# Economic, Resource, and Environmental Consequences of Changes in By-Product use by Dairies

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*ABSTRACT.* By-product feeds are widely used by dairy farms, especially in places with diverse crop agriculture. For example, more than 70 distinct by-product feeds are used in California dairy rations—ranging from manufacturing waste like brewery spent grains to first stage processing of farm products, such as almond hulls and cotton seed. Some of these by-products are major contributors to dairy feed rations. In this paper we develop and apply stochastic simulation models of by-product supply from crop industries and demand for by-product feeds from dairy farms. We simulate the likely effects of (a) reductions in the demand for the by-product from dairies, say due to a decline in the size of the local dairy industry, and (b) effects of reduction in supply of the by-products that are available to dairies. Results indicate that large changes in demand for, or supply of, almond hulls lead to quite small changes in the prices or quantities of milk and almonds. However, we find that large by-product demand shifts can have substantial resource use and environmental consequences.

**Key Words**: by-product feeds, dairy rations, almond hulls, feed resource use

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Dairies provide an important outlet for by-products from farm commodity processing by using these by-products as feed. As part of an associated study, we surveyed California dairies about by-product use and found that that 97% of cows were fed by-product feeds during 2018. Use of by-products reduce dairy production costs and demand for other, resource-intensive, feeds. By-product use on dairies also provides a source of revenue (or reduction in costs) for industries that may otherwise face disposal costs. For example, a national survey from the Brewers Association found that for small breweries, 90% of spent grain (a by-product of brewing) is used as animal feed (BA, 2013). That survey also found that spent grain removal operations provided a net income, or were revenue neutral, for 89% of small breweries.

Not only is there an economic benefit for dairies and other industries from by-product use, but there are also positive environmental contributions mainly because of reduced use of natural resources and less pollution (including methane) from otherwise disposed organic matter.

Focusing in detail on the almond industry as illustrative of other substantial by-product feed suppliers, we show how they would respond to a reduction in by-product demand from dairies and how the dairy industry would respond to a reduction in supply availability of the by-product. We derive and apply simulation models for dairies and by-product supplying industry.

A careful model of a by-product supplying industry allows us to simulate the effects of a reduction in the dairy demand for the industry by-product. Such a reduction in by-product demand could occur, for example, if the dairy industry were to shrink because of regulations or other market disadvantages. With fewer cows to feed, the demand for by-product feeds would decline, which implies a fall in quantity of output and related impacts in the by-product industry. Impacts include resource and environmental consequences. A model of milk production and feed use shows implications of reduced supply of by-products to the dairy industry. Such a reduction in supply of by-products could be the result, for example, of a policy change mandating by-products be subject to more costly government regulations. The consequences are higher production costs and milk prices, and lower the quantity of milk output. At the same time the quantity of other feeds used by the dairy industry rises. Shifts in demand for other feeds allow us to quantify implications of resources that would be required to produce replacement feeds, and to estimate associated environmental consequences.

**Model of By-Product Industry Response to Demand Change**

Consider a model of supply and demand of two goods, one of which we label as the by-product that is used as feed by dairies. We characterize the model in a general functional form so it may be adapted for the almond and other by-product industries. We use this model to trace the potential impact of a shift in by-product demand by dairies through the industry producing the by-product. This shift is introduced in the demand function for by-products, and we determine its effect on the good associated with the by-product. We also determine additional consequences for resource use or the environment and simulate changes in inputs used to produce the by-product and its associated good.

Two outputs, the main good (subscript G) and the by-product (subscript B), are produced as a function of inputs such as water, land, labor, capital, etc., which we combine to a composite input $z_G$, under constant returns to scale technology:

(1) $Q_G = G(z_G)$ and

(2) $Q_B = B(z_G)$,

where $Q_G$ is the quantity produced of the good as a function of the input, and $Q_B$ is the quantity produced of the by-product as a function of the same inputs. By-products are sometimes considered as inputs to production of the main good, because there is sometimes a cost associated with their disposal. However, in our model, we consider them as outputs, and they may receive a positive price from dairies. We assume that the good and its by-product are produced in fixed proportions ($Q_G = \lambda Q_B$, where $\lambda$ is a factor expressing the proportion of units of by-product and units of the good that are produced from the same set of inputs).

Quantities of inputs and outputs depend on relative prices so we can express the output supplies and the input demands as functions of prices: $P_G$, the price of the good; $P_B$, the price of the by-product; and $P_{z_G}$, the composite input price.

The revenue per unit of the good produced, is the sum of the prices for the good and the by-product, with the proportionality factor included:

(3) $R_G = P_G + \frac{1}{\lambda} P_B$,

where $P_G$ is the price of the good, and $P_B$ is the average price of the by-product (share weighted sum of the by-product sold to dairies or other farms and the cost of by-product disposal.

Considering almond hulls for example, two pounds of almond hulls are produced per pound of almond kernels, so that $\lambda = 1/2$.

For simplicity, we assume inputs are used in fixed proportions, and technology has constant returns to scale (CRS); therefore, industries have homothetic production functions, and input ratios are constant with respect to scale of production of firms and the industry. For simplicity, firms treat input and output prices as exogenous. We also assume that the price of the composite input used in production of the good and by-product remains constant. We could incorporate a technology shift in the magnitude of $\lambda$ in the model, but we assume the ratio does not change in response to the shocks considered here. Instead we focus on a change in demand of by-products from dairies.

*By-Product Supply and Demand Model*

We have a set of supply and demand equations for the good and its corresponding by-product,

(4) $Q_G = Q_G^S(R_G; P_{z_G})$,

(5) $Q_G = Q_G^D(P_G)$,

(6) $Q_f = Q_f^D(P_B; \theta)$, and

(7) $Q_o = Q_o^D(P_B)$.

In equation (4), $Q_G$ is the quantity supplied of the good as a function of the revenue from the good and the composite input price. In equation (5), $Q_G$ is the quantity demanded of the good as a function of the price of the good. Equation (6) represents the demand for by-products as a function of the by-product price, $P_B$, where $\theta$ represents a potential vertical shift in demand for by-product feeds by the dairy industry. Equation (7) represents the quantity of by-products demanded by all others (such as from other farms or disposal, if there is no demand at a positive price).

The model is constructed to consider a vertical demand shift (change in willingness to pay at a given quantity), but by multiplying the shift by the own-price elasticity for the by-product, it is equivalent to a horizontal shift (change in quantity demanded at a given price). The total quantity demanded of by-products is equal to the sum of the two quantities demanded,

(8) $Q_B = Q_f + Q_o$.

As discussed previously, both the good and its by-product are produced in fixed proportion. In equilibrium, they must be consumed in the same proportion (where disposal is part of by-product consumption). We express the market-clearing condition in terms of the inverse supply function and sum of the inverse demand functions:

(9) $$R_G\left(Q_G^S; P_{z_G}\right) = P_G\left(Q_G^D\right) + \frac{1}{\lambda} P_B\left(Q_f^D, Q_o^D; \theta\right).$$

The next section expresses the model in log-differential form to facilitate the simulations that can be parameterized by shares and elasticities.

*Economic Model for By-Product Market Simulations*

We consider a simple model based on the set of equations above to simulate how the market for a good adjusts if demand changes for the by-product of the good, which is used by California dairies as feed. Relevant expositions of this framework for our model include Alston and James (2002) and Wohlgenant (2011), who describes a general approach with multiple outputs or inputs. A recent paper of Lee, Sumner, and Champetier (2019), describes a system with two connected output markets and a production possibility frontier (almonds and honey bees), and includes simulated confidence intervals, based on distribution assumptions about parameters. Sambucci, Sumner and Goldstein (2020) apply a similar approach to consider impacts of policy change in two closely related Cannabis markets (one regulated and one not).

We derive the impact on our markets of interest using supply and demand equations of the good and its by-product and the market-clearing condition. The model has no need for a demand equation for input to production of the good and its by-product. The quantity of input demanded by good and by-product producers is determined by the supply and demand conditions for these products. This condition, which stems from the assumptions of CRS and fixed proportions production, allows us to use the model to determine quantity of input into good and by-product usage.

The demand and supply equations may be expressed in log-differential form for the good and its by-product using the same notation as in equations (1) - (9). Equations (10) - (14) are derived from the system of supply and demand functions for the by-product and its good. Equation (10) is the inverse supply function with revenue per unit as the dependent variable, where the elasticity of supply is denoted as $\epsilon$. Equation (10) is derived from equation (4) and revenue per unit is defined in equation (3).

(10) $$dlnR_G = dlnQ_G/\epsilon$$

Equation (11) is the inverse demand of the good, where $\eta_G$ is an own-price elasticity of demand for the good. It is derived from equation (5).

(11) $dlnP_G = dlnQ_G/\eta_G$

Equation (12) is the share weighted sum of by-products demanded by dairies and others, where $\psi$ is the share of by-products demanded by dairies.

(12) $dlnQ_B = \psi dlnQ_f + (1-\psi)dlnQ_o$

Equations (13) and (14) are derived from equations (6) and (7). They express the quantity demanded of by-products, where $\eta_f$ and $\eta_o$ are own-price elasticities of demand, and $\theta$ represents a vertical shift in demand, expressed as a willingness to pay per unit, for by-products from dairies. The proportional horizontal shift in quantity demanded is therefore $\eta_f\theta$.

(13) $dlnQ_f = \eta_f dlnP_B - \eta_f\theta$

(14) $dlnQ_o = \eta_o dlnP_B$

Equation (15) is the revenue per unit of the good as a function of the good and by-product prices, where $\omega$ is the revenue share of the good as a percentage of the total revenue per unit of the good. This share would be greater than 1 when the by-product price is negative (that is when there is a disposal cost).

(15) $dlnR_G = \omega dlnP_G + (1-\omega)(dlnP_B - dln\lambda)$

Equation (16) relates the change in quantity demanded of the by-product to the change in quantity demanded of the good. The percent changes are equal as they are produced in fixed proportions.

(16) $dlnQ_G = dlnQ_B$

Table 1 displays all the notation and definitions. It includes quantities, revenue, prices, shares, function shift parameters, the by-product production ratio, and supply and demand elasticities.

**Table 1. Supply and Demand Model Notation and Definitions**

| Parameter | Definition |
|---|---|
| $Q_G$ | Quantity of the good, units of the good |
| $Q_B$ | Quantity of the by-product, units of the by-product |
| $Q_f$ | Quantity of the by-product going to dairies, units of by-product |
| $Q_0$ | Quantity of the by-product going elsewhere, units of by-product |
| $R_G$ | Revenue per unit of the good and by-product, \$/unit of good |
| $P_G$ | Price of the good, \$/unit of good |
| $P_B$ | Price of the by-product, \$/unit of by-product |
| $\psi$ | Share of by-products going to dairies |
| $\omega$ | Revenue share of the good |
| $\theta$ | Vertical shift in demand for by-products from dairies |
| $\eta_f\theta$ | Horizontal shift in demand for by-products from dairies |
| $\lambda$ | Ratio of goods produced per unit of by-product produced |
| $\eta_G$ | Elasticity of demand for the good |
| $\eta_f$ | Dairies' elasticity of demand for by-products |
| $\eta_o$ | Other's and disposal's elasticity of demand for by-products |
| $\epsilon$ | Elasticity of supply for the good relative to the net revenue per unit of good and by-product |

Solving the system yields the following equilibrium solutions for the log differential changes in prices and quantities:

(17) $$dlnR_G = \eta_G(1-\omega)\left(\left((\eta_G-\epsilon\omega)\psi\eta_f\theta-(1-\omega)\epsilon\eta_G dln\lambda\right)/\Gamma-dln\lambda\right)/(\eta_G-\epsilon\omega),$$

(18) $$dlnP_G = \epsilon(1-\omega)\left(\left((\eta_G-\epsilon\omega)\psi\eta_f\theta-(1-\omega)\epsilon\eta_G dln\lambda\right)/\Gamma-dln\lambda\right)/(\eta_G-\epsilon\omega),$$

(19) $$dlnP_B = \left((\eta_G-\epsilon\omega)\psi\eta_f\theta-(1-\omega)\epsilon\eta_G dln\lambda\right)/\Gamma,$$

(20) $$dlnQ_B = dlnQ_G = \eta_G\epsilon(1-\omega)\left(\left((\eta_G-\epsilon\omega)\psi\eta_f\theta-(1-\omega)\epsilon\eta_G dln\lambda\right)/\Gamma-dln\lambda\right)/(\eta_G-\epsilon\omega),$$

(21) $$dlnQ_f = \eta_f\left(\left((\eta_G-\epsilon\omega)\psi\eta_f\theta-(1-\omega)\epsilon\eta_G dln\lambda\right)/\Gamma\right)-\eta_f\theta,$$ and

(22) $$dlnQ_o = \eta_o\left(\left((\eta_G-\epsilon\omega)\psi\eta_f\theta-(1-\omega)\epsilon\eta_G dln\lambda\right)/\Gamma\right),$$

where, in order to make expressions less cumbersome we have used the additional notation,

$$\Gamma = \psi\eta_f\eta_G + (1-\psi)\eta_o\eta_G - \omega\psi\epsilon\eta_f - \omega(1-\psi)\epsilon\eta_o - (1-\omega)\epsilon\eta_G.$$

Using equation (17) and the change in quantity of the good expressed in equation (20), we can determine the total change in revenue for the by-product producer as a result of the change in demand for by-product feed. Equations (18) and (19), combined with (20), (21), and (22), allow us to assess the change in revenue specific to the primary good, by-products sold to dairies, and by-products sold to others.

Based on the implied changes in quantity of by-product produced and quantity of by-product going to dairies as feed, we can determine the implied change in the quantity of disposed by-product. This quantity is of particular interest because it may have important environmental consequences.

**Model of Dairy Response to Supply Change of By-Product**

Next consider a model of supply and demand for milk and the derived demand for by-product feeds.

Milk (subscript M) is produced using by-product feed (subscript B), other feed (subscript N), and a composite input, $z_M$, including factors such as land, labor, capital, etc.,:

(23) $Q_M = M(x_B, x_N, z_M)$,

where $Q_M$ is the quantity produced of milk as a function of the inputs mentioned above.

The quantity supplied of milk can be expressed as a function of the price of milk and input prices:

(24) $Q_M = Q_M^S(P_M; P_B, P_N, P_{z_M})$,

where $P_M$ is the price of milk, $P_B$ is the price of by-product feed, $P_N$ is the price of other feed, and $P_{z_M}$ is the price of the composite input.

For simplicity, inputs are used in fixed proportions (the aggregate of by-product and non-by-product feeds are used proportionally to other inputs), technology has constant returns to scale (CRS)—that is, the production function is homogeneous of degree one, and therefore industries have homothetic production functions and input ratios are constant with respect to scale of production of firms. Markets are competitive in the sense that firms treat prices as exogenous.

*Milk Supply and Demand Model*

Because of fixed proportions in milk production, the supply of milk is defined by the supply conditions for the underlying inputs. We have a set of equations for milk supply, milk demand, and supply and derived demand equations for milk input:

(25) $Q_M = Q_M^D(P_M)$,

(26) $Q_M = Q_M^S(P_M; P_B, P_N, P_{z_M})$,

(27) $x_B = x_B^D(P_B, P_N)$,

(28) $x_N = x_N^D(P_B, P_N)$,

(29) $x_{z_M} = x_{z_M}^D(P_{z_M})$,

(30) $x_B = x_B^S(P_B; \zeta)$,

(31) $x_N = x_N^S(P_N)$, and

(32) $x_{z_M} = x_{z_M}^S(P_{z_M})$,

where (25) is the quantity demanded of milk as a function of the price of the milk, and (26) is the quantity supplied of milk as a function of input prices and the price of milk. Equations (27) and (28) are demand for by-product and other feeds as a function of prices, and equation (29) is the demand for the composite input as a function of its price. By-product and other feed demands are a function of their own and each other's prices to allow for substitution between the two. Equations (30)-(32) are input supply functions, where $\zeta$ is a shift parameter representing a vertical shift in supply (change in marginal cost at given quantity supplied). The shift parameter can be multiplied by the supply elasticity to consider a horizontal shift instead (change in quantity supplied at a given price).

Lastly, we have the market-clearing condition that quantity produced of milk is equal to quantity demanded:

(33) $Q_M = Q_M^D(P_M) = Q_M^S(P_M; P_B, P_N, P_{z_M})$.

We next express the model in log-differential form to arrive at our empirical solutions for the model.

*Economic Model for Dairy in Log Differential Form*

We consider our general model from the previous section in log differential form to simulate how dairies adjust if availability of by-product feed changes. We introduce exogenous shocks in the market to simulate the effects of a price shock for by-product feed. Such a price shock may be the result of policy change that calls for increased regulation of the transportation of by-products to dairies.

We consider demand and supply equations in log-differential form for the good and its by-product using the same notation as before. For simplicity, we assume that the composite input is used in fixed proportions to feed, therefore the percent change in quantity demanded of the composite input is equal to the percent change in quantity demanded of milk. We derive a general set of solutions with no restrictions on parameter values; a second scenario, found in the appendix, provides a set of solutions in which by-product feed and other feeds are perfect substitutes.

Table 2 include the notation and definitions for the dairy market quantities, prices, shares, shift parameter, and elasticities.

**Table 2. Dairy Supply and Demand Model Notation and Definitions**

| | Parameter definition |
|---|---|
| $Q_M$ | Quantity of milk, hundredweight (cwt) |
| $x_B$ | Quantity of by-product feed, units of the by-product feed |
| $P_M$ | Price of milk, \$/cwt |
| $P_B$ | Price of by-product feed, \$/unit of by-product feed |
| $\omega_B$ | Value share of by-product feed in price of milk |
| $\omega_N$ | Value share of other feed in price of milk |
| $\omega_z$ | Value share of the composite input in price of milk |
| $\zeta$ | Vertical shift in supply of by-product feeds |
| $\epsilon_B\zeta$ | Horizontal shift in supply of by-product feeds |
| $\sigma$ | Elasticity of substitution for by-product and other feeds |
| $\eta_M$ | Elasticity of demand for milk |
| $\epsilon_B$ | Elasticity of supply for by-product feed |
| $\epsilon_N$ | Elasticity of supply for other feed |
| $\epsilon_z$ | Elasticity of supply for the composite input |

*Note:* Value shares sum to 1 ($\omega_B + \omega_N + \omega_Z = 1$).

Equations (34)-(41) are derived from the system of supply and demand functions for milk and its inputs. Equation (34) is the quantity demanded of milk, where $\eta_M$ is an own-price elasticity of demand.

(34) $$dlnQ_M = \eta_M dlnP_M$$

Equation (35) is the percent change in the price of milk as a function of input prices, where $\omega$ is the value share for the corresponding input and $\omega_B + \omega_N + \omega_z = 1$.

(35) $$dlnP_M = \omega_B dlnP_B + \omega_N dlnP_N + \omega_z dlnP_{z_M}$$

Equations (36)-(38) are input demand equations where $\sigma$ represents the elasticity of substitution for by-product and other feeds.

(36) $$dlnx_B = -\omega_N \sigma dlnP_B + \omega_N \sigma dlnP_N + dlnQ_M$$

(37) $$dlnx_N = \omega_B \sigma dlnP_B - \omega_B \sigma dlnP_N + dlnQ_M$$

(38) $$dlnx_{z_M} = dlnQ_M$$

Equations (39)-(41) are input supply equations, where $\epsilon_B$ and $\epsilon_N$ are elasticities of supply, and $\zeta$ is a vertical shift in the marginal cost curve for by-product feed. The proportional horizontal shift in the input supply curve is $\epsilon_B \zeta$. (We show the solution for the case of perfect substitution between the by-product feed and other feed in an appendix.)

(39) $$dlnx_B = \epsilon_B (dlnP_B - \zeta)$$

(40) $$dlnx_N = \epsilon_N dlnP_N$$

(41) $$dlnx_{z_M} = \epsilon_z dlnP_{z_M}$$

The following equilibrium solutions show impacts on the changes in prices:

(42) $$dlnP_B = \zeta \epsilon_B \left( (\epsilon_N + \omega_B \sigma) * \left( \frac{\epsilon_z}{\eta_M} - \omega_z \right) - \omega_N \epsilon_z \right) / \Lambda,$$

(43) $$dlnP_N = \zeta \omega_B \epsilon_B \left( \frac{\epsilon_z \sigma}{\eta_M} - \omega_z \sigma + \epsilon_z \right) / \Lambda,$$

(44) $$dlnP_{z_M} = \zeta \omega_B \epsilon_B (\omega_B \sigma + \omega_N \sigma + \epsilon_N) / \Lambda,$$ and

(45) $$dlnP_M = \zeta \omega_B \epsilon_B \epsilon_z (\omega_B \sigma + \omega_N \sigma + \epsilon_N) / \eta_M \Lambda,$$

where $\Lambda = (\epsilon_B \epsilon_N + \omega_B \epsilon_B \sigma + \omega_N \epsilon_N \sigma) \left( \frac{\epsilon_z}{\eta_M} - \omega_z \right) - (\epsilon_N + \omega_B \sigma) \omega_B \epsilon_z - (\epsilon_B + \omega_N \sigma) \omega_N \epsilon_z - 2 \omega_B \omega_N \epsilon_z \sigma$.

The equilibrium solutions for quantity changes are:

(46) $$dlnx_B = \epsilon_B \left( \zeta\epsilon_B \left( (\epsilon_N + \omega_B\sigma) * \left( \frac{\epsilon_z}{\eta_M} - \omega_z \right) - \omega_N\epsilon_z \right) \right) / \Lambda - \epsilon_B\zeta,$$

(47) $$dlnx_N = \zeta\omega_B\epsilon_B\epsilon_N \left( \frac{\epsilon_z\sigma}{\eta_M} - \omega_z\sigma + \epsilon_z \right) / \Lambda, \text{ and}$$

(48) $$dlnx_z = dlnQ_M = \zeta\omega_B\epsilon_B\epsilon_z(\omega_B\sigma + \omega_N\sigma + \epsilon_N)/\Lambda.$$

Equation (42) and the change in by-product quantity (46), determine the total change in expenditure for the by-product as a result of the price shock to by-product feed. Equations (43) and (44) combined with (47) and (48) determine the change in expenditure for other feed and the input. Equations (45) and (48) determine the change in milk revenue for dairies. Finally, changes in quantity of by-product and other feed demanded by dairies, along with some additional physical relationships, determine the change in resources used by dairies and the environmental consequences of using less by-product feed.

**Data and Parameter Values for the Application to Almond Hulls as a Dairy Feed**

Almonds delivered to the huller and sheller for first stage processing comprises of three main components: the hull, shell, and kernel. As noted above, hulls weigh twice as much as kernels (Almond Board of California, 2019). In 2019, California produced 1.28 million tons of almond kernels (USDA, 2020), about 2.55 million tons of hulls. More than 95% of almond hulls are used for dairy cattle feed (Almond Board, personal conversation, 2020).

Almond hulls are the largest by-product by weight from the almond industry, and the by-product of interest in this study. Almond shells, skins, meal, and cull almonds are other by-products produced from the almond processing that are suitable as feeds. Almond shells are used mostly for cow and heifer bedding, and the other almond by-products are tiny in comparison to the tons of hulls produced and used.

Table 3 details prices, quantities, and other parameters needed for our simulations pertaining to almond hulls. Annual production of California almond kernels is 1.28 million tons (USDA, 2020). Because, each pound of kernels, comes with two pounds of hulls, (Almond Board of California, 2019), 2.55 million tons of almond hulls were produced in 2019. Roughly 95% of the almond hulls produced are used as dairy feed (informed by Almond Board, personal conversation, 2020), meaning 2.42 million tons of almond hulls were used as dairy cattle feed in 2019. The 5% balance of almond hulls are used in other markets and face the same market price as that paid by the dairy industry. Producers of almonds received a price of $4,860/ton for kernels in 2019 and $121/ton for hulls. With 2 pounds of kernels produced for every pound of kernels, the total revenue from almond kernels and hulls is $5,102/ton of almond kernels, meaning 95% of the revenue comes from kernels. The almond industry is a substantial contributor to the California economy, especially in the Central Valley (Matthew, Baratashvili and Sumner, 2020).

We use a price elasticity of demand for almonds of -1, which means a 1% increase in the price of almonds decreases quantity demanded by 1%. The demand for almond hulls by the dairy industry is elastic, -3, because other feeds, mainly forages, readily substitute for hulls in dairy rations. Almond hull demand is less elastic than the demand for other by-product feeds, for example spent grains, because almond hulls have nutritional and palatability characteristics that are not as easily matched by substituting other feeds for hulls. Other's and disposal's elasticity of demand for almond hulls is highly elastic, -10.

Almond orchards take years to establish and require suitable land and irrigation water access. Therefore, the almond industry adapts production gradually to moderate price and cost conditions over a horizon of a few years. So, the elasticity of supply of almonds relative to the revenue from almonds and hulls is unit elastic, 1, meaning a 1% reduction in revenue from almonds and hulls could cause a 1% reduction in quantity supplied

The model is used to simulate a 100% horizontal shift back in demand for almond hulls from dairies. That is, quantity demanded for almond hulls from dairies would fall to zero at the current price (although induced price changes partially offset the decrease in quantity demanded).

**Table 3. Almond Hull Supply and Demand Model: Notation, Definitions, Values and Sources**

| | Parameter definition | Value | Source |
|---|---|---|---|
| $Q_G$ | Annual production of almonds in California, million tons | 1.28 | (USDA, 2020) |
| $Q_B$ | Annual production of almond hulls in California, million tons | 2.55 | (Almond Board of California, 2019) |
| $Q_f$ | Quantity of almond hulls going to dairies, million tons | 2.42 | * |
| $Q_0$ | Quantity of almond hulls going elsewhere, million tons | 0.128 | * |
| $R_G$ | Revenue from almond kernels and hulls per ton of almonds produced, $/ton | 5102 | Calculated from quantities and prices |
| $P_G$ | Price producers receive for almonds, $/ton | 4,860 | (USDA, 2020) |
| $P_B$ | Price producers receive for almond hulls, $/ton | 121 | (USDA AMS, 2020) |
| $\psi$ | Share of almond hulls going to dairies | 0.95 | * |
| $\omega$ | Revenue share of almonds | 0.95 | Derived from data above |
| $\theta$ | Change in demand for almond hulls from dairies | 100% | Simulated impact |
| $\lambda$ | Tons of almonds produced per ton of hulls produced | 0.50 | (Almond Board of California, 2019) |
| $\eta_G$ | Elasticity of demand for almonds | -1 | ** |
| $\eta_f$ | Dairy elasticity of demand for almond hulls | -3 | ** |
| $\eta_o$ | Other uses elasticity of demand for almond hulls | -10 | ** |
| $\epsilon$ | Elasticity of supply for almonds relative to the revenue from almonds and hulls | 1 | ** |

* Almond Board, personal conversation (2020).

** Author calculations based on underlying industry situation, market shares, and academic literature.

Parameters for the California dairy industry are shown in Table 4. Our model uses California milk production, price, and the elasticity of the demand for milk facing California. Milk production of 405 million hundredweight produced in California in 2019 is close to the average production from 2015 through 2019 (USDA, 2020). The price of milk increased from $15.4/cwt in 2015 to $16.5/cwt in 2017 and up to $18.11/cwt in 2019 (USDA, 2020). A price of milk of $16.5/cwt represents the market situation in California in recent years as informed by

USDA (2020). The quantity and price of spent grains in Table 4 are equal to those reported in Table 3.

The value share of spent grains and the value share of other feeds were calculated from CDFA (2018a, 2018b) and CDFA cost of production data (no date). The value share of the non-feed input was taken from (CDFA, 2018a). CDFA (2018a) reports total feed costs as a percentage of total cost which we use as the value share of total feed costs in the price of milk because the dairy industry is competitive and long run profits are zero. State wide total feed costs as a percentage of total costs declined from 59% in 2015 to 55.8% in 2016 to 54.4% in 2017 (CDFA, 2018b). The total feed costs as a percentage of total costs of 55% was chosen to best reflect feed costs percentage on San Joaquin Valley dairies. The calculation of the value share of almond hulls, the value share of other feeds, and the value share of non-feed composite input is similar to the calculation done for spent grains. The value share of almond hulls in total cost of milk is 0.017, the value share of other feeds in the cost of milk is 0.53, and the value share of non-feed composite input in the cost of milk is 0.45.

The model uses several elasticities for the California dairy and by-product industries. The elasticity of substitution for almond hulls and other feeds is high, 5, because other feeds readily substitute for almond hulls. The elasticity of demand for milk facing California is relatively high and much higher than the demand for milk in aggregate. California milk products are mostly shipped to the rest of the United States or exported and are a close substitute for milk products from other places, meaning that changes in California milk production do not affect the price of milk in California much and do not change the world price of milk. We use a price elasticity of demand for milk of -5, which is highly elastic

The tons of almond hulls produced is proportional to the tons of almonds produced. Revenue from almonds is 95% of combined revenue from almonds and almond hulls. That means that when the price of hulls increases by, say 10%, the revenue to producers rises by only 0.5%. Therefore, almond producers will not respond much to an increase in hull prices, but rather respond to almond kernel prices. We use an elasticity of supply for almond hulls of 0.1 to reflect this lack of supply response to the by-product price.

Replacement heifers and farm labor are two non-feed inputs that share a large proportion of the cost of the non-feed composite input. Both the number of replacement heifers and farm labor supplied to the industry would increase in response to an increase in price. Our elasticity of supply for non-feed composite input is 2.

**Table 4. Dairy Supply and Demand Model: Notation, Definitions, Values and Sources, Almond Hulls**

| | Parameter definition | Value | Source |
|---|---|---|---|
| $Q_M$ | Quantity of milk, million cwt | 405.64 | (USDA, 2020) |
| $x_B$ | Quantity of almond hull feed, millions of tons | 2.42 | * |
| $P_M$ | Price of milk, $/cwt | 16.5 | ** |
| $P_B$ | Price of almond hull feed, $/ton | 121 | *** |
| $\omega_B$ | Value share of almond hull feed in cost of milk | 0.0166 | (CDFA COP Data, no date) |
| $\omega_N$ | Value share of other feed in price of milk | 0.5334 | (CDFA, 2018a) |
| $\omega_z$ | Value share of the composite input in price of milk | 0.4500 | (CDFA, 2018a) |
| $\zeta$ | Vertical shift in supply of almond hull feed | 100% | Simulated impact |
| $\sigma$ | Elasticity of substitution for almond hull and other feeds | 5 | **** |
| $\eta_M$ | Elasticity of demand for milk | -5 | **** |
| $\epsilon_B$ | Elasticity of supply for almond hull feed | 0.1 | **** |
| $\epsilon_N$ | Elasticity of supply for other feed | 1 | **** |
| $\epsilon_z$ | Elasticity of supply for the composite non-feed input | 2 | **** |

* Calculated from almond kernel weight (USDA, 2020) and 2 pounds of hulls are produced for each pound of kernels (Almond Board of California, 2019)

** Price represent the market situation in California in recent years and informed by USDA (2020).

***Authors calculation. 12-month average in 2019. Prices from (USDA AMS, 2020)

****Author calculations based on underlying industry situation, market shares, and academic literature.

**Simulation Results: Almond Impacts of a Decline in the Demand for Almond Hulls from Dairies and Dairy Impacts of a Decline in the Supply of Almond Hulls**

Simulation results for a 100% horizonal shift in demand for almond hulls from dairies are reported in Table 5. Almond hulls account for a relatively small share of revenue from almond production (5%), therefore the decrease in production of almonds (and almond hulls) in response to a large reduction in demand for almond hulls is also quite small (-0.68%). The 100% horizonal shift in demand does not equate to a 100% decrease in quantity demanded of almond hulls because the shift causes a fall in almond hull price, which partially offsets the decrease in quantity demanded. Given a relatively elastic response to of quantity demanded to price, the equilibrium is at a 15.54% decrease in quantity of almond hulls used on dairies, and a 28.15% decrease in the price of almond hulls. The decrease in quantity of almond hulls used by dairies is almost offset by an increase in quantity of almond hulls taken by other users, such as other livestock farms or spread on crop fields.

**Table 5. Summary of Estimated Impacts to Almond Industry from Almond Hull Demand Change, Percentage Changes**

| Variable | Symbol | Proportionate Change |
|---|---|---|
| Almond quantity | $dlnQ_G$ | -0.68% |
| Almond hull quantity | $dlnQ_B$ | -0.68% |
| Quantity of almond hulls going to dairies | $dlnQ_f$ | -15.54% |
| Quantity of almond hulls going elsewhere | $dlnQ_0$ | 281.54% |
| Revenue from almonds and hulls per pound of almonds | $dlnR_G$ | -0.68% |
| Price of almonds | $dlnP_G$ | 0.68% |
| Price of almond hulls | $dlnP_B$ | -28.15% |
| Almond producer revenue | $(1 + dlnR_G) * (1 + dlnQ_B)$ | -1.36% |
| Almond producer input use | $dlnz_G$ | -0.68% |

Table 6 reports the simulation results for a 100% shift back in the quantity of almond hulls supplied to dairies. The price increase in almond hulls (36%) is caused by the supply shift that would eliminate quantity supplied.  Similar to the almond hull demand shift simulation, the price increase is enough to encourage some additional almond hull supply. Because of the availability of substitute feeds, the demand function is relatively elastic. That means as the price of almond hulls rise dairies shift to more of alternative feeds in their rations. The corresponding hull price increase combined with the supply shift results in dairies using 96.4% less almonds hulls as feed.

The contribution of almond hulls to dairy rations is significant, about 3% of ration costs and about 8% of total dry matter. The feed ration cost, therefore, rises significantly as the price of hulls rise. The increase in the marginal cost of milk production causes the equilibrium price of milk to producers to increase by 0.45%, and given the elastic demand for milk facing the California industry, the quantity of milk produced in California falls by about 2.26%. Likewise, the quantities and prices of other feeds and non-feed composite inputs respond as well to the decline in supply of almond hulls.

**Table 6. Summary of Estimated Impacts to Dairies from Almond Hull Supply Change, Percentage Changes**

| Variable | Symbol | Base case ($\sigma = 5$) | Perfect feed substitution ($\sigma = \infty$) |
|---|---|---|---|
| Milk quantity | $dlnQ_M$ | -2.26% | -1.73% |
| Almond hull quantity | $dlnx_B$ | -96.40% | -99.87% |
| Other feed quantity | $dlnx_N$ | 0.68% | 1.33% |
| Composite input quantity | $dlnx_{z_M}$ | -2.26% | -1.73% |
| Price of milk | $dlnP_M$ | 0.45% | 0.35% |
| Price of almond hulls | $dlnP_B$ | 35.98% | 1.33% |
| Price of other feed | $dlnP_N$ | 0.68% | 1.33% |
| Price of composite input | $dlnP_{z_M}$ | -1.13% | -0.86% |
| Dairy revenue | $(1 + dlnP_M) * (1 + dlnQ_M)$ | -1.82% | -1.39% |

**Resource and Environmental Consequences**

Let us now turn to resource and environmental consequences of changes in by-product feeding that follow from the simulation results for supply and demand changes for almond hulls. We consider the role of almond hulls in typical dairy rations and how much other feeds would be required to replace almond hulls based on nutritional content. From there we can use data on typical farm yields in the San Joaquin Valley to calculate the implied additional area and additional irrigation water to produce the needed feed. Recall that almond production falls by only about 0.68%. With about one million acres of almonds grown in California, that implies a reduction of about 7,000 acres and about 28,000 acre-feed at four acre-feet per acre. These resource use reductions must be considered to get net effects.

Of course, feed rations differ, but to get a reasonable set of projections we simply increase use of the ration ingredient that is already included in most rations and most closely substitutes for almond hulls in energy and forage characteristics. Almond hulls are primarily a sugar and fiber source, and we assume corn silage can substitute for almond hulls in rations. The conversion from almond hulls to a nutritionally equivalent quantity of corn silage is based on total digestible nutrients (TDN). Calculations of non-by-product equivalents for almond hulls are based on the National Research Council (NRC, 2001).

Table 7 provides the annual changes in almond hulls fed on California dairies shown in Tables 5 and 6. The implications of the 100% horizontal shift in demand for almond hulls is displayed in row 1 of Table 7. Recall the elasticity of demand for almond hulls at other uses is -10. In addition, the elasticity of substitution between almond hulls and other feeds is 5. The 100% horizontal shift in demand for almond hulls from dairies implies a decline in almond hull use by 380,000 tons and an increase in corn silage by 799,000 tons of corn silage (which is fed wet) as a substitute. At yield of about 26.6 tons to the acre, an additional 30 thousand acres of corn silage must be produced. In the San Joaquin Valley where most of the silage would be produced, farms use 3.6 acre-feet of water, which translated into 108 thousand acre-feet of additional irrigation water demand. The net change in irrigation water use, from reduced almond production and increased corn silage, is an increase in 80,000 acre feet of water, under the 100% horizontal demand shift simulation.

The resource consequences for a 100% horizontal shift in supply of almond hulls to dairies, with an elasticity of feed substitution of 5 is provided in rows 2 of Table 7. Such a supply shift would reduce almond hull use by 2.3 million tons and require an additional 4.9 million tons of corn silage. The resource demand of this much additional corn silage is substantial and just feasible. An additional 181,000 acres of land and 665,000 acre-feet of irrigation water would need to shift to corn silage. To put these implied increases in acreage in perspective, corn silage area was 315 thousand acres in the drought year of 2016 and increased to 415 thousand acres in 2019 (USDA, 2020). The highest acreage of corn silage in California was 495 thousand acres in 2008.

**Table 7. Annual changes in almond hulls, corn silage, and resources required to produce corn silage based on equivalent nutritional content**

| Simulation | Almond Hull Quantity | Almond Hulls | Corn silage | Area | Irrigation water |
|---|---|---|---|---|---|
| | (%) | ('000 tons) | ('000 tons) | ('000 acres | ('000 acre-feet) |
| Demand shift, $\eta_o = -10$ | -15.5 | -380 | 799 | 30 | 108 |
| Supply shift, $\sigma = 5$ | -96.4 | -2,330 | 4,897 | 181 | 665 |

*Notes:* Conversions according to nutritional content based on NRC (2001). Fresh weight of almond hulls fed on California dairies in 2019, based on USDA (2020) data for almond kernels, and 95% of almond hulls fed on California dairies. Substituted for corn silage on a TDN conversion basis. Corn silage was chosen as the substitute feed here because corn silage is an energy forage, and similar in crude protein to almond hulls.

## Conclusions

By-products are pervasive in California dairy rations. Many are of local or seasonal availability and may not be individually a large share of ration nutrition or cost, but as a group comprise more than 30% of the ration by dry matter or cost. In this paper we considered two related questions pertaining to almond hulls (one of the most important by-product feeds) as a dairy feed. First, we modeled and simulated the economic effects of reduced demand for almond hulls from the California dairy industry. Such a reduction could occur if, for example, the California dairy herd declined. Second, we modeled and simulated the implications of a severe reduction in the supply of by-product feeds to California dairies. Such a supply reduction could occur, for example if the almond industry declined or if some policy precluded the delivery of the almond hull by-product to dairies.

Our results show small effects on the almond industry from reducing demand for almond hulls by dairies. Hulls are about 5% of total almond revenue, so even if the price of hulls fell substantially, the impact on almond producer revenue would be small—the quantity adjustment would be just -0.68% from the dramatic shift back in demand.

The impact of a large reduction in almond hull supply to dairies would be significant and substantial, but still marginal. Almond hulls represent about 3% of dairy feed costs and 1.7% of total production costs. The marginal cost of production would rise, but by a small amount because other feeds can replace almond hulls in the ration. Removing availability of almond hulls would reduce milk production in California by more than 2%. This is because California production is a small share in a large market for almost homogenous products, therefore California processed milk products face high demand elasticities in national and international markets.

Without using as much almond hull tonnage, other feed would be grown to replace the nutritional contribution of almond hulls in dairy rations. That means more land and more water used to supply dairy feeds than when almond hulls remained in the ration. Economic forces would drive other feed production to expand to replace the hulls, but at significant economic and resource cost. We estimate that if supply of almond hulls were cut, use of land for silage would rise by about 181,000 acres or about 44%. The implied increase in irrigation water is about 665,000 acre-feet, and this at a time of extreme water pressure flowing from implementation of the Sustainable Groundwater Management Act.

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