Food *and* Fuel:
Modeling Food System Wide Impacts of Increase in Demand for Soybean Oil

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Executive Summary

Accelerating food price inflation has occurred alongside a rising share of soybean oil going to biofuel production, which has raised questions about the extent to which biofuel policy and expansion have contributed to rising retail food prices for consumers. To address this issue, an economic model of the soybean value chain, from farm to fork, was constructed to identify the effects of shifts in demand for soybean oil for use in biofuels on retail food prices. A summary of overall industry trends and model results are as follows.

- The share of soybean oil going toward biofuel production has quadrupled over the past decade. In the most recent marketing year, 43% of all soybean oil used in the United States went toward biofuel production. While wholesale, crude soybean oil prices held steady for much of the past decade, beginning in the fall of 2020, prices began to rise and have approximately doubled since that time. Moreover, from January 2020 to August 2022, overall grocery prices have increased 21% and retail fat and oil prices have increased 30%.
- Economic model results indicate that a 20% increase in the quantity of soybean oil demanded for use in biofuels (an amount equal to a 1.85 billion lbs of oil equivalent to the increase from the 2020/2021 to the 2021/22 marketing years), occurring in isolation of any other market shocks, has the following effects:
    - Farm-level soybean prices increase 0.73%. Farm revenue for soybean producers increases 0.92%.
    - Crude soybean oil prices increase 8.17%. The fact that actual crude soybean oil prices have increased by a larger amount in recent years suggest that factors beyond increasing biofuel demand have contributed to the price rise.
    - Retail prices for oil used in frying/baking, margarine, salad/cooking oil, and other oil-containing food items increase 0.16%, 0.82%, 4.41%, and 0.16%, respectively. The retail oil price increases are smaller than the wholesale price increases because soybean oil is only a small share of the overall cost involved in producing these retail foods.
    - Retail prices for animal protein products *fall* as a result of rising demand for soy-based biofuels. Retail dairy, beef, pork, chicken, and egg prices are projected by fall by -0.02%, -0.01%, -0.06%, -0.13%, and -0.16%, respectively. Animal product prices fall because soybean meal, a primary animal feed input, is a co-product of the soybean crush, which also produces oil. Rising soybean oil prices leads to an increased supply of oil, which also leads to an increased supply of meal, thereby bringing down meal prices and the prices of animal products that rely on meal.
    - Overall impacts of increased demand for soy-based biofuels on the Consumer Price Index are mixed, but the reductions in meat, dairy and egg prices partially offset the increases in oil and bakery prices, leaving the overall food at home portion of the Consumer Price Index essentially unchanged.

Introduction

Over the past year, consumer prices have increased at a rate not witnessed since the 1970s. The overall Consumer Price Index (CPI) increased 8.3% from August 2021 to August 2022. Food prices have experienced even higher rates of price increases. From August 2021 to August 2022, the food component of the CPI increased 11.4% and the portion of the CPI focused on grocery prices (i.e., food purchased for at-home consumption) increased 13.5%. Figure 1 shows the change in food prices since January 2020. Over this two and a half year time period, grocery prices have increased over 21%. Even higher still, prices of fats and oils have increased almost 30%.

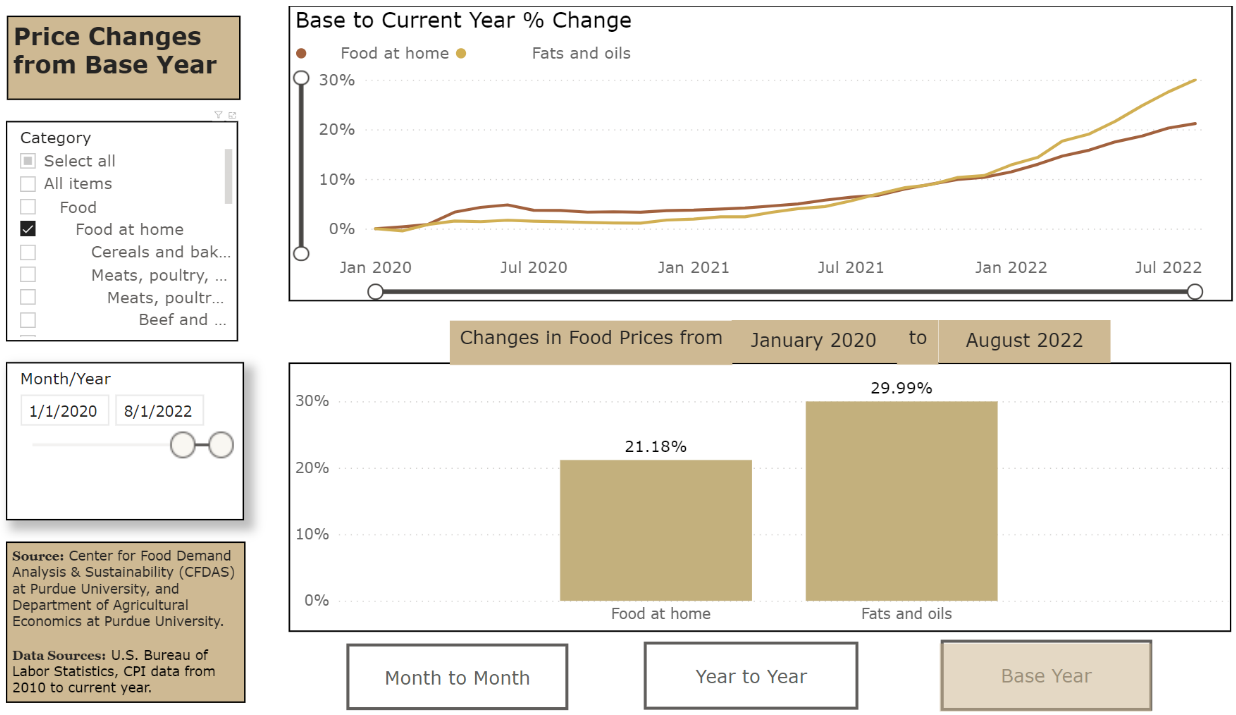

Figure 1. Changes in retail grocery prices from January 2020 to August 2022 (note: underlying data is from the US Bureau of Labor Statistics; additional calculations and illustrations are from the Center for Food Demand Analysis and Sustainability at Purdue University https://ag.purdue.edu/cfdas/resource-library/changes-in-u-s-food-prices/)

Although there are many factors contributing to rising food prices generally, including higher energy and transportation costs, higher wage rates, supply chain disruptions, drought in the Western portion of the U.S., and the war in Ukraine, one factor specific to oils and fats is the increasing amount of soybean oil being used for biofuels.

As shown in figure 2, over the past twenty years, there has been a substantial rise in the share of soybean oil used in the production of biofuels. In 2000, less than 1% of soybean oil was used in the production of biofuels. Today, more than 40% of soybean oil is used in biofuel production. The rate of increase has accelerated in recent years, with the year-over-year use of soybean oil used in biofuel production increasing 12.6% from the 2019/20 to the 2020/21 marketing year and then 20.9% from the 2020/21 to the 2021/22 marketing year.

Although the price of soybean oil fell and then stagnated for the decade leading up to 2019, since that time, crude, wholesale soybean oil prices have increased dramatically, as shown in figure 2. Crude soybean oil prices increased 86% from the 2019/20 to the 2020/21 marketing year and then another 20% from the 2020/21 to the 2021/22 marketing year. Crude soybean oil prices are now at their highest levels in over twenty years in both real and nominal terms. The dramatic increase in crude soybean oil prices coupled with the increased use of soybean oil in biofuels has raised questions about the extent to which increased use of soybean oil in biofuels has contributed to the rising retail prices of food products for consumers.

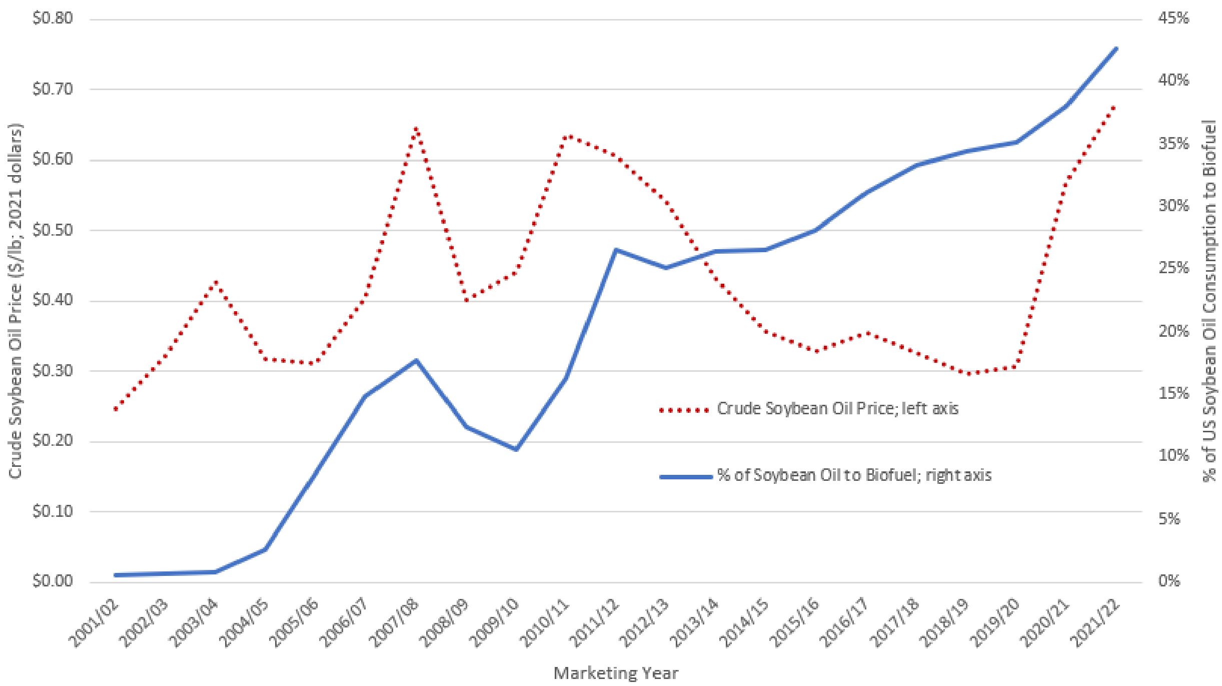

Figure 2. Real Price of Crude Soybean Oil and Use of Soybean Oil in Biofuels, 2001-2022
(note: data are primarily derived from USDA-ERS Oilseed Yearbooks)

The overall objective of this research is to determine the impacts of rising demand for soybean oil in biofuels on retail consumer food prices. While it might seem obvious that rising soybean oil prices would imply higher retail food prices, the situation is more complicated than might be initially presumed.

First, the cost of wholesale soybean oil is only a small part of the overall cost of producing retail food items. The U.S. Department of Agriculture (USDA), Economic Research Service (ERS) estimates that for every $1 consumers spend on food, only about $0.14 is a result of cost of raw farm commodities, implying $0.86 is a result of other post-farm factors such as the costs of transportation, processing, packaging, and retailing. Thus, while increases in the costs of raw-farm commodities have some impact on the retail price of food, the effects are muted because the farm commodity cost share of the retail dollar is relatively low, and as a result, changes in the cost of labor, packaging, transportation, and energy are often have larger impacts on retail food prices than movements in farm commodity prices.

Second, as shown in figure 3, while more soybean oil has been going for use as biofuel, it has not necessarily come at the expense of use of soybean oil for food and other uses.

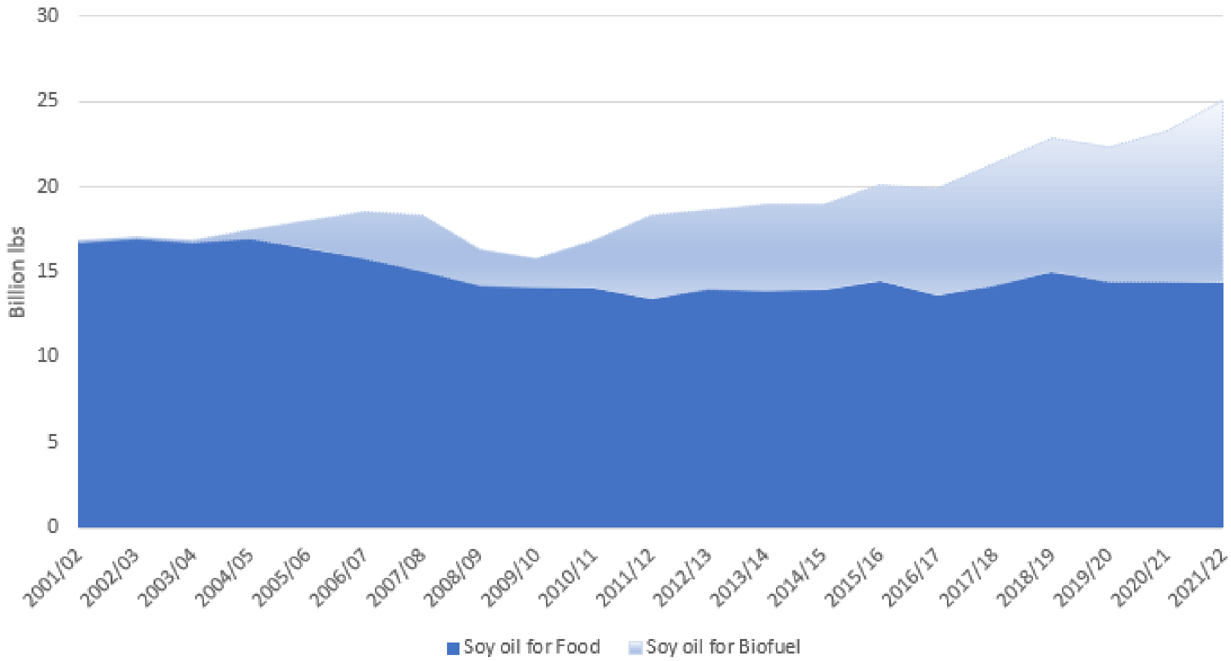

Figure 3. U.S. Soybean Oil Use, 2001-2022 (note: data from USDA-ERS Oilseed Yearbooks)

Third, soybean oil is jointly produced with soybean meal. Soybeans are processed (or "crushed") to produce meal and oil. For every bushel of soybeans weighing 60 lbs, about 11 lbs of soybean oil and 44 lbs of soybean meal are produced. Thus, an increased demand for soybean oil will result in both a larger quantity of soybean oil supplied *and* a larger quantity of soybean meal supplied. A larger quantity of soybean meal on the market will result in lower soybean meal prices (assuming no demand shifts for animal products). That rising demand for soy-based biofuels reduces soybean meal prices is something also observed in prior research (Cui and Martin, 2017). Soybean meal is primarily used as a protein feed source for animal agriculture, which ultimately results in dairy, beef, pork, poultry, and eggs. As a result, lower meal prices reduce the costs of producing animal-based food products, yielding lower retail prices for these food items.

To quantify the magnitude effects of rising soybean oil demand on retail food prices, an economic model is constructed linking farm-supply of soybeans to retail-demand for various food items. The model and model parameterization are described in the next two sections, after which the results are presented.

Economic Model of the U.S. Soybean Value Chain

Figure 3 outlines an economic model of the soybean value chain, with different segments of the chain linked through supply and demand relationships. An equilibrium displacement model is constructed, where endogenous variables consist of changes in quantities and prices from an initial equilibrium that result from a specific exogenous shock to the system (Alston, 1991; Wohlgenant, 2011). The primary shock of interest in this case is an increase in demand for soy-based biofuels.

The model is a simplified version of reality. We do not explicitly model some smaller uses of soybean and soy by-products, such as the relatively small share of soybeans that go directly into animal feed or to human food consumption (e.g., tofu, soy sauce, soy milk); amounts which would be captured in the seed/residual category shown in figure 4. Moreover, we ignore other aspects of the soybean value chain which are relatively small (e.g., soybean imports) or which are not key to the main research question and which can be ignored without changing the central insights (e.g., exports and imports of pork and beef).

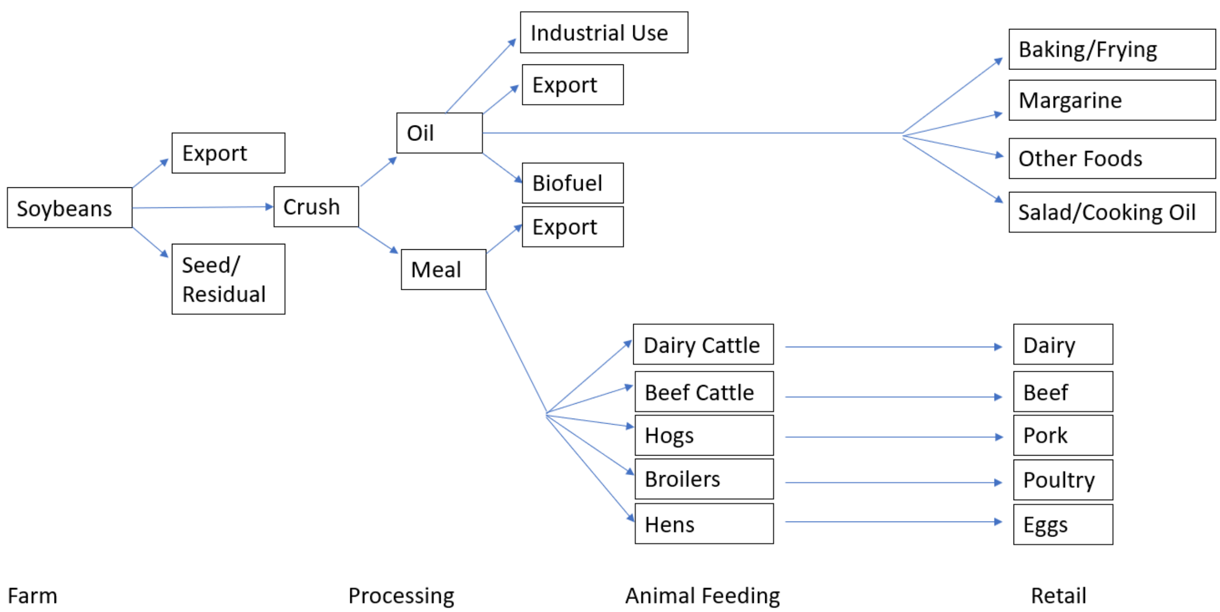

Figure 4. Value chain linking farm production of soy to retail food products

The visual representation of the value chain in figure 3 can be converted to a mathematical representation of the sector. The following characterizes the equilibrium displacement economic model, starting with farm supply of soybeans (the left-hand side of figure 3) and working toward final retail demand (the right-hand side of figure 3).

Farm

The farm-level supply of soybeans is given by:

1) $\hat{x}_{soy} = \varepsilon_{soy}(\widehat{w}_{soy} + k)$

where $\hat{x}_{soy}$ is the proportionate change in soybean supplied by U.S. farmers (note: $\hat{x} = \Delta x/x \approx \text{dln}x/x$), $\widehat{w}_{soy}$ is the proportionate change in farm-level soybean price, ε_{soy} is the own-price elasticity of supply for soybeans, and k is a potential exogenous supply shock associated with a proportional change in marginal cost of soybean production.

The farm supply of soybeans is allocated to three possible uses or markets (see figure 3): export, crush, and seed/feed/residual, as shown in equation (2):

2) $\hat{x}_{soy} = S_{soy\to export}\hat{x}_{soy-export} + S_{soy\to crush}\hat{x}_{soy-crush} + S_{soy\to resid}\hat{x}_{soy-resid}$

where $\hat{x}_j$ is the proportionate change in quantity soybeans allocated to the j^{th} market, and where $S_{soy\to j}$ is the quantity share of soybeans going to the j^{th} market.

Demands for U.S. soybeans by foreign buyers and by seed/feed/residual uses are given by equations (3) and (4), respectively:

3) $\hat{x}_{soy-export} = \eta_{soy-export}\left(\widehat{w}_{soy} + \delta_{soy-export}\right)$

4) $\hat{x}_{soy-resid} = \eta_{soy-resid}\left(\widehat{w}_{soy} + \delta_{soy-resid}\right)$

where η_j is the own-price elasticity of demand for soybeans by market *j*, and δ_j is a potential demand shift (i.e., a proportionate change in willingness to pay by the j^{th} buyer of soybeans).

Processing

The portion of the model related to the soybean crush sector is critical in determining how a change in demand for oil translates into changes in quantity of meal supplied. As such, we characterize this portion of the model as flexibly as possible. In particular, an indirect profit function for the crush sector is characterized as $\pi = f(w_{oil}, w_{meal}, w_{soy}, w_{otherinputs})$, where maximum profit is determined by output (oil and meal) prices and by input (soybean and other inputs such as energy) prices. Hotelling's lemma indicates that the first derivatives of this indirect profit function with respect to an output price yields the supply curve for the good in question, and the first derivative of the indirect profit function with respect to an input price yields the derived demand for the input (multiplied by negative one). These output supply and derived demand equations can be expressed in differential form as a function of supply and demand elasticities.

The derived demand for soybeans by the crushing sector is (assuming the supply of other inputs is perfectly elastic):

5) $\hat{x}_{soy-crush} = \eta_{soy-crush,oil}\widehat{w}_{oil} + \eta_{soy-crush,meal}\widehat{w}_{meal} + \eta_{soy-crush,soy-crush}\widehat{w}_{soy}$

where $\eta_{j,k}$ is the derived demand elasticity for good *j* with respect to a change in the price of input/output *k*. Economic theory imposes restrictions on the signs and magnitudes of these parameters as a result homogeneity and symmetry properties; intuitively, one would expect $\eta_{soy-crush,soy-crush} < 0$, i.e., demand for soybeans for crush in the U.S. falls as soybean prices rise. By contrast, one would expect $\eta_{soy-crush,oil} > 0$ as crushers would demand more soybeans if the price of an output (in this case oil) rises.

The associated output supplies of oil and meal from the crush are given by equations 6) and 7)
6) $\hat{x}_{oil} = \varepsilon_{oil,oil}\widehat{w}_{oil} + \varepsilon_{oil,meal}\widehat{w}_{meal} + \varepsilon_{oil,soy-crush}\widehat{w}_{soy}$
7) $\hat{x}_{meal} = \varepsilon_{meal,oil}\widehat{w}_{oil} + \varepsilon_{meal,meal}\widehat{w}_{meal} + \varepsilon_{meal,soy-crush}\widehat{w}_{soy}$
where $\varepsilon_{j,k}$ are supply elasticities. Again, economic theory places restrictions on the signs and magnitudes of these elasticities. One would expect the own-price supply elasticities, e.g., $\varepsilon_{meal,meal}$, to be positive as crushers seek to produce more output as output prices rise. Importantly, if the cross-price output elasticities are positive, e.g., $\varepsilon_{meal,oil} > 0$, it would imply that more meal is supplied when oil prices rise; a likely outcome give the joint nature of production.

Oil

Now, we focus on the oil-side of the model and extend it completely to final retail consumption before returning to the meal-side of the model. The supply of oil is allocated to one of four different markets: industrial use, exports, food, or biofuels:
8) $\hat{x}_{oil} = S_{oil\to industrial}\hat{x}_{oil-industrial} + S_{oil\to export}\hat{x}_{oil-export} + S_{oil\to food}\hat{x}_{oil-food} + S_{oil\to biofuel}\hat{x}_{oil-biofuel}$
where $S_{oil\to j}$ is the quantity share of soybean oil going to the j^{th} market.

Demands for soy oil for industrial use, by foreign buyers, and by biofuel are given by:
9) $\hat{x}_{oil-industrial} = \eta_{oil-industrial}(\widehat{w}_{oil} + \delta_{oil-industrial})$
10) $\hat{x}_{oil-export} = \eta_{oil-export}(\widehat{w}_{oil} + \delta_{oil-export})$
11) $\hat{x}_{oil-biofuel} = \eta_{oil-biofuel}(\widehat{w}_{oil} + \delta_{oil-biofuel})$

Equation (11) is of key interest and $\delta_{oil-biofuel}$ is the size of the shift in demand for soybean oil used in biofuels. In particular, $\delta_{oil-biofuel}$ is the proportionate change in willingness-to-pay for biofuels (e.g., $\delta_{oil-biofuel} = -0.1$ would imply a 10% increase in willingness-to-pay for soybean oil for use in biofuels). It is the size of the vertical shift in demand curve (i.e., in the price-direction) expressed relative to the initial equilibrium price. It might also be useful to re-write equation (11) as:
11') $\hat{x}_{oil-biofuel} = \eta_{oil-biofuel}\widehat{w}_{oil} + \delta'_{oil-biofuel}$.
Written in this way, the shock, $\delta'_{oil-biofuel}$, is the size of the horizontal shift in demand curve (i.e., in the quantity-direction) expressed relative to the initial equilibrium quantity. So, for example, $\delta'_{oil-biofuel} = 0.1$ would imply a 10% increase in the quantity of soybean oil demanded for use in biofuels. By comparing 11) and 11'), it should be obvious that a horizontal shift in demand of size $\delta'_{oil-biofuel}$ is equivalent to a vertical shift in demand of size $\eta_{oil-biofuel}\delta_{oil-biofuel}$. We make use of 11') in specifying the size of the shock to the model.

Soy oil makes its way to one of four foodstuffs: baking/frying, margarine, other foods using soybean oil, or salad dressing/cooking oil; we chose these four categories because these are the categories for which the United Soybean Board tracks and reports data on soybean oil use for food:

12) $\hat{x}_{oil-food} = S_{oil-food\rightarrow baking}\hat{x}_{oil-baking} + S_{oil-food\rightarrow margarine}\hat{x}_{oil-margarine} + S_{oil-food\rightarrow other}\hat{x}_{oil-other} + S_{oil-food\rightarrow cooking\_oil}\hat{x}_{oil-cooking\_oil}$

where $S_{oil-food\rightarrow j}$ is the quantity share of food-grade soybean oil going to the j^{th} market.

Output constrained derived demands, assuming perfectly elastic supplies of other inputs, for food grade oil by the baking, margarine, salad dressing, and cooking oil industries are:

13) $\hat{x}_{oil-baking} = \eta_{oil-baking}\widehat{w}_{oil} + \hat{Q}_{baking}$

14) $\hat{x}_{oil-margarine} = \eta_{oil-margarine}\widehat{w}_{oil} + \hat{Q}_{margarine}$

15) $\hat{x}_{oil-other} = \eta_{oil-other}\widehat{w}_{oil} + \hat{Q}_{dressing}$

16) $\hat{x}_{oil-cooking\_oil} = \eta_{oil-cooking\_oil}\widehat{w}_{oil} + \hat{Q}_{cooking\_oil}$

where $\hat{Q}_j$ is the proportionate change in the retail quantity of good *j*.

Output supplies, assuming constant returns to scale, for the four oil-based foodstuffs are:

17) $\hat{P}_{baking} = CS_{oil\rightarrow baking}\widehat{w}_{oil}$

18) $\hat{P}_{margarine} = CS_{oil\rightarrow margarine}\widehat{w}_{oil}$

19) $\hat{P}_{other\_food} = CS_{oil\rightarrow other}\widehat{w}_{oil}$

20) $\hat{P}_{cooking\_oil} = CS_{oil\rightarrow cooking\_oil}\widehat{w}_{oil}$

where $\hat{P}_j$ is the proportionate change in the retail price of food *j*, and $CS_{oil\rightarrow j}$ is the share of total cost of producing food output *j* that is explained by the cost of soybean oil.

To complete the oil-side of the model, final retail demands for oil-derived foodstuffs are given by:

21) $\hat{Q}_{baking} = \sum_{j\in\{baking,margarine,other\_food,cooking\_oil\}}\eta_{baking,j}(\hat{P}_j + \delta_j)$

22) $\hat{Q}_{margarine} = \sum_{j\in\{baking,margarine,other\_food,cooking\_oil\}}\eta_{margarine,j}(\hat{P}_j + \delta_j)$

23) $\hat{Q}_{other\_food} = \sum_{j\in\{baking,margarine,other\_food,cooking\_oil\}}\eta_{dressing,j}(\hat{P}_j + \delta_j)$

24) $\hat{Q}_{cooking\_oil} = \sum_{j\in\{baking,margarine,other\_food,cooking\_oil\}}\eta_{cooking\_oil,j}(\hat{P}_j + \delta_j)$

where $\eta_{j,k}$ is the elasticity of demand for retail product *j* caused by a 1% change in the price of product *k*, and δ_j are retail demand shifters indicating the proportionate change in consumer willingness-to-pay for product *j*. Again, note that baking includes both baking and frying oil and cooking oil includes dressing.

Meal

Backing up and moving on to the other side of the crush, the supply of meal is allocated to one of six different markets, exports, dairy cattle, beef cattle, hogs, poultry (meaning meat-producing poultry), and egg-laying hens:

25) $\hat{x}_{meal} = S_{meal\rightarrow export}\hat{x}_{meal-export} + S_{meal\rightarrow dairy\_cattle}\hat{x}_{meal-dairy\_cattle} + S_{meal\rightarrow beef\_cattle}\hat{x}_{meal-beef\_cattle} + S_{meal\rightarrow hogs}\hat{x}_{meal-hogs} + S_{meal\rightarrow poultry}\hat{x}_{meal-poultry} + S_{meal\rightarrow hens\_eggs}\hat{x}_{meal-hens\_eggs}$

where $S_{meal\rightarrow j}$ is the quantity share of soybean meal going to the j^{th} market.

Demand for U.S. meal by foreign buyers is given by

26) $\hat{x}_{meal-export} = \eta_{meal-export}\left(\hat{w}_{meal} + \delta_{meal-export}\right)$.

Output constrained derived demands for meal by dairy cattle, beef cattle, hogs, poultry, and egg-laying hens (assuming perfectly elastic supplies of other marketing inputs) are:

27) $\hat{x}_{meal-diary\_cattle} = \eta_{meal-dairy\_cattle}\hat{w}_{meal} + \hat{x}_{dairy\_cattle}$

28) $\hat{x}_{meal-beef\_cattle} = \eta_{meal-beef\_cattle}\hat{w}_{meal} + \hat{x}_{beef\_cattle}$

29) $\hat{x}_{meal-hogs} = \eta_{meal-hogs}\hat{w}_{meal} + \hat{x}_{hogs}$

30) $\hat{x}_{meal-poultry} = \eta_{meal-poultry}\hat{w}_{meal} + \hat{x}_{poultry}$

31) $\hat{x}_{meal-hens\_eggs} = \eta_{meal-hens\_eggs}\hat{w}_{meal} + \hat{x}_{hens\_eggs}$.

Assuming constant returns to scale, output supply of dairy cattle, beef cattle, hogs, poultry, and egg laying hens.

32) $\hat{w}_{dairy\_cattle} = CS_{meal\rightarrow dairy\_cattle}\hat{w}_{meal}$

33) $\hat{w}_{beef\_cattle} = CS_{meal\rightarrow beef\_cattle}\hat{w}_{meal}$

34) $\hat{w}_{hogs} = CS_{meal\rightarrow hogs}\hat{w}_{meal}$

35) $\hat{w}_{poultry} = CS_{meal\rightarrow poultry}\hat{w}_{meal}$

36) $\hat{w}_{hens\_eggs} = CS_{meal\rightarrow hens\_eggs}\hat{w}_{meal}$

where $CS_{meal\rightarrow j}$ is the share of total cost of producing output *j* that is explained by the cost of meal.

Output constrained derived demands for diary cattle, beef cattle, hogs, poultry, and egg-laying hens, assuming other marketing inputs have perfectly elastic supply, are:

37) $x_{dairy\_cattle} = \eta_{dairy\_cattle}\hat{w}_{dairy\_cattle} + \hat{Q}_{dairy}$

38) $x_{beef\_cattle} = \eta_{beef\_cattle}\hat{w}_{beef\_cattle} + \hat{Q}_{beef}$

39) $x_{hogs} = \eta_{hogs}\hat{w}_{hogs} + \hat{Q}_{pork}$

40) $x_{poultry} = \eta_{poultry}\hat{w}_{poultry} + \hat{Q}_{poultry}$

41) $x_{hens\_eggs} = \eta_{birds\_eggs}\hat{w}_{birds\_eggs} + \hat{Q}_{eggs}$

where $\hat{Q}_j$ are proportionate changes in retail food quantities.

Assuming constant returns to scale, output supply of dairy, beef, pork, poultry, and eggs are:

42) $\hat{P}_{dairy} = CS_{dairy\_cattle\rightarrow dairy}\hat{w}_{dairy\_cattle}$

43) $\hat{P}_{beef} = CS_{beef\_cattle\rightarrow beef}\hat{w}_{beef\_cattle}$

44) $\hat{P}_{pork} = CS_{hogs\rightarrow pork}\hat{w}_{hogs}$

45) $\hat{P}_{poultry} = CS_{birds\rightarrow poultry}\hat{w}_{poultry}$

46) $\hat{P}_{eggs} = CS_{hens\rightarrow eggs}\hat{w}_{hen\_eggs}$

where $CS_{j \to k}$ is the share of total cost of producing retail output *k* that is explained by the cost of input *j*.

Final retail demands for animal-derived foodstuffs are given by:

47) $\hat{Q}_{dairy} = \sum_{j \in \{dairy, beef, pork, poultry, eggs\}} \eta_{dairy,j}(\hat{P}_j + \delta_j)$

48) $\hat{Q}_{beef} = \sum_{j \in \{dairy, beef, pork, poultry, eggs\}} \eta_{beef,j}(\hat{P}_j + \delta_j)$

49) $\hat{Q}_{pork} = \sum_{j \in \{dairy, beef, pork, poultry, eggs\}} \eta_{pork,j}(\hat{P}_j + \delta_j)$

50) $\hat{Q}_{poultry} = \sum_{j \in \{dairy, beef, pork, poultry, eggs\}} \eta_{poultry,j}(\hat{P}_j + \delta_j)$

51) $\hat{Q}_{eggs} = \sum_{j \in \{dairy, beef, pork, poultry, eggs\}} \eta_{eggs,j}(\hat{P}_j + \delta_j)$

The model consists of a total of 51 endogenous variables: proportionate changes in farm- and wholesale-level quantities, $\hat{x}_j$, and prices, $\hat{w}_j$, as well as retail-level quantities, $\hat{Q}_j$, and prices, $\hat{P}_j$. Exogenous shocks consist of supply shifters, *k*, or demand shifters, δ_j. The specific shock of interest in this paper is $\delta'_{oil-biofuel}$. The model can be solved with matrix algebra. Let the 51x1 vector of endogenous variables be represented by **Y**, the 51x1 vector of exogenous shocks be given by **Z**, and let **B** be a 51x51 matrix of model parameters. The aforementioned equations can be written as **YB**=**Z**. The values for the endogenous variables (changes in prices and quantities) are given by: $\mathbf{Y} = \mathbf{B}^{-1}\mathbf{Z}$.

Model Parameterization

To implement the model, values must be assigned to each of the parameters in equations (1) through (51). Table 1 shows each of the values assigned to model parameters and the sources for each value.

Table 1. Assignment of Parameter Values in Equilibrium Displacement Model

Parameter	Eqn	Description	Assigned Value	Source
ε_{soy}	1	Own-price elasticity of supply of soybeans	0.26	Hendricks, Smith, and Sumner (2014)
$S_{soy\rightarrow export}$	2	Quantity share of soybean use going to export	0.476	USDA ERS, Oil Crops Yearbook, Table 3, Average of five marketing years from 2016/17 to 2020/21
$S_{soy\rightarrow crush}$	2	Quantity share of soybean use going to crush	0.496	USDA ERS, Oil Crops Yearbook, Table 3, Average of five marketing years from 2016/17 to 2020/21
$S_{soy\rightarrow resid}$	2	Quantity share of soybean use going to seed, feed, and residual	0.028	USDA ERS, Oil Crops Yearbook, Table 3, Average of five marketing years from 2016/17 to 2020/21
$\eta_{soy-export}$	3	Own-price elasticity of demand for U.S. soy by foreign buyers	-1.45	Reimer, Zheng, and Gehlhar (2012)
$\eta_{soy-resid}$	4	Own-price elasticity of demand for U.S. soy by seed, feed, and residual market	-1	Assumed
$\eta_{soy-crush,oil}$	5	Elasticity of demand for soy for crush with respect to oil price	0.458	Estimated (see description below)
$\eta_{soy-crush,meal}$	5	Elasticity of demand for soy for crush with respect to meal price	0.805	Estimated (see description below)
$\eta_{soy-crush,soy-crush}$	5	Own-price elasticity of demand for soy for crush	-1.031	Estimated (see description below)
$\varepsilon_{oil,oil}$	6	Own-price elasticity of supply of oil from crush	0.506	Estimated (see description below)
$\varepsilon_{oil,meal}$	6	Elasticity of supply of oil with respect to meal price	0.830	Estimated (see description below)
$\varepsilon_{oil,soy-crush}$	6	Elasticity of supply of oil with respect to soybean price	-1.065	Estimated (see description below)
$\varepsilon_{meal,oil}$	7	Elasticity of supply of meal with respect to oil price	0.452	Estimated (see description below)
$\varepsilon_{meal,meal}$	7	Own-price elasticity of supply of meal from crush	0.787	Estimated (see description below)
$\varepsilon_{meal,soy-crush}$	7	Elasticity of supply of meal with respect to soybean price	-1.018	Estimated (see description below)
$S_{oil\rightarrow industrial}$	8	Quantity share of soy oil going to industrial use	0.079	USDA ERS, Oil Crops Yearbook, Table 5, and USB Market View database,

				Average of five marketing years from 2016/17 to 2020/21
$S_{oil \rightarrow export}$	8	Quantity share of soy oil going to export	0.095	USDA ERS, Oil Crops Yearbook, Table 5, and USB Market View database, Average of five marketing years from 2016/17 to 2020/21
$S_{oil \rightarrow food}$	8	Quantity share of soy oil going to food	0.503	USDA ERS, Oil Crops Yearbook, Table 5, and USB Market View database, Average of five marketing years from 2016/17 to 2020/21
$S_{oil \rightarrow biofuel}$	8	Quantity share of soy oil going to biofuel	0.323	USDA ERS, Oil Crops Yearbook, Table 5, and USB Market View database, Average of five marketing years from 2016/17 to 2020/21
$\eta_{oil-industrial}$	9	Own-price elasticity of demand for soy oil for industrial use	-0.50	Kojima et al. (2016)
$\hat{\eta}_{oil-export}$	10	Own-price elasticity of demand for U.S. soy oil by foreign buyers	-1.29	Uri et al. (1994)
$\hat{\eta}_{oil-biofuel}$	11	Own-price elasticity of demand for U.S. soy by biodiesel	-0.60	Assumed
$S_{oil-food \rightarrow baking}$	12	Quantity share of soy oil for food going to baking or frying	0.32	Market View database, Average of five marketing years from 2016/17 to 2020/21
$S_{oil-food \rightarrow margarine}$	12	Quantity share of soy oil for food going to margarine	0.02	Market View database, Average of five marketing years from 2016/17 to 2020/21
$S_{oil-food \rightarrow other}$	12	Quantity share of soy oil for food going to other edible products	0.01	Market View database, Average of five marketing years from 2016/17 to 2020/21
$S_{oil-food \rightarrow cooking\_oil}$	12	Quantity share of soy oil for food going to salad and cooking oil	0.65	Market View database, Average of five marketing years from 2016/17 to 2020/21
$\eta_{oil-baking}$	13	Own-price elasticity of derived demand for soy oil for baking and frying	-0.25	Assumed
$\eta_{oil-margarine}$	14	Own-price elasticity of derived demand for soy oil for margarine	-0.50	Yen et al. (2002)

$\eta_{oil-other}$	15	Own-price elasticity of derived demand for soy oil for other edible products	-0.25	Assumed
$\eta_{oil-cooking\_oil}$	16	Own-price elasticity of derived demand for soy oil for salad and cooking oil	-0.25	Yen et al. (2002)
$CS_{oil\rightarrow baking}$	17	Share of the total cost of producing baking and frying products explained by the cost of producing soybean oil	0.02	Based on data in Lusk (2022)
$CS_{oil\rightarrow margarine}$	18	Share of the total cost of producing margarine explained by the cost of producing soybean oil	0.10	Based on data in Lusk (2022)
$CS_{oil\rightarrow other}$	19	Share of the total cost of producing other foods explained by the cost of producing soybean oil	0.02	Based on data in Lusk (2022)
$CS_{oil\rightarrow cooking\_oil}$	20	Share of the total cost of producing salad and cooking oil explained by the cost of producing soybean oil	0.54	Based on data in Lusk (2022)
η_{baking}	21	Own-price elasticity of demand for baking and frying	-0.50	Assumed
$\eta_{margarine}$	22	Own-price elasticity of demand for margarine	-1.00	Yen et al. (2002)
η_{other}	23	Own-price elasticity of demand for other edible products	-0.50	Assumed
$\eta_{cooking\_oil}$	24	Own-price elasticity of demand for salad and cooking oil	-0.50	Yen et al. (2002)
$S_{meal\rightarrow export}$	25	Quantity share of soybean meal that is exported	0.27	USDA ERS, Oil Crops Yearbook, Table 4. Average of five marketing years from 2016/17 to 2020/21
$S_{meal\rightarrow dairy\_cattle}$	25	Quantity share of soybean meal going to dairy cattle	0.09	USB Market View database, USDA ERS, Oil Crops Yearbook, Table 4. Average of five marketing years from 2016/17 to 2020/21
$S_{meal\rightarrow beef\_cattle}$	25	Quantity share of soybean meal going to beef cattle	0.08	USB Market View database, USDA ERS, Oil Crops Yearbook, Table 4. Average of five marketing years from 2016/17 to 2020/21
$S_{meal\rightarrow hogs}$	25	Quantity share of soybean meal going to hogs	0.14	USB Market View database, USDA ERS, Oil Crops Yearbook, Table 4. Average of five marketing years from 2016/17 to 2020/21
$S_{meal\rightarrow poultry}$	25	Quantity share of soybean meal going to poultry meat production	0.32	USB Market View database, USDA ERS, Oil Crops

				Yearbook, Table 4. Average of five marketing years from 2016/17 to 2020/21. Assumes 75% of poultry feed is for meat production
$S_{meal \rightarrow poultry}$	25	Quantity share of soybean meal going to egg laying hens	0.10	USB Market View database, USDA ERS, Oil Crops Yearbook, Table 4. Average of five marketing years from 2016/17 to 2020/21. Assumes 25% of poultry feed is for egg laying
$\eta_{meal-export}$	26	Own-price elasticity of derived demand for soy meal exports	-1.49	Uri et al. (1994)
$\eta_{meal-dairy\_cattle}$	27	Own-price elasticity of derived demand for U.S. soy meal for dairy cattle	-0.38	Suh and Moss (2016)
$\eta_{meal-beef\_cattle}$	28	Own-price elasticity of derived demand for U.S. soy meal for beef cattle	-0.38	Suh and Moss (2016)
$\eta_{meal-hogs}$	29	Own-price elasticity of derived demand for U.S. soy meal for hogs	-0.38	Suh and Moss (2016)
$\eta_{meal-poultry}$	30	Own-price elasticity of derived demand for U.S. soy meal for poultry	-0.38	Suh and Moss (2016)
$\eta_{meal-hens\_eggs}$	31	Own-price elasticity of derived demand for U.S. soy meal for egg laying hens	-0.38	Suh and Moss (2016)
$CS_{meal \rightarrow dairy\_cattle}$	32	Share of the total cost of producing dairy cattle explained by the cost of producing soybean meal	0.03	USB Market View database, USDA NASS value of production. Average of five years from 2016 to 2020
$CS_{meal \rightarrow beef\_cattle}$	33	Share of the total cost of producing beef cattle explained by the cost of producing soybean meal	0.01	USB Market View database, USDA NASS value of production. Average of five years from 2016 to 2020
$CS_{meal \rightarrow hogs}$	34	Share of the total cost of producing hogs explained by the cost of producing soybean meal	0.10	USB Market View database, USDA NASS value of production. Average of five years from 2016 to 2020
$CS_{meal \rightarrow poultry}$	35	Share of the total cost of producing poultry explained by the cost of producing soybean meal	0.16	USB Market View database, USDA NASS value of production. Average of five years from 2016 to 2020
$CS_{meal \rightarrow hens\_eggs}$	36	Share of the total cost of producing egg laying hens explained by the cost of producing soybean meal	0.14	USB Market View database, USDA NASS value of production. Average of five years from 2016 to 2020

η_{dairy_cattle}	37	Own-price elasticity of derived demand for dairy	-1.40	Lee et al. (2022), table 9
η_{beef_cattle}	38	Own-price elasticity of derived demand for slaughter cattle	-0.60	Lee et al. (2022), table 9
η_{hogs}	39	Own-price elasticity of derived demand for slaughter hogs	-0.47	Lee et al. (2022), table 9
$\eta_{poultry}$	40	Own-price elasticity of derived demand for wholesale poultry	-0.49	Lee et al. (2022), table 9
η_{birds_eggs}	41	Own-price elasticity of derived demand for eggs	-0.25	Lee et al. (2022), table 9
$CS_{dairy\_cattle \rightarrow dairy}$	42	Farm share of retail dollar for dairy	0.33	Lee et al. (2022), table 8
$CS_{beef\_cattle \rightarrow beef}$	43	Farm share of retail dollar for beef	0.53	Lee et al. (2022), table 8
$CS_{hogs \rightarrow pork}$	44	Farm share of retail dollar for pork	0.31	Lee et al. (2022), table 8
$CS_{birds \rightarrow poultry}$	45	Farm share of retail dollar for poultry	0.43	Lee et al. (2022), table 8
$CS_{hens \rightarrow eggs}$	46	Farm share of retail dollar for eggs	0.58	Lee et al. (2022), table 8
$\eta_{dairy,dairy}$	47	Own-price elasticity of retail demand for dairy	-0.14	Lee et al. (2022), table 8
$\eta_{beef,beef}$	48	Own-price elasticity of retail demand for beef	-0.70	Lee et al. (2022), table 8
$\eta_{pork,pork}$	49	Own-price elasticity of retail demand for pork	-1.26	Lee et al. (2022), table 8
$\eta_{poultry,poultry}$	50	Own-price elasticity of retail demand for poultry	-0.81	Lee et al. (2022), table 8
$\eta_{egg,egg}$	51	Own-price elasticity of retail demand for eggs	-0.24	Lee et al. (2022), table 8

Estimation of Crush Sector Parameters

Given the important role of the economic relationships in the soybean crush sector, the derived demand and output supplies are estimated. Conceptually, an indirect profit function for the crush sector is characterized as $\pi = f(w_{oil}, w_{meal}, w_{soy}, w_{otherinputs})$. Following, Diewert and Wales (1988), Lau (1978), Shumway and Alexander (1988) and Shumway, Saez, and Gottret (1988), this indirect profit function can be approximated using the normalized quadratic form, which has the benefit of easily imposing several theoretical restrictions on the supply/demand relationships. First, homogeneity can be imposed by normalizing prices with respect to one of the inputs/outputs. Normalizing with respect to the price of other inputs, define $\pi^* = \pi / w_{otherinputs}$ and $w_j^* = w_j / w_{otherinputs}$. Then, the normalized quadratic indirect profit function is:

$$\pi^* = \alpha_0 + \alpha_1 w_{oil}^* + \alpha_2 w_{meal}^* + \alpha_2 w_{soy}^* + 0.5(\beta_{oil,oil} {w_{oil}^*}^2 + \beta_{oil,meal} w_{oil}^* w_{meal}^* + \beta_{oil,soy} w_{oil}^* w_{soy}^* + \beta_{meal,oil} w_{meal}^* w_{oil}^* + \beta_{meal.meal} {w_{meal}^*}^2 + \beta_{meal,soy} w_{meal}^* w_{soy}^* + \beta_{soy,oil} w_{soy}^* w_{oil}^* + \beta_{soy.meal} w_{soy}^* w_{meal}^* + \beta_{soy,soy} {w_{soy}^*}^2).$$

Symmetry is imposed by all the cross-products equal., e.g., by setting $\beta_{oil,meal} = \beta_{meal,oil}$. Hotelling's lemma gives the output supply equations for oil and meal and the input demand equation for soybeans:

$$\frac{\partial \pi^*}{\partial w^*_{meal}} = x_{meal} = \alpha_{meal} + \beta_{meal,meal} w^*_{meal} + \beta_{meal,oil} w^*_{oil} + \beta_{meal,soy} w^*_{soy}$$

$$\frac{\partial \pi^*}{\partial w^*_{oil}} = x_{oil} = \alpha_{oil} + \beta_{meal,oil} w^*_{meal} + \beta_{oil,oil} w^*_{oil} + \beta_{oil,soy} w^*_{soy}$$

$$\frac{\partial \pi^*}{\partial w^*_{soy}} = -x_{soy} = \alpha_{soy} + \beta_{meal,soy} w^*_{meal} + \beta_{oil,soy} w^*_{oil} + \beta_{soy,soy} w^*_{soy}.$$

Once the parameters have been estimated, elasticities are straightforward to estimate. For example, the own-price elasticity of demand for soybeans for crush is calculated as $\eta_{soy-crush,soy-crush} = \beta_{soy,soy}(\frac{\bar{w}^*_{soy}}{-\bar{x}_{soy}})$, where $\bar{w}^*_{soy}$ is the mean value of the normalized price of soybeans and $\bar{x}_{soy}$ is the mean quantity of soybeans going to crush. As another example, the own-price elasticity of supply of oil from crush is: $\varepsilon_{oil,oil} = \beta_{oil,oil}(\frac{\bar{w}^*_{oil}}{\bar{x}_{oil}})$.

Data from the USDA ERS, Oil Crops Yearbook from marketing years 1980/81 to 2021/22 are used for all the quantity and price variables except the price of "other inputs." For this variable, electricity prices obtained from the Bureau of Labor Statistics over the same time period were used.[1] The parameters of the input demand and output supply equations are estimated jointly using iterative seemingly unrelated regressions. Estimates are shown below in table 2, where quantity values are in billions of pounds and prices of oil, meal, and soybeans ($/lb) are normalized by the price of electricity ($/kwh). Estimates are of expected signs and magnitude. Of particular note is the cross-price supply elasticities between oil and meal are positive, meaning the two outputs are complements in production, which is expected given the two are jointly produced as a part of the crush process.

[1] As an alternative to electricity prices, the price of natural gas sold to commercial consumers obtained from the Energy Information Administration was also considered. However, using electricity prices provided yielded a model with better fit (average R^2 across the three equations of 0.17) than using natural gas prices (average R^2 across the three equations of 0.07). In either case, the parameters are all of the same sign and elasticities are of similar magnitude.

Table 2. Estimates of Normalized Quadratic Profit Function Parameters for the Crush Sector

Parameter	Estimate
α_{meal}	56.996*[a] (6.948)[b]
α_{oil}	12.761* (1.827)
α_{soy}	-71.176* (8.846)
$\beta_{meal,meal}$	47.833* (16.737)
$\beta_{meal,oil}$	12.053* (4.386)
$\beta_{meal,soy}$	-61.716* (21.335)
$\beta_{oil,oil}$	3.221* (1.157)
$\beta_{oil,soy}$	-15.437* (5.602)
$\beta_{soy,soy}$	79.020* (27.260)
$\eta_{soy-crush,oil}$	0.458* (0.166)
$\eta_{soy-crush,meal}$	0.805* (0.278)
$\eta_{soy-crush,soy-crush}$	-1.031* (0.356)
$\varepsilon_{oil,oil}$	0.506* (0.182)
$\varepsilon_{oil,meal}$	0.830* (0.302)
$\varepsilon_{oil,soy-crush}$	-1.065* (0.387)
$\varepsilon_{meal,oil}$	0.452* (0.165)
$\varepsilon_{meal,meal}$	0.787* (0.276)
$\varepsilon_{meal,soy-crush}$	-1.018* (0.352)

Note: Model estimated via iterative seemingly unrelated regression using 42 annual observations from 1980/81 to 2021/22.

[a]One asterisk represents statistical significance at the 0.01 level or lower.

[b]Numbers in parentheses are standard errors.

Results

Equations (1) through (51) outline a system of equations linking farm supply of soybeans to the retail consumption of food products produced with soybean oil and meal. Along with the parameters reported in table 1, the remaining parameter needed to implement the model is the exogenous shock affecting the equilibrium prices and quantities. For this, the value of $\delta'_{oil-biofuel} = 0.2$ is assigned. This implies a 20% increase in the quantity of soybean oil demanded for use in biofuels. This amount is equivalent to a 1.85 billion lb increase in use of soybean oil in biofuels that occurred from the 2020/2021 to the 2021/22 marketing years. The reported results below are those occurring from the 20% demand increase in soybean oil used in biofuel production, assuming no other supply or demand shocks to the soybean value chain.

Starting at the farm level, the shift in demand for soybean oil for use in biofuels increases the quantity of soybeans produced (0.19%) and the farm-level price of soybeans (0.73%), as shown in table 3. As a result, revenue for soybean producers increases by 0.19% + 0.73% = 0.92%. Soybean exports fall by 1.06% and use of soybeans for residual use falls 0.73%. Soybeans going to domestic crush increase 1.44%. Soybean oil price increases 8.17% and the quantity of oil produced increases 1.76%. There is a corresponding increase in meal production (+1.44%) and a reduction in price of meal (-1.93%).

Table 3. Changes in Prices and Quantities

Item	Quantity	Price
Soybean production	0.19%	0.73%
Soybean exports	-1.06%	
Soybean crushed	1.44%	
Soybean residual	-0.73%	
Soybean oil	1.76%	8.17%
Soybean meal	1.44%	-1.93%

Because soybean meal and oil are co-products of the soybean crush, an increase in demand for soybean oil results in an increase in quantity of both oil and meal supplied. Soybean meal is a primary input to animal protein production. Falling soybean meal prices ultimately lead to lower animal product prices.

Figure 5 shows the projected changes in retail food prices resulting from the underlying changes in oil and meal prices and production. As shown in figure 4, the retail prices of oil-containing food prices rise. The largest projected increase is for salad and cooking oil (4.41%) followed by margarine (0.82%) and baking and frying oil and other foods containing oil (0.16%). These increases are much smaller than the increase in crude, wholesale soybean oil price rise (8.17%). A key explanation for this difference is that cost of wholesale soybean oil only represents a small share of the cost of retail food items.

These results are very similar to the simple price pass-through analysis conducted by Lusk (2022). In that report, it was calculated that for every 1% increase crude soybean oil prices, the retail price of, for example, cookies would increase by 0.0184% and the retail price of cooking oil would increase 0.54%. Using the 8.17% increase in crude soy oil prices implied by the model in this paper (see table 3) and the pass-through rates in the prior analysis (Lusk, 2022) would imply an 8.17 * 0.0184 = 0.15% increase in retail cookie prices (very similar to the value for bakery items shown in figure 4) and an 8.17 * 0.54 = 4.41% increase in cooking oil prices, exactly what is found in the present study. The advantage of the model presented in the present research is that it can also make projections about impacts upstream soybean prices and downstream meat prices.

Although oil-containing food prices rise, prices of retail animal products fall as a result of the increased demand for soybean oil used in biofuels. As shown in figure 4, retail dairy, beef, pork, chicken, and egg prices are projected to fall by -0.02%, -0.01%, -0.06%, -0.13%, and -0.16%, respectively. These price changes, while negative, are small primarily because the cost of soybean meal is a relatively small share of the cost of retail food products. Costs of producing egg and poultry are more dependent on cost of soybean meal (see table 1), and as a result, these final retail products are the ones with the largest declines.

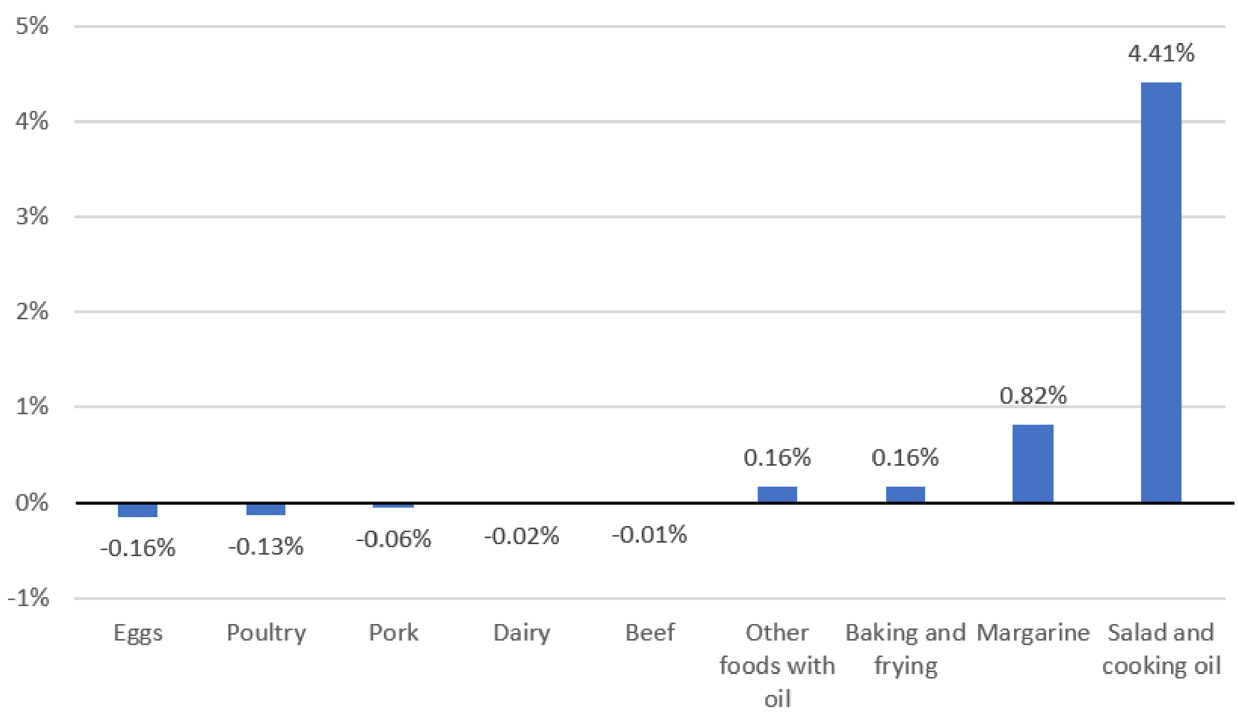

Figure 5. Change in Retail Food Prices Resulting from 20% Increase in Demand for Soybean Oil Used in Biofuels

Coupling changes in retail prices (figure 5) with projected changes in the quantity of each retail product consumed provides an estimate of the change in consumer expenditures on each food item (see figure 6). Although the price of salad and cooking oil is projected to rise by 4.41%, consumer expenditures on salad and cooking oil only rise by about half that amount, 2.21%. The reason is that consumers reduce the quantity of salad and cooking oil consumed as they substitute toward more affordable alternatives. Overall figure 5, suggests changes in consumer spending resulting from the increased demand for soy-based biofuels are very small for most items.

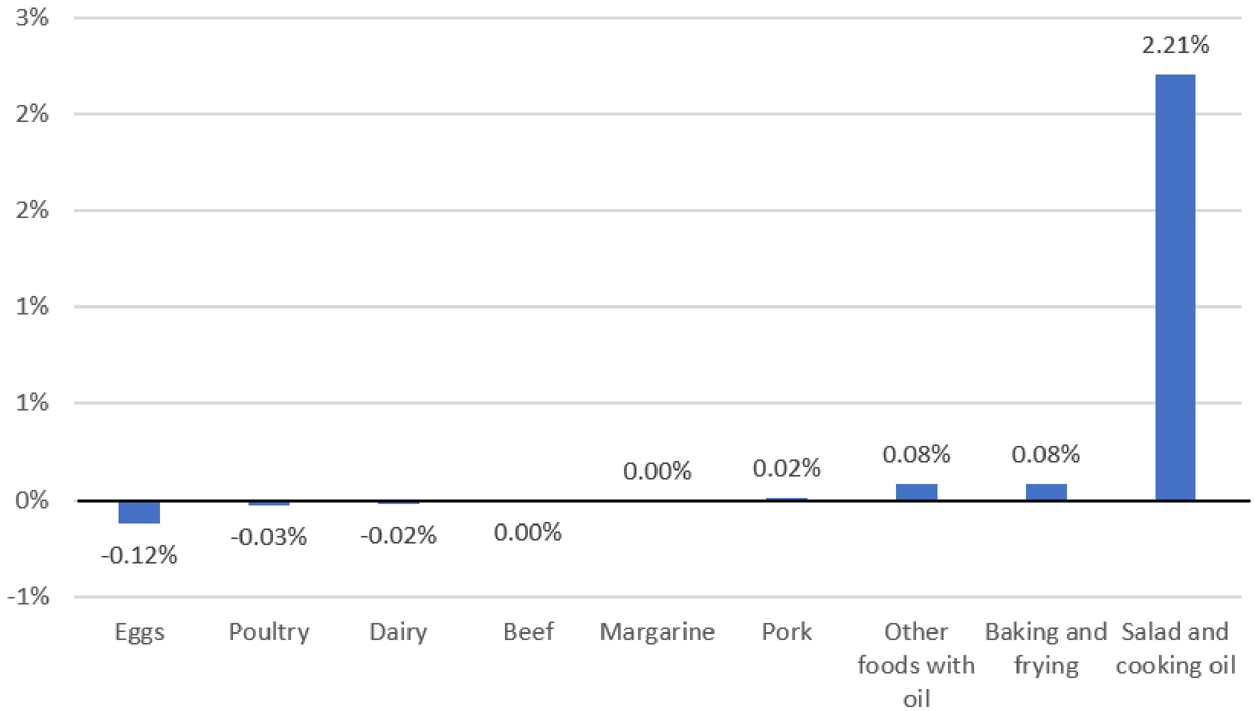

Figure 6. Change in Retail Consumer Food Expenditures Resulting from 20% Increase in Demand for Soybean Oil Used in Biofuels

Because oil-based retail food prices increase and meal-based food prices decline, the net impact on the overall cost of food for consumers is mixed. To determine the overall net effect on retail food prices, one can utilize the expenditure weights reported by the Bureau of Labor Statistics (BLS) in their calculation of the Consumer Price Index (CPI). In particular, focus is on expenditure weights used in the food-at-home (i.e., grocery) component of the CPI. The categories used by the BLS do not perfectly match that of the model in this paper and their categories combine soy-based and non-soy-based items (e.g., butter and margarine is one combined category as is fats and oils). Nonetheless, making assumptions about the share of expenditures in a combined category resulting from soy-based products, one can determine the net impact on the food-at-home component of the CPI. The estimated price changes in figure 4 coupled with the adjusted BLS expenditure weights suggest a 20% increase in quantity of soybean oil demanded for use in biofuels increases the food-at-home component of the CPI by only 0.05%.

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