linear equilibrium trajectories that more closely track nonlinear (i.e., constant elasticity) demand and supply functions.

The iterative EDM procedure requires the identification of initial equilibrium quantity and price levels. If available, initial output and input prices and quantities can be used as a base for applying percentage changes that result from the first step of the iterative EDM process. In the present example, an initial equilibrium price and quantity exist for leafy greens (Table 1). However, as is often the case, our input categories represent an amalgam of many inputs. Hence, initial equilibrium input prices and quantities (which are necessary for the iterative process described above) do not exist. If an initial input price could be established, then at each step of the iterative EDM process, the quantity of each input could be obtained using input cost shares. In the absence of such price data, however, one can use any numeraire price and known input cost shares to calculate input quantity values which are essentially indices. The specific selection of a numeraire price has no effect on the final EDM percentage change calculations because the choice of numeraire does not affect relative prices (Reis and Watson, 2007). We use a numeraire of $w_g^L = w_g^I = w_g^O = 1.0$ for initial input prices and use input cost shares to calculate initial input quantities as $x_g^L = K_g^L PQ_g$, $x_g^L = K_g^L PQ_g$, and $x_g^O = K_g^O PQ_g$ for all regions.

Throughout the process, we maintain constant demand and supply elasticities. After each small step (shock), new values for all input and output prices and quantities are calculated using the percentage changes obtained from the solution to the EDM in that step. After the final step, final values are calculated for these metrics. Then, the final values are divided by their respective beginning values to obtain percentage changes for all endogenous variables resulting from an (almost nonlinear) set of piecewise equilibrium trajectories.

6. EDM results for increased irrigation costs

The EDM model (equations 1–12) was used to estimate the impacts of a 38.9% increase in the cost of irrigating leafy greens in the Imperial Valley and non-California production regions ($E(\theta_I) = 0.389$). After parameterizing the $\boldsymbol{A}$ matrix, the shock is entered in vector $\boldsymbol{b}$ of equation (14), and equation (15) is used to calculate changes in the endogenous variables.

6.1. Changes in the endogenous variables using the linear (one step) EDM

The first column of Table 3 lists the endogenous variables, while the second column presents changes in the endogenous variables attributable to increased irrigation costs obtained from equation (15). The total output of leafy greens from all sources declines by 1.05% and the price of leafy greens increases by 0.62%. Leafy greens production in the Imperial Valley and non-California region declines by 5.56%. The two values are equal because we use identical input cost shares and elasticities of substitution across all regions. Although these input cost shares and elasticities are also used in the other California region, that region will not incur increased

[5]We note that with J EDM iterations or stages, the original exogenously specified increases in irrigation cost levels θ_{IV}^{I} and θ_{NC}^{I} and the required decrease in land use $dx_{IV,R}^{L}$ are divided by J giving J *equal levels* of change that are held constant in each stage. Each stage's exogenously specified *proportional* changes $\frac{\theta_{IV}^{I}}{w_{IV}^{I}}$, $\frac{\theta_{NC}^{I}}{w_{NC}^{I}}$, and $\frac{dx_{IV,R}^{L}}{x_{IV}^{L}}$ are then recomputed by dividing by the "beginning of stage" prices w_{IV}^{I}, w_{NC}^{I}, and land quantity x_{IV}^{L}.

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Table 3. Changes in the endogenous variables resulting from increased irrigation costs

Variable	Linear EDM results for increased irrigation costs	Nonlinear EDM results for increased irrigation costs	Percent difference
Q	−1.05%	−0.99%	−5.31%
P	0.62%	0.59%	−4.63%
Q_{IV}	−5.56%	−5.29%	−4.99%
Q_{OC}	1.64%	1.57%	−4.67%
Q_{NC}	−5.56%	−5.29%	−4.99%
x^L_{IV}	−2.98%	−2.86%	−4.15%
x^I_{IV}	−11.98%	−10.64%	−11.17%
x^O_{IV}	−5.0%	−4.77%	−4.62%
w^L_{IV}	−12.96%	−11.90%	−8.22%
w^{LS}_{IV}	−12.96%	−11.90%	−8.22%
w^I_{IV}	21.28%	20.93%	−1.66%
w^O_{IV}	−1.00%	−0.97%	−2.93%
x^L_{OC}	1.11%	1.06%	−4.89%
x^I_{OC}	1.28%	1.22%	−4.75%
x^O_{OC}	1.70%	1.62%	−4.62%
w^L_{OC}	4.84%	4.68%	−3.36%
w^I_{OC}	1.88%	1.80%	−4.51%
w^O_{OC}	0.34%	0.32%	−5.17%
x^L_{NC}	−2.98%	−2.86%	−4.15%
x^I_{NC}	−11.98%	−10.64%	−11.17%
x^O_{NC}	−5.01%	−4.77%	−4.62%
w^L_{NC}	−12.96%	−11.90%	−8.22%
w^I_{NC}	21.28%	20.93%	−1.66%
w^O_{NC}	−1.00%	−0.97%	−2.93%

irrigation costs. Consequently, supply reductions in the other two regions increase farmgate prices which increases the quantity supplied by the other California region (1.64%).

Table 3 also presents changes in input usage and prices. The use of irrigation inputs to produce leafy greens (x^I_{IV} and x^I_{NC}) declines by 11.98%, and the price of irrigation inputs (w^I_{IV} and w^I_{NC}) increase by 21.28% in the Imperial Valley and non-California regions. Opposite effects occur in the other California region due to increased production. The use of both land and other inputs decreases in the Imperial Valley and non-California regions (x^L_{IV} and x^L_{NC}) but by a smaller percentage due to the substitution of land and other inputs for irrigation inputs. Imperial Valley and non-California land use decreases by 2.98% while land use in the other California region (x^L_{OC}) increases by 1.11%. Land prices decrease by 12.96% in the two regions affected by the FDA rule but increase (by 4.84%) in the other California region. The same regional patterns hold for the use and price of other inputs used to produce leafy greens.

The overall changes in leafy greens production and price are relatively small, which should be expected. Although the cost increases for individual producers in the Imperial Valley and non-California producers are substantial, the small irrigation input cost share (8.95%) and regional production shares (9.9% and 27.4%) result in relatively small aggregate effects.[6]

6.2. Changes in the endogenous variables using an almost nonlinear EDM

The effects of increases in irrigation costs ($E(\theta_g^I) = 0.389$) in the Imperial Valley and non-California production regions were also evaluated using the nonlinear EDM described above. Following the above discussion, we break these shocks into 10 equal smaller exogenous irrigation cost shocks.[7] The equal small shocks are entered iteratively until the desired total shock is obtained.[8]

The results are presented in the third column of Table 3 while the fourth column presents the percentage differences between the two methodologies. In every case, the nonlinear approach produces estimates of changes in the endogenous variable that are slightly smaller than the linear approach. Most of the estimates are approximately 5% smaller with a range from 1.66% to 11.17%. Consequently, the linear EDM overstates the price and quantity effects by an average of 6.4%. Given the size of the vertical shifts in the relevant irrigation cost supply curves induced by the policy, namely 38.9%, the linear EDM one step approximation errors are relatively modest when examining only changes in irrigation costs.

7. A restriction on land use in the Imperial Valley

A potential expansion of buffer areas around CAFOs and composting facilities would restrict the use of land for leafy green production. Most of these operations are in the Imperial Valley.

The increase would cause 45% of the land currently used to produce leafy greens in the Imperial Valley to be unusable for that purpose. Of course, that land could be used for other crop production and leafy greens production could move to other non-restricted land. Nonetheless, these options are second-best profitability solutions. Hence, in terms of leafy green production, we model a 45% reduction in land suitable for leafy green production in the Imperial Valley.

As Gardner (1987, pp. 22, 90) notes, restrictions on the use of an input in EDMs can be represented as a price wedge between the demand price of land (w_{IV}^L) and the supply price of land (w_{IV}^{LS}). Figure 2 illustrates this restriction as a vertical dashed line at $x_{IV,R}^L$ that is left of the original equilibrium land use quantity $x_{IV,0}^L$. The reduction associated with this restriction $dx_{IV,R}^L = x_{IV,R}^L - x_{IV,0}^L$ represents an exogenous shock. The size of the corresponding price wedge, $\theta_{IV}^L = w_{IV,R}^L - w_{IV,R}^{LS}$, is endogenous and depends upon the size of the supply and (endogenously determined) derived demand elasticities for land. That is, the elasticities obtained by allowing the relevant endogenous variables in the model to adjust to the land restriction.

[6]EDM estimates are necessarily dependent upon selected elasticity estimates. We use procedures developed by Brester, Atwood, and Boland (2023, pp 233–238) to conduct a sensitivity analysis of the above results. The results reported in Table 3 are all within the 95% confidence intervals obtained from the sensitivity analysis using 1,000 independently and triangularly distributed joint elasticity values.

[7]As the number of small shocks increase, the resulting equilibrium trajectories converge to nonlinear constant elasticity demand and supply functions. We find that 10 piecewise linear trajectories are quite close to the results obtained from 100 steps. We term the resulting trajectories "almost non-linear" because an exact nonlinear trajectory can only occur if an infinite number of piecewise steps are used.

[8]We have programmed the EDM using 10 linked worksheets within a single Excel workbook. As an error checking and accuracy exercise, the process was also programmed using R. We find identical results between the two programs. Both are available from the authors upon request.

7.1. Results for increased irrigation costs and expanded buffer zones using the linear (one step) EDM

The potential increase of the buffer zone in the Imperial Valley is modeled with equations (1)–(11), (12') and (13). Upon reconfiguring the matrices in equation (14), equation (15) is solved while simultaneously imposing increased irrigation costs in the Imperial Valley and non-California regions ($E(\theta_g^I) = 0.389$) and the land restriction in the Imperial Valley ($\frac{dx_{IV,R}^L}{x_{IV,0}^L} = -0.45$). The traditional one step EDM results are presented in the second column of Table 4. While all the proportional results are larger than those derived from an increase in irrigation costs only (Table 3), the traditional one step EDM results are clearly invalid as the ending supply price of land in the Imperial Valley (w_{IV}^{LS}) is projected to be negative having declined by 195%.[9] This is illustrated by the end point of the lower solid arrow in Figure 2. We note that the traditional EDM projects a 24.15% reduction in Imperial Valley production, a smaller decline (relative to Table 3) of 4.37% in the non-California production region and a larger increase (2.84%) in the other California production region. The traditional EDM results indicated a 155% increase in the Imperial Valley derived demand price w_{IV}^L for land, a 3.64% increase in the irrigation input price (w_{IV}^I) and a 4.69% decrease in price of other inputs (w_{IV}^O).

7.2. Results for increased irrigation costs and expanded buffer zones using an almost nonlinear EDM

The iterative EDM approach was used to estimate the impacts of jointly imposing increased irrigation costs and larger buffer zones in the Imperial Valley. In addition to the 38.9% increase in the cost of irrigating leafy greens in the Imperial Valley and non-California production regions, the 45% reduction in land that could be used for leafy greens production in the Imperial Valley is enforced. The results are presented in the third column of Table 4. We note that, with the multistage EDM approach, the supply price of land in the Imperial Valley (w_{IV}^{LS}) is reduced by 94% but remains positive as contrasted to the results of the one-stage EDM which projected a negative land supply price. The supply price of land remains positive, although it approaches zero because of the highly inelastic own-price elasticity of supply of land.

With the Imperial Valley land restriction, the total output of leafy greens from all sources declines by 2.07% and the farmgate price of leafy greens increases by 1.24%. The multistage EDM estimates that leafy greens production in the Imperial Valley declines by 31.93% (which is larger than the 24.15% decline predicted by the one-stage EDM model) while leafy greens production in the other California production region increases by 3.29%. The latter occurs because of an increase in output price. Leafy greens production in the non-California region declines by 3.61%

Table 4 also presents changes in input usage and prices resulting from the combined effect of the two exogenous shocks. The use of land (x_{IV}^L) for producing leafy greens in the Imperial Valley declines by the restricted amount of 45% while its demand price $E(w_{IV}^L)$ (i.e., its marginal value in leafy green production) increases by a substantially larger amount (299%) than with the traditional EDM model (155%). The shadow value price "wedge" of land in the Imperial Valley, $E(\theta_{IV}^L)$, is 393% which equals the sum of the increase in the land demand price ($w_{IV}^L = 299\%$) and the absolute value of the reduction in land supply price ($|w_{IV}^{LS}| = 94\%$). The reduction in the land supply price represents the movement along the assumed constant elasticity leafy greens land supply schedule. Unlike the linear model, the land supply price does not become negative using the almost nonlinear EDM.

The Imperial Valley land use restriction creates a wedge between the region's land supply price and its derived demand price. The derived demand price represents the opportunity cost of land currently used to produce leafy greens and represents the value of that land with respect to leafy

[9]Since $w_{IV,R}^{LS} = w_{IV,0}^{LS}\left(1 + \frac{dw_{IV}^{LS}}{w_{IV,0}^{LS}}\right) = w_{IV,0}^{LS}\left(1 + E(w_{IV}^{LS})\right)$ and $E(w_{IV}^{LS}) = -1.95$ or -195%, the traditional one step EDM approach gives a negative price.

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Table 4. Changes in the endogenous variables resulting from increased irrigation costs and expanded buffer zones

Variable	Linear EDM results for increased irrigation costs and expanded buffer zones	Nonlinear EDM Results for increased irrigation costs and expanded buffer zones	Percent difference
Q	−1.81%	−2.07%	14.4%
P	1.07%	1.24%	15.9%
Q_{IV}	−24.15%	−31.93%	32.2%
Q_{OC}	2.84%	3.29%	15.8%
Q_{NC}	−4.37%	−3.61%	−17.4%
x_{IV}^{L}	−45.00%	−45.00%	0.0%
x_{IV}^{I}	−23.97%	−28.42%	18.6%
x_{IV}^{O}	−23.43%	−31.33%	33.7%
w_{IV}^{L}	155%	299%	93%
w_{IV}^{LS}	−195%	−94%	−51.6%
w_{IV}^{I}	3.64%	−8.88%	−344%
w_{IV}^{O}	−4.69%	−7.13%	52.0%
θ_{IV}^{L}	351%	393%	12.2%
x_{OC}^{L}	1.93%	2.22%	15.0%
x_{OC}^{I}	2.22%	2.56%	15.3%
x_{OC}^{O}	2.94%	3.41%	16.0%
w_{OC}^{L}	8.37%	9.99%	19.4%
w_{OC}^{I}	3.26%	3.79%	16.3%
w_{OC}^{O}	0.59%	0.67%	13.6%
x_{NC}^{L}	−2.17%	−1.71%	−21.2%
x_{NC}^{I}	−11.04%	−9.36%	−15.2%
x_{NC}^{O}	−3.77%	−3.03%	−16.9%
w_{NC}^{L}	−9.43%	−7.23%	−23.3%
w_{NC}^{I}	22.66%	23.12%	2.0%
w_{NC}^{O}	−0.75%	−0.61%	−18.7%

greens production. Note that the marginal value of an additional acre of land in this region substantially exceeds its "supply cost." Suppose a producer could circumvent the buffer region restriction (i.e., an action that would be prohibited). The model suggests that a very high value would be placed on the first acre of land brought back into leafy greens production within the buffer area. However, the marginal value of this activity declines rapidly along the estimated nonlinear derived demand function if additional acres could circumvent the buffer requirement. For example, if the land shock were reduced to 30%, then the shadow value of land in the Imperial Valley declines to 228%. If the shock were further reduced to 10%, then the shadow value becomes 55.8%. The fourth column of Table 4 presents the percentage difference of changes in the endogenous variables between the linear and almost nonlinear EDMs. Most of the differences are between the linear and nonlinear EDM results are relatively larger than reported in Table 3 and range from the smallest difference of 2% for the price of irrigation in the non-California region to as much 344% for the price of irrigation in the Imperial Valley.

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We conclude this section by examining an interesting result of the multi-step EDM. The traditional EDM model predicts that the price of Imperial Valley irrigation inputs w_{IV}^{I} will increase by 3.64 % while the nonlinear EDM results predict an 8.88% decrease in w_{IV}^{I}. A closer examination of the stage-by-stage EDM solutions revealed an increasing price in the first two stages followed by price decreases in stages 3-10. This result occurred because of interactions between the two exogenous shocks and would not have been discovered by a traditional one step approach in which the relative slopes of the supply and demand curves do not change from the initial starting point.[10] These results suggest that the multistage or iterative EDM approach is not only useful when examining relatively large exogenous shocks but should also be considered in models with smaller simultaneous (possibly interacting) exogenous shocks.

8. Summary, caveats, and conclusions

Food safety issues often result in government regulatory actions. In addition, these issues are sometimes addressed by private actions as well. For example, the Leafy Greens Marketing Agreement (LGMA) is a private certification program designed to improve the safety of leafy greens throughout the supply chain. Recent leafy greens food safety events have resulted in revisions to the Produce Safety rule designed to further improve food safety. Furthermore, the FDA has recently instituted new protocols for the testing and treatment of surface water used for irrigating leafy greens. This change will primarily affect the Imperial Valley and non-California (i.e., Arizona and Mexico) production regions. In addition, some have suggested a second mitigation strategy that would increase buffer areas for leafy greens production near CAFO and composting facilities from the current 1-mile radius to a 2-mile radius. This action would primarily affect leafy greens production in the Imperial Valley.

We develop a traditional EDM for these production regions and consider the effects of added irrigation costs on the leafy greens input and output markets. We present a multi-step or "almost nonlinear" EDM methodology that can more accurately assess the effects of relatively large exogenous shocks. The FDA requirements regarding surface irrigation water testing and treatment are estimated to reduce leafy greens production by 5.29% in the Imperial Valley and non-California production regions. These declines are somewhat offset by increases in leafy greens production in the other California region (1.57%). This increase results from an increase in the farmgate price of leafy greens (0.59%). Overall, total leafy greens production would decline by 0.99%. When estimating the effects of the regulatory increase in irrigation costs, the multi-step EDM model estimates that the linear EDM overstates changes in the endogenous variables caused by the policy-induced increases in irrigation costs. However, the overstatement is generally modest and averages 6.4%.

Differences between the conventional and the multistage EDM results are larger when estimating the effects of reducing the Imperial Valley leafy green acreage by 45%. Because of the size of shock (−45%) and the restriction of an input (land) with an inelastic point estimate of its own-price elasticity of supply, the traditional EDM predictions are clearly invalid as the single stage EDM predicts a negative land supply price in the Imperial Valley. The multi-step EDM procedure allows for movements from initial equilibria to follow almost nonlinear equilibrium trajectories. We find that increased irrigation costs and expansion of the buffer areas would reduce overall leafy greens production by 2.07% and increase prices by 1.24%. The multistage EDM results predicts larger declines in Imperial Valley irrigation and other inputs and substantially higher derived demand land prices than the levels predicted by the traditional one step EDM model (a 299% predicted increase rather a 155% increase).

[10]In the multistage approach, the elasticities at the iterated points on the demand and supply curves do not change with each iteration but the implied slopes change as the denominators of the exogenous shock variables are updated.

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We also discovered that, when examining the effects of two simultaneous policy shocks, the almost nonlinear EDM process provides a more accurate assessment of policy interactions because of changes in relative slopes. These results were not anticipated and suggest the need for further exploration in models imposing two or more simultaneous exogenous shocks. We also remind the reader that, due to a lack of data, we imposed the same elasticities of input supply and input substitution across all regions. We suggest that future researchers examine the sensitivity of results using region-specific data.

We conclude this discussion by noting that from a policy perspective, it could be that surface water testing and treatment may obviate the need for expanded buffer areas. We recommend that policy makers at least evaluate if the new FDA rules regarding water treatment and testing accomplishes the goal of improving the safety of leafy greens before expanding mandatory buffer zones. Finally, the reported results are likely lower bound estimates for two reasons. First, the number of CAFO sites in Arizona are increasing. Hence, additional buffer regions could be required in non-California leafy greens production areas. Second, the EDM results represent annual changes. However, leafy greens are a seasonal crop across production regions. During winter months, the Imperial Valley produces approximately 25% of leafy greens consumption. The EDM indicates that the FDA rule may reduce production by 2.66% and increase prices by 1.58% during those months.

Data availability statement. Data are available from the authors upon request.

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