POLLINATION MARKETS AND THE COUPLED FUTURES OF ALMONDS AND HONEY BEES: SIMULATING IMPACTS OF SHIFTS IN DEMANDS AND COSTS

HYUNOK LEE, DANIEL A. SUMNER, AND ANTOINE CHAMPETIER

Honey bees have garnered much attention in recent years. Concerns about long-term sustainability of pollinator populations have been coupled with concerns about implications for food supplies. We use a novel formulation of a multiple input, multiple output, two season equilibrium simulation model to explore economic linkages across the markets of buyers and sellers of pollination services and honey. We specify and calibrate in a tractable way the empirical relationships between pollinators and the crops they pollinate, especially almonds. Our model highlights the sequential nature of the pollination season and implication for revenue from pollination and honey production. We demonstrate how shifts in almond supply and demand and the much-discussed honey bee hive health problems cause price and quantity adjustments in horizontally and vertically related markets and quantify these effects. We show that the economic fortunes of the almond industry, including demand growth, cost concerns, and the potential for new almond varieties that use fewer bees, crucially affect the returns to beekeeping and the number of hives. These drivers of almond economics also have substantial effects on the cost of pollination for crops that are pollinated later.

Key words: Bees, almonds, pollination, market linkages, simulation.

JEL codes: Q11, Q12, Q13, Q55.

Over the past decade, honey bees have received growing attention for two reasons. First, threats to the health of honey bee colonies have been perceived as emblematic of broader concerns regarding the interface between commercial agriculture and ecosystem services. Second, recognition of the importance of honey bee pollination has accompanied increases in demand for pollination services.

Concerns regarding the sustainability of the pollinator populations became widespread after mass honey bee colony losses in the United States during the winter of 2006–2007, when the term “Colony Collapse Disorder” was coined. In the background of the bee decline debate, demand for pollination services continued to increase, especially in conjunction with the expansion of almond acreage from about 610,000 bearing acres in 2006 to about 1.0 million bearing acres in 2017 (USDA 2017a). Each almond kernel must be individually pollinated by a bee (or another pollinator) in order to set fruit, necessitating several million bee visits per acre. During almond pollination season, more than 70% of all commercial honey bee colonies in the United States are used to pollinate almond orchards, which provides as much
revenue for U.S. beekeepers as honey production (USDA 2017b).

Several economic studies have examined the interaction between honey bees and the crops they pollinate. Sumner and Boriss (2006) and Lee et al. (2017) briefly describe relationships between the use of bees for almond crops and the pattern of pollination fees. Other economists have also recently modeled and measured the pattern of pollination fees. Other economists have also recently modeled and measured the pattern of pollination fees. Other economists have also recently modeled and measured the pattern of pollination fees. Other economists have also recently modeled and measured the pattern of pollination fees. Other economists have also recently modeled and measured the pattern of pollination fees.

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The present study builds on prior literature by investigating more thoroughly the markets that connect the honey bee industry, which uses forage to supply pollination services and honey, to crop industries that demand pollination services. We develop a novel simulation model that incorporates salient features of the crop and honey bee industries to assess the economic impacts on almonds and honey bees resulting from the important variables that affect pollination demand and supply.

We consider four detailed scenarios that reflect vital future issues for honey bees and almonds: (1) the continuing increase in adoption of self-fertile almond varieties, which results in the use of far fewer honey bees for pollination; (2) an increase in hive losses, which represents adverse shocks to honey bee health; (3) an increase in the cost of irrigation water for almonds; and (4) a decline in consumer demand for California almonds. In addition to these four scenarios, specifically motivated by recent experience, we also consider the impact of a shift in the price of honey, a central factor in the economics of the beekeeping industry (Muth et al. 2003). The linkage between honey bees and the almond market is crucial to all the scenarios we consider. Though market fluctuations are considered common in agriculture, the emergence of self-fertile almond varieties represents a fundamental technical innovation with the potential to permanently reduce the demand for honey bee pollination services. Moreover, increased water costs, reversals in demand trends, and additional hive losses may constitute long-term factors determining market conditions for commercial honey bees.

Following Rucker, Thurman, and Burgett (2012), we use an equilibrium approach based on maximization behavior of crop growers and beekeepers, and following Champetier, Sumner, and Wilen (2015), our model explicitly tracks the linkage between periods that are delineated by pollination season, thus incorporating an intertemporal constraint on bee populations. A beekeeper can engage successively in multiple pollination contracts and receive pollination fees that are determined by periodic seasonal market conditions. To capture the linkages across periods in pollination supply and demand, we represent the annual pollination market in terms of two differentiated markets: an almond market and a post-almond market (Rucker, Thurman, and Burgett 2012). These two pollination markets are linked through the optimization of annual income by the beekeeper; beekeepers’ decisions regarding the supply of almond pollination are explicitly tied to their supply decisions in the post-almond pollination period.

To model such dynamic dependency across pollination periods and multiple output decisions, we develop an equilibrium displacement model (EDM). The broad EDM approach has a long lineage, but our modeling innovations are crucial to adapting this simulation approach to better understand the interactions between honey bees and the crops they pollinate (Muth 1964; Gardner 1975; Sumner and Wohlgemant 1985; Davis and Espinoza 1998; Dharmasena, Davis, and Capps 2014). Our novel adaptation of EDMs in a multiple market setting employs an explicit product transformation curve to portray optimal tradeoffs between the two post-almond honey bee outputs: pollination and marketable honey.

This article contributes to a better understanding of pollination economics and the use of applied simulations in the context of complex agricultural production relationships. Through useful empirical insights about the most important foreseeable economic

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1 California is the sole commercial producer of almonds in the United States and currently supplies about 80% of the world almond market. California almonds represented more than 20% both in harvested acreage and value of all tree and vine crops in the country (USDA 2017a).
adjustments in markets that are interlinked across products and periods, we extend the sparse existing literature on pollination. This article represents, to our knowledge, the first attempt to model a product transformation curve within an EDM framework, which we use to appropriately represent the most salient trade-off faced by beekeepers.

The first section briefly summarizes the key features of the California almond and beekeeping industries, focusing on their interactions and the multiple outputs produced by the honey bee industry. Next we present a model of optimizations for the almond producers and beekeepers, where the beekeeper problem is characterized by several outputs over two time periods. Based on the optimization conditions, we then develop a simulation model, and describe data and parameter specifications for empirical simulations. Next we outline simulation scenarios that explore implications of dominant trends and drivers for the future of commercial honey bees in the United States. We discuss empirical implications in light of a comprehensive sensitivity analysis. Extensive online materials provide details about background, methodology, data, parameter choices, and additional sensitivity results.

The U.S. Beekeeping Industry and Almond Pollination

Almond pollination in California is the largest managed pollination event in the world. With about one million bearing acres in 2017 and about two hives per acre, the California almond industry employs roughly two million hives, which, as of April 2017, constitutes nearly 70% of the almost 2.9 million commercial hives in the country (USDA 2017c). Figure 1 presents almond pollination fees and almond bearing acreage in California for the period 1995–2017. Almond pollination fees per hive almost tripled in inflation adjusted terms over this period. Fees grew slowly from 1995 through 2004 before the surge in 2005 and almost doubling in 2006. Fees have stabilized since, with small fluctuations within a 10% range in real terms over the last decade. With fees of about $170 per hive, pollination services for almond crops generate about $340 million in revenue for the U.S. beekeeping industry, an amount comparable to honey revenues, which have ranged between $330 and $380 million in recent years (USDA 2017b).

Ample pollination is elemental to commercial almond harvests, and typical U.S. almond orchards require cross-pollination between varieties. Most orchards have different varieties in alternating rows; pollinators are needed to move pollen between the flowers of these tree rows. Unlike other tree crops, almonds require virtually 100% saturated pollination to get the desired 40–60% fruit set (Traynor 1993). With no effective wind or feral pollination for almonds, commercial honey bee hives have been essential for all commercial almond production.
Given that only half the necessary two million hives are based in California, almond pollination relies on hives brought from out of state (USDA 2017c). The migration of colonies to California begins in late fall, in preparation for the six-week almond pollination season that starts in February. According to our informal survey of beekeepers conducted in California at the end of the almond bloom of 2016, six out of twenty-seven honey bee suppliers came from out of state.² Migrating out-of-state beekeepers tend to operate on a large scale, accounting for 46% of the total 111,748 hives represented in our sample. These figures are consistent with the official national aggregate data (USDA 2017c).

Almond pollination is the first major activity for managed honey bees after they emerge from winter hibernation. Once almond pollination is over, the massive presence of honey bees, further strengthened by rich forage from almond blossoms, creates strong demand for suitable crops and other plants for bees to forage on (Champetier, Sumner, and Wilen 2015). During this post-almond period that usually starts in mid-March and ends in September, beekeepers seek to either supply hives for paid pollination, find safe foraging areas for honey production, or a combination of the two. Our 2016 survey of beekeepers found that about one third of beekeepers reported additional (fee paying) pollination contracts in California for crops such as cherries, sunflowers, and avocados. Two-thirds of respondents reported some type of foraging arrangements for which they did not receive pollination fees. Beekeepers facing these post-almond options allocate their bees and other resources according to incentives for pollination income, honey income, and hive health.

Among the most important factors characterizing the pollination fee for a crop is the crop’s bloom period, which determines when pollination is required. In 2017, pollination fees ranged from $18 to $185 per hive (CSBA 2017). Crops that bloom early, such as almonds and early cherries and plums, command much higher fees than crops that bloom later. The differences in fees across dates, such as between plums and prunes, underscore the crucial importance of pollination-seasonality. Plums bloom at the same time as almonds and thus compete with almonds for pollination services; on the other hand, prunes bloom just after almonds, meaning that hives that were attracted to California by high almond pollination fees are available for lower pollination fees.

Though honey and pollination services are joint products, the viability and value of honey production varies across crops that provide forage for bees. The value of honey production during foraging and pollination is termed “in-kind payments” and serves to lower the market pollination fee.³ Almonds provide forage that nurtures bees but no marketable honey, while prunes are one of the lowest pollination fee crops, as they not only flower after almonds but also serve as a valuable honey crop. Rucker, Thurman, and Burgett (2012) find that the degree to which a crop facilitates honey production, especially that of marketable honey, accounts for differences in pollination fees across crops in their data.

Optimization Framework

We start with two profit maximizations: that of almond growers as users of pollination services and that of beekeepers as suppliers of pollination services. To represent the distinct effects of different bloom periods on market outcomes, the beekeepers’ profit maximization is split into two sequential periods: an almond bloom period and a post-almond bloom period (indicated as period 1 and period 2).

Almond Producer Maximization

Almonds, Y, are produced in period 1 using two inputs, almond pollination service, y, and the composite input z under the constant returns to scale technology φ:

³ Economists have long recognized that pollination markets involve no major externalities associated with forage, honey and pollination services, as has been also empirically supported by Sumner and Boriss (2006) and Rucker, Thurman and Burgett (2012) who showed the systematic pattern of low pollination fees for honey-producing crops. The earlier literature that argues “hidden” benefits are actually accounted for in the formal or informal pollination contracts includes Cheung (1973), Johnson (1973), and Muth et al. (2003).
(1) \[ Y = \varphi(y^1, z). \]

To put the focus on pollination, input \( y^1 \) is singled out while input \( z \) aggregates the rest of an orchard’s inputs such as land, trees, labor, fertilizers, and irrigation water.\(^4\) Profit-maximizing input quantities are determined by equating the marginal value product of each input to its price:

(2) \[ \varphi_z p^Y = p^1 \]
(3) \[ \varphi_z p^Y = w^z \]

where \( p^Y, p^1, \) and \( w^z \) are prices of \( Y, y^1, \) and \( z, \) respectively, and the subscripts denote partial differentiations. At given input and output prices, equations (1)–(3) characterize the almond market equilibrium.

Characterization of Production Technology for Beekeepers

Production activities of beekeepers occur over two consecutive periods: period 1 includes almond pollination and period 2 is the post-almond period. We model the production of three distinct outputs: almond pollination services \( (y^1) \) in period 1, post-almond pollination services \( (y^2) \) in period 2 and honey \( (y^h) \) in period 2 (recall that almonds do not yield marketable honey).

In period 1, a single output, almond pollination services \( (y^1) \), is produced using two inputs, the bee input \( (b) \) and the composite of other inputs \( (k) \), under a constant returns to scale technology:

(4) \[ y^1 = F(b, k). \]

The bee input, \( b, \) represents immature bees. The idea here is that beekeepers may own or buy immature bees (brood or even queen bees) and grow them into adult bees, which can perform pollination services and produce honey. In practice, \( b \) is measured by the number of nucleus colonies, each of which is ready to be developed into a full hive.\(^5\) Pollination services are typically measured in terms of the number of hives; adopting this measure, \( y^1 \) measures the total number of hives used for almond pollination. The composite of other inputs, \( k, \) represents beekeeper labor, feed for bees, and other variable inputs used prior to entering the orchards.

Once hives are fully developed, and assuming forage sources are relatively abundant, beekeepers incur hardly any feeding expenses.\(^6\) Based on this observation, period 2—production employs only fixed inputs \( (X) \), which can be allocated between two outputs, post-almond pollination services \( (y^2) \) and honey \( (y^h) \). Allocating \( X \) in different ways can produce different combinations of \( (y^2, y^h) \), which is summarized in the technology set, \( \Phi(y^2, y^h: X) \). An illustration of this relationship is provided in figure 2 using a product transformation curve. Each point on the curve represents the combination of maximum \( y^2 \) and \( y^h \) that can be produced for a given input level, and all points on or within the curve are part of the production set. Thus, the inner curve represents the combination of maximum outputs associated with a lower level of input, \( X \). The slope along the curve represents the tradeoff between \( y^2 \) and \( y^h \) at the given input amount.

We consider two fixed factors, \( X = \{n, t\} \), where \( n \) is the number of hives and \( t \) is the total time available for bee activities. The total time \( t \) can be thought of as the number of days that the bees can be engaged in production activities. Our model to allocate these fixed factors between outputs is consistent with observed beekeeper behavior after the almond pollination season: the primary output decisions involve shifting hives among productive activities that have set durations (often measured by the number of weeks). Period 2 technology, \( \Phi \), is assumed to exhibit constant returns to scale with respect to each of the fixed inputs. That is, for \( x > 0, (xt, xy^2, xy^h: n) \in \Phi \) and \( (xn, xy^2, xy^h: t) \in \Phi \), if the

\(^{4}\) Aggregating all nonpollination inputs allows the model to be manageable and tractable even though we cannot investigate interactions among non-pollination inputs, which are not part of our focus.

\(^{5}\) New honey bee colonies can be initiated from established colonies, nucleus colonies, package bees, and swarms. Overwintered or established colonies cost the most. Nucleus colonies consist of four or five frames of brood, honey and pollen, adult bees, and a laying queen, and are ready to be fully established. Packaged bees are relatively cheap, but they do not have bloods (Penn State Extension 2012).

\(^{6}\) Note that our study abstracts from the situation described by Champetier, Sumner, and Wilen (2015), where forage is a limiting factor. In their model, whereas limited forage causes returns to foraging by bees to be diminishing, dynamic interactions also occur between forage availability and the bee population who uses forage as a source for food. Availiability of forage can be incorporated in our model as a predetermined fixed factor, which will not change our results. However, the main feature of the model by Champetier, Sumner, and Wilen stems from the dynamic effect of forage on the bee population. Such a dynamic feature is beyond the complexity that our model can handle.
number of hives \((n)\) is held constant, output changes by the same rate as the change in \(t\), and if \(t\) is held constant, output changes by the same rate as the change in \(n\). The number of hives, \(n\), represents the quantitative measure of bee stock at a given point of time.\(^7\)

Without a loss of generality, we use period 1-output, \(y^1\), to represent the period 2 input, \(n\). The use of \(y^1\) as an input in period 2 provides modeling convenience by linking period 1 and period 2 in production. Here, as with other livestock, the level of bee input utilized in period 1 determines the bee stock available for use in period 2. Using the property of constant returns to scale, period 2 technology, \(U(y^2, y^h; y^1, t)\), can be rewritten as:

\[
\begin{align*}
(5) & \quad h(v, q : t) = 0 \\
(6) & \quad v = y^2/y^1 \\
(7) & \quad q = y^h/y^1.
\end{align*}
\]

Beekeeper Maximization

Beekeepers maximize their stream of net income over periods connected by a certain stock of bees. We are now ready to express beekeepers’ maximization of profit over both periods:

\[
\begin{align*}
(8) & \quad \max_{b, k, v, q} \left[ p^1 F(b, k) + p^2 F(b, k) v + p^h F(b, k) q - w^b b - w^k k \right] \\
& \quad \text{subject to } h(v, q : t) = 0
\end{align*}
\]

where \(p^2, p^h, w^b\) and \(w^k\) are the prices of \(y^2, y^h, b\) and \(k\). Note that allowing only almond pollination in period 1 while allowing multiple products in period 2 is consistent with the empirical findings by Rucker, Thurman, and Burgett (2012): “higher honey prices do not bid beekeepers away from almonds...[they] trigger a substitute supply response away from non-almond crops...when honey production is a more viable alternative...” (p. 974).

Solving for the first order conditions for equation (8) yields:

\[
\begin{align*}
(9) & \quad F_b \left( p^1 + p^2 v + p^h q \right) = w^h \\
(10) & \quad F_k \left( p^1 + p^2 v + p^h q \right) = w^k \\
(11) & \quad p^2 F(b, k) = \lambda h_v \\
(12) & \quad p^h F(b, k) = \lambda h_q \\
(13) & \quad h(v, q : t) = 0
\end{align*}
\]

where \(\lambda\) is a Lagrangian multiplier and the subscripts denote partial differentiation.

\(^7\) The fixed factors, \(t\) and \(n\), can be represented as a single factor, the multiplication of \(n\) and \(t\), \(n^t\). Alternatively, the fixed factor can be specified with \(n\) alone, given \(t\) is predetermined. All these approaches yield the same market outcome. However, our explicit inclusion of \(t\) and \(n\) helps our model reflect the real world situation where the beekeeper specifies each post-almond production activity with the number of hives and the duration of the service.
Eliminating $\lambda$ by combining equations (11) and (12) yields:

$$p^2 h_q = p^h h_v$$

The slope of $h(.)$ represents tradeoffs between $v$ and $q$, that is, $h_q/h_v = -dv/dq$, the marginal rate of transformation between $v$ and $q$. The marginal rate of transformation becomes steeper as more $v$ is produced, meaning that producing one additional unit of $v$ requires giving up more units of $q$ as we move toward larger $v$. Combining $h_q/h_v = -dv/dq$ with equation (14) yields $p^h/p^v = -dv/dq$, which states that the ratio of honey price to post-almond pollination fees must be equal to the marginal rate of transformation between the two outputs at the equilibrium (figure 2).

Construction of the Simulation Model

We develop an equilibrium displacement model to trace how the markets for almond and honey bee products adjust to a new equilibrium when perturbed by exogenous shocks or shifters. The market equilibriums are characterized by a structural model, which consists of first order conditions from the previous section’s and supply and demand equations (Muth 1964; Gardner 1975; Sumner and Wohlgenant 1985). We first present the structural model, followed by the derivation of the equilibrium displacement model and concluding with an explanation of our choice of parameter values.

Structural Model

The structural model consists of the eight first-order conditions developed in the previous section and five additional equations describing output market demands and input market supplies. The eight first-order conditions included in the structural model are: equation (1) presenting almond supply, equations (2) and (3) representing input demands in almond production, equation (4) representing the supply of almond pollination services ($y^1$), equations (9) and (10) representing demands for inputs used in production of $y^2$, and equations (13) and (14) jointly representing the supply of post-almond pollination services ($y^h$) and honey ($y^h$). In addition to these eight equations, the structural model includes five additional market equations describing output demand functions for $Y$, $y^2$ and $y^h$, and input supply functions for $z$ and $b$. These five equations are used to endogenize the prices, $p^Y$, $y^2$, $y^h$, $w^2$, and $w^h$. Variable definitions are provided in table 1. A comprehensive presentation of the structural model is provided in the online supplementary appendix.

Log-Differential Model for Market Equilibrium Displacement

The log-differential model is obtained by totally differentiating the structural model. The model consisting of equations (15)–(27) is presented in terms of $y^2$ and $y^h$, by replacing $v$ and $q$ using the identities $v = y^2/y^1$ and $q = y^h/y^1$ (equations (6) and (7)).

$$Y = \tau_1 \ln y^1 + (1 - \tau_1) \ln z$$
$$p^1 = -(1 - \tau_1) \sigma^{-1} \ln y^1 + (1 - \tau_1) \sigma^{-1} \ln y^1 + \ln p^Y$$
$$w^z = -\tau_1 \sigma^{-1} \ln z + \tau_1 \sigma^{-1} \ln y^1 + \ln p^Y$$
$$y^1 = s_k \ln b + s_k \ln k$$
$$w^b = -s_k \delta^{-1} \ln b + s_k \delta^{-1} \ln k + r_1 \ln p^1 + r_1 \ln p^1 + r_2 \ln p^2 + r_2 \ln p^2 + r_3 \ln p^h + r_3 \ln p^h$$
$$y^1 = g_2 \ln y^2 + (1 - g_2) \ln y^h$$
$$p^h - \ln p^2 = \left(\frac{1}{y^2}\right) (\ln y^2 - \ln y^h)$$
$$Y = \eta_Y \ln p^Y$$
$$y^2 = \eta_2 \ln p^2$$
$$y^h = \eta_h \ln p^h$$
$$z = \varepsilon_z \ln w^2$$
$$b = \varepsilon_b \ln w^b$$

Equations (15)–(17), derived from equations (1)–(3), represent the first-order conditions for almond producers, where $\tau_1$ is the cost share of $y^1$ and $\sigma$ is the elasticity of input substitution in almond production. Equation (18) is derived from equation (4) and represents the supply of $y^1$, where $s_k$ and $s_k$ are the cost shares of inputs $b$ and $k$. Equations (19) and (20) are derived from equations (9) and (10) and describe input demands by
beekeepers, where $\delta$ is the elasticity of input substitution in $y^1$ production and $r_i$ ($i = 1, 2, 3$) are the revenue shares of $y^1$, $y^2$, and $y^h$. Equations (21) and (22) are derived from equations (13) and (14) and describe the supplies of $y^2$ and $y^h$, where $g_2$ is the revenue share of $y^2$ in period 2 revenue ($g_2 = p^2 y^2 / (p^2 y^2 + p^h y^h)$) and $\gamma$ is the elasticity of output transformation between $y^2$ and $y^h$. Equations (23)–(27) are derived from assumed market equations, where $\eta_Y, \eta_Y, \eta_h, \zeta$, and $\epsilon_h$ are corresponding market demand and supply elasticities. For reference, all parameters are listed and defined in Table 2 along with parameter values and sources.

Derivations of the above log differential equations are standard except for equation (22), which involves a product transformation curve and thus the elasticity of output substitution as a parameter. This is a novel feature in the equilibrium displacement literature and the online supplementary appendix provides its full derivation.8

The thirteen equation-system identifies thirteen unknowns, which are total log derivatives of $Y, pY, y^1, y^2, z, b, k, p^1, p^2, p^h, w^z$, and $w^h$. The linkages across the multiple input and output markets are illustrated in Figure 3, which illustrates the flow between markets using the supply and demand curves as well as equilibrium prices and quantities.

**Specifications of Parameter Values**

Parameter values are drawn from many sources, including discussions with industry participants and our best assessments of industry practices and responses to recent changes in market conditions. Market demand elasticities are adopted from the literature (when available) and input cost shares are based on industry cost information and sample cost budgets developed by researchers from academic institutions (Penn State Extension 2012; Duncan et al. 2016; Yaghmour et al. 2016). For the revenue shares of bee products, we rely on our recent survey of beekeepers servicing almonds in California, which provides the most recently available revenue information specific to commercial beekeepers pollinating California almonds. The online supplementary appendix provides additional information on parameter specifications, with additional discussion and evidence for the low substitution elasticities between the two inputs in production of almonds and honey bee hives and moderate substitution between outputs in period 2. Given the limited information available for some parameter values, we implement an extensive sensitivity analysis to ensure the robustness of our findings.

**Important Emerging Industry Shifts and Corresponding Simulation Scenarios**

We develop four simulation scenarios to represent the most critical ongoing and potential developments in the economic prospects of both the almond and honey bee industries: (S1) the emergence of self-fertile almond varieties, (S2) increased colony losses, (S3) increased costs of irrigation water, and (S4) weakened demand for almonds.

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8 Allen (1938) notes, “The same concepts are also of use in other problems involving the notion of a transformation function… The corresponding elasticities of substitution then follow as before except that a negative sign must be added, the transformation curves being concave, and not convex, to the origin in the plane Oxy” (p. 345).
| Parameter | Definition | Value | Source |
|-----------|------------|-------|--------|
| $\eta_Y$  | Demand elasticity of California almonds | -0.27 | Russo, Green, and Howitt (2008) |
| $\tau_1$  | Cost share of input $y_1$ in almond production | 0.12 | University of California almond cost study |
| $\sigma$  | Allen Uzawa elasticity of input substitution in almond production | 0.1 | Authors’ assessment |
| $\varepsilon_z$ | Supply elasticity of composite input $z$ | 1.5 | Authors’ survey |
| $s_j$     | Cost share of input ($j = b, k$) in $y_1$ production | $s_b = 0.12$, $s_k = 0.88$ | Penn State Extension (2012), 2014 PNW survey (Caron and Sagili 2014) |
| $g_2$     | Revenue share of $y_2$ in period 2 ($= p_2 y_2 / (p_2 y_2 + p_1 h)$) | 0.3 | Authors’ survey |
| $\delta$  | Allen Uzawa elasticity of input substitution in $y_1$ production | 0.2 | Authors’ assessment |
| $r_i$     | Revenue share of $y_i$ in total revenue earned from both periods for $i = 1, 2$, and $h$ | $r_1 = 0.6$, $r_2 = 0.12$, $r_h = 0.28$ | Authors’ survey |
| $\gamma$ | Elasticity of product transformation for multi-output production | -1 | Authors’ assessment |
| $\varepsilon_b$ | Supply elasticity of bee stock | 1 | Various sources |
| $\eta_2$ | Demand elasticity of $y_2$, post-almond pollination services | -0.3 | Authors’ assessment |
| $\eta_h$ | Demand elasticity of $y_h$, honey | -0.765 | Ward (2014) |

Figure 3. Full graphic representation of model in supply and demand diagrams: Relationships among input and output markets for almonds and honey bees.
11% of Total Almond Area

Self-fertile varieties of almonds do not require cross-variety pollination and therefore exhibit much lower pollination needs from commercial pollinators such as honey bees.9 Self-fertile almond trees became available for commercial planting in California about a decade ago and new plantings of self-fertile trees have been expanding gradually (USDA 2017d). The variety called “Independence” has emerged as the dominant self-fertile variety. Independence accounted for just 1% of bearing acreage, but 18% of nonbearing acreage in 2016, indicating the potential future growth of self-fertile almond area. In our simulation scenario, we consider a situation in which 11% of total almond acreage is of the self-fertile variety, a likely outcome for the industry within five years, as indicated by the recent path of plantings by variety. The online supplementary appendix provides details of our projections based on current data on new almond plantings and the share of Independence variety.

Increases in self-fertile acreage will result in a lower use of honey bee pollination inputs without lowering almond yields. Implementing this scenario in our model is challenging because the choice of an almond variety using fewer bees must be incorporated as a nested shock, even though self-fertile acreage may represent a technology that is different from traditionally-pollinated almond production. Nevertheless, the fact that the same amount of output is feasible with less input suggests that the adoption of a self-fertile variety can be modeled as factor-augmenting technical change. This notion of technical change facilitates our description of the input adjustments associated with the shock of self-fertile almond production. Recall that with factor-augmenting technical change, an increase or decrease in input use depends on the degree of input substitutability. Under limited input substitutability, the immediate consequence of factor-augmenting technical change is that the marginal product of factor-augmented inputs approaches zero, leading to a decrease in the use of those inputs and an increase in the use of other inputs. Such an outcome, in which the use of the factor-augmented input, almond pollination services, falls and the use of other inputs expands, is likely for pollination and other inputs in almond production.10

To parameterize the shift in the existing production function, we denote the rate of factor augmentation as a and rewrite the y1 input as ay1. Then the self-fertile variety scenario can be described as a change in a from 1 to a > 1. Assuming, for this scenario, that self-fertile orchards use no commercial honey bees and suffer no loss in yield, our scenario of 11% self-fertile acreage entails that the same level of output is feasible with only 89% of y1.11 The associated factor-augmentation rate of a = 1.12 is calculated by solving for a from y1 = 0.89 * ay1. To implement the change in a from 1 to 1.12, we write ay1 in log differential form, dlnay1 = dlna + dlny1, and the term dlna = 0.12 can be simply appended to equations describing almond production, (15), (16) and (17).

S2. Increased Colony Losses: 20% Additional Loss at the Beginning of the Almond Pollination Season

The mass colony losses that emerged in the United States during the winter of 2006–2007 were termed “Colony Collapse Disorder.” This event and subsequent losses raised and spread concern regarding the long-term survival of the honey bee pollinator population. Recent data show that colony losses, occurring throughout dormant and active periods, have averaged between 20% to 40% per

9 To ensure the economically optimum commercial yield, a self-fertile variety may not completely eliminate the use of commercial pollinators. In that case, a low stocking density of honey bees may be employed when the presence of bees increases nut set. No conclusive and formal agronomic information or recommendations have yet become available about production methods with self-fertile varieties, including the effects of stocking density of honey bees and yields under alternative conditions. Industry specialists indicate that yields of self-fertile varieties are similar to varieties that use the typical amount of honey bee pollination. Experimental research on the optimal honey bee density is underway (Doll 2012; Romero 2016).

10 The contraction of the factor-augmented input under low input substitutability is seen clearly in the extreme case of Leontief technology. With the fixed factor proportions, the immediate impact of the factor-augmenting technical change in y1 is a reduction in the factor augmented input, y1 because the marginal product of y1 would be zero and an increase in the use of the other input, z. This is a typical path of factor adjustments when input substitution is limited. As discussed later, we set the elasticity of input substitution as 0.1, which is fairly close to the Leontief case.

11 If the self-fertile varieties use many fewer bees, but not zero, we could simply adjust the value of a. For example, the use of one hive per acre means that the 94.5% of pollination input produces the same level of output and the implied value of a is 1.058.
year. Based on a survey of 19% of all U.S. colonies, Lee et al. (2015) reported that colony losses were 20% for surveyed colonies during the summer of 2013, 24% during the winter of 2013–2014, and 34% for the whole year. While no systematic increases in colony losses have occurred in recent years, prospects of high winter losses remain a critical concern for the industry and broader public (USDA 2017c).

An increase in colony loss can be implemented in our model by specifying a reduction in pollination services in period 1, given an initial bee input. In this way, higher colony loss percentages can be represented by appending a coefficient to output $y^1$. Denoting the output as $cy^1$, pre-shock output is represented by $c = 1$ and post-shock pollination output is represented by $0 < c < 1$. With the additional colony loss of 20%, the change in $c$ from 1 to 0.8 implies that $dlnc = -0.2$, which can be incorporated into the supply equation for $y^1$.

S3. Increase in Cost of Irrigation Water for Almond Production: The Supply Curve of Input $z$ Shifts up by 20%

The recent multiyear drought in California emphasized the vulnerability of irrigation water availability (Medellín-Azuara et al. 2016). Almonds require substantial amounts of water per acre, with little flexibility in the amount required (Duncan et al. 2016; Yaghmour et al. 2016). Access to irrigation water during drought years can be costly, with irrigation water usually reallocated to higher revenue-per-acre-foot crops. For example, in the heart of the almond growing region of California’s Central Valley, the price of irrigation water rose from a normal price of $60 per acre foot to $264 per acre foot during the recent drought (Frate et al. 2012; Yaghmour et al. 2016). Recent water policy changes and further climate change-related concerns are likely to cause substantial permanent reductions in water availability and accompanying increases in irrigation costs for almonds. Because irrigation water is a component of the composite input $z$, a shift back in water supply is expressed as a 20% upward shift of the supply function of $z$.

S4. Weakened Demand for Almonds: Almond Demand Shifts down by 20%

Almond prices rose from $1.10 per pound in 2001 to $3.74 per pound in 2014 (in constant 2010 dollars). The trajectory of prices observed over the past couple decades has, until 2014, been clearly upward. After seven straight years of price increases, almond prices fell markedly in 2015 and have remained about 40% below their peak in 2014. There is widespread concern that the steady increase in almond demand is over. With about two-thirds of commercial bee hives relying on almonds for a large share of their revenue, a reversal in the demand for almonds has large and direct implications for pollination demand and revenue. We represent this potential negative price trend as a 20% downward shift in the almond demand curve.

Implications of the Four Shocks for Prices and Quantities of Honey Bee Products and Almonds

Table 3 presents the quantitative assessment of the impacts of shocks described above as percentage changes in prices and quantities of the markets considered. The table also reports corresponding changes in revenues and costs for beekeepers and almond growers. We first discuss the results of each scenario and then compare implications across scenarios. Figure 4, discussed in detail in the sensitivity analysis section, provides a handy overview of the results for all scenarios.

SI: Self-Fertile Almond Area

The main implication of S1, under which 11% of bearing almond acres are dedicated

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12 We note that some colony losses occur throughout the entire bee season (periods 1 and 2 in our context). For simplicity, we assume that the colony loss occurs only in period 1, meaning that the colony loss affects the production of $y^1$.

13 Some colony losses are natural. Considering this natural rate as a baseline, the total colony loss depends on the natural rate of colony loss. If the natural rate is 30%, an additional 20% of colony loss ($dlnc = -0.2$) amounts to 14% (20% of the remaining 70% population) of the population before the natural death. With $dlnc = -0.2$, the total colony loss increases from 30% to 44%.

14 We use the recent experience at the peak of the latest drought to calibrate this change. A water price increase from $60/acre foot (af) to $264/af at the water application rate of 3.5 af/acre implies a 25% increase in the $2,913 pre-shock per acre cost of composite input (for more data information, refer to the supplementary online appendix). Thus, the 20% shift assumed in scenario 3 is a substantial shock but less than the 25% increase experienced at the peak of the recent drought.
to self-fertile varieties, is a decline in pollination demand in period 1, which implies a reduction in the quantity and price of pollination services in period 1. This shock also causes a slight increase in almond quantity as well as a reduction in their price, stemming from the positive output effect precipitated by the decline in cost. The technical change causes almond supply to shift out, but the derived demand for the honey bee pollination input shifts inward due to the low input substitutability between almond pollination and composite inputs. The quantitative consequences of these shifts at the new equilibrium are a 0.5% increase in almond production, a 10.3% decline in the quantity of almond pollination and a 13.3% decline in almond pollination fees. The shift in derived input demand for almond pollination allows us to calculate the implied supply elasticity of almond pollination service in period 1 by dividing 10.3% by 13.3%, which is 0.77.

With fewer bees in period 1, the quantity of post-almond pollination falls by 6.39% and honey quantity falls by 12% in period 2. The demand for these products is inelastic; therefore, the price of post-almond pollination rises by 21.29% and honey price rises by 15.68%. Beekeeper revenues in period 2 rise, offsetting some of the losses from period 1, resulting in overall beekeeper revenue and cost falling by about 11%.15

\[ \frac{\Delta Y}{\Delta C} = 0.77 \]

\[ \frac{\Delta Y}{\Delta C} = 0.13 \]

\[ \frac{\Delta Y}{\Delta C} = 0.37 \]

\[ \frac{\Delta Y}{\Delta C} = 2.9 \]

S2: Higher Colony Losses

Higher colony losses constitute an upward shift in the supply curve of honey bees and thus in the supply of almond pollination services. Under this scenario, the quantity of honey bees falls by 0.37% and pollination fees rise by 2.9%. These changes in price and quantity allow us to estimate the demand elasticity for bees in almond pollination to be about \(-0.13\) (dividing \(-0.37\) by 2.9). Rucker, Thurman, and Burgett (2012) estimate an inelastic demand for pollination services, explained by the small cost share of pollination services in most crop production. A relatively small decline of 0.37% in honey bee numbers in period 1 implies similarly small declines of 0.23% and 0.43% in post-almond pollination services and honey production in period 2. A reduction in the fixed input (honey bees) in period 2

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production shifts the product transformation curve inward, which is described in figure 2 with the new curve depicted in blue. At the same time, the inward shift of the product transformation curve is also represented by upward shifts of supply curves for post-almond pollination, \( y^2 \), and honey, \( y^h \). Again, the equilibrium expressed as a movement along the demand curve for each product allows us to calculate the implied demand elasticity for post-almond pollination, calculated here as \(-0.3\), by dividing \(-0.23\) by \(0.76\). Overall, beekeepers’ revenue increases by \(1.6\%\), but their cost of production rises by almost \(22\%\) due to the dominant effect of colony losses.

Figure 4. Sensitivity of simulated values to nondeterministic parameters: simulation results summarized in modes, 50% percentiles and 100% percentiles of the results.

Note: Quantities are in blue, prices in red, beekeeper cost and revenue in gold and almond cost and revenue in green. See tables 1 or 3 for variable names.
S3: Lower Irrigation Water Supply

The third scenario simulates the effects of an irrigation water shortage as an upward shift of the supply curve of composite almond input $z$, which increases the price of $z$ by 20%. The quantity of almonds falls by 3.3% accompanied by a 9.4% increase in almond price. The quantity of bees pollinating almonds declines by 2.1% and the price of pollination falls by 2.7%. These changes in almond pollination are consistent with the implied supply elasticity of pollination services in period 1 of 0.77, which was obtained earlier. The new pollination equilibrium is determined along its supply curve, at the intersection with its new demand curve generated under the shock to input $z$. A decline in honey bee use in period 1 triggers a decline in both period 2 bee products, post-almond pollination and honey. Overall, beekeepers’ revenue and cost both decline by 2.3%.

S4: Reduction in Almond Demand

Lastly, a decline in almond demand by 20% causes a reduction in almond output by 16% and a fall in almond price by 11.7%. Input use also declines; honey bee use in almond production falls by 15%, and the price of pollination falls by 19.5%. The fall in honey bee use in almonds leads to large declines in period 2 products, a 9.4% decline in post-almond pollination and a 17.6% decline in honey. However, prices of post-almond pollination and honey rise by more than quantities fall, curtailing beekeeper losses. Nevertheless, given the large share of annual revenue derived from almond pollination, beekeeper revenue loss in period 1 ($-18.7\%$ based on their revenue from both periods) dominates the small revenue gain in period 2 (2.3%), resulting in an overall revenue loss by 16.4% for beekeepers.

Comparisons across Scenarios

The scenarios just considered were designed to explore reductions in demand for almond pollination services, $y^1$. A reduction in almond pollination service quantity (measured by the number of bee hives) implies that fewer hives are available to be utilized in period 2 production, meaning that quantities of period 2 products must be lower. While the post-shock quantities of all three bee products are lower in every scenario, the new equilibrium prices of these products depend on how the shock was transmitted. Three of the shocks originating from almond market dynamics transmit effects through a downward shift in the almond grower derived demand for $y^1$. The results are lower pollination quantities of $y^1$ at lower prices. However, with an upward shift in the supply curve of bees ($y^1$) in the form of higher colony losses, the resulting lower quantity of bees implies a higher price on the demand curve. In period 2, the lower $y^1$ shifts up supply curves of both bee products, resulting in lower quantities and higher prices of both products, post-almond pollination and honey.

Additional Considerations Regarding the Demand for U.S. Honey

Now, we briefly consider the implications of relaxing our assumption of an endogenous price of honey used in our simulation. Imported honey has a significant presence in the U.S. honey market. In 2016, the United States imported 367 million pounds of honey, which accounted for about 70% of domestic consumption (USDA 2017e). In the U.S. honey market, domestic honey and imports are not perfect substitutes and tend to serve separate segments of the market. Domestic honey commands higher prices and is more often directly purchased by households than imported honey. However, the dominance of imports in U.S. honey consumption implies that any price effect of supply shocks on domestic honey production would be diminished under the presence of imports. To gain some insight into the importance of the world honey market, we conduct additional simulations of our model under the world market assumption of honey price.

Our results indicate that with an exogenous honey price, the bee population ($y^1$) falls more from almond market shocks that reduce the derived demand for honey bees (S1, S3, and S4) than from the colony loss shock (S2). Recall that in previous results, the price of honey rose in all scenarios due to honey supply declines. Here, fixing the price of honey results in more resources being shifted away from honey and into pollination during the post-almond period. Consistent with this expectation, substantial substitution occurs between post-almond pollination and honey production in period 2. Nevertheless, under the assumption of exogenous honey prices, directional changes are all preserved, and the quantitative results change only moderately.
This is especially the case for S2 and S3 where the post shock changes in endogenous honey prices were found to be very small. Overall, beekeepers’ revenues and costs change only by small magnitude. For example, beekeepers’ revenue and cost under S1 fall by an additional 1.17% and 1.32% (from −11.23% and −11.28% from the initial model), respectively, and changes under other scenarios are in similar proportions. Detailed simulation results from simulations with a fixed price of honey are presented in the online supplementary appendix.

Overall, our simulation results underscore the key role played by the derived demand for almond pollination in determining the economic outcome of beekeepers and honey bee populations. The irrigation cost and almond demand scenarios emphasize the interconnected fortunes of the honey bee industry and the almond industry.

Sensitivity Analysis

In this section, we develop a systematic analysis of the sensitivity of our simulation results to alternative parameter values. Evaluating the sensitivity to alternative parameter values is crucial for any simulation study and has long been an important part of EDM work, as highlighted by Davis and Espinoza (1998), among others (Griffiths and Zhao 2000; Rickard and Sumner 2008; Dharmasena, Davis, and Capps 2014). In addition to serving as an indication of the degree of confidence one should have regarding one’s results and their implications, a sensitivity analysis can highlight the areas in which further empirical research would be most useful.

As with other studies, the parameters in our model may be grouped as shares (revenue and cost) or response elasticities. Values for shares are linked directly to relatively solid data, and elasticity values are adopted from the empirical literature or based on informed assessment by the researchers. In line with the literature cited above, our sensitivity analysis focuses on elasticities and treats shares as known data.16

We use a Monte Carlo procedure to examine the sensitivity of our results. Each elasticity is drawn from a distribution with a mode set at the value used in the simulation results discussed above and listed in table 2. The distribution of almond demand elasticity is specified as a beta distribution, while all other parameters follow truncated normal distributions. The beta distribution is rescaled and parameterized so that the resulting distribution has a mode of −0.27, a mean of −0.35 and a range between −1.0 and −0.2.17 This specification gives a coefficient of variation of 0.29. The dispersions of normal distributions for other elasticities are standardized using a coefficient of variation of 0.15. The means are those of the simulations presented above. We assume that the parameters are independently distributed, reflecting our belief that there is no expectation that, for instance, a low elasticity of demand for post-almond pollination services should be linked to a low (or high) elasticity of demand for honey, or other parameters in the sensitivity analysis. A comprehensive explanation of the parameter distributions is provided in the supplementary online appendix.

We randomly drew 5,000 sets of parameter values from our distributions of elasticity values. These sets of values were then used in our EDM to simulate the impacts of elasticity values. We calculated summary statistics to characterize the resulting distributions of model outputs. We present the graphic summary of sensitivity outputs in figure 4 and defer more detailed results including the means, modes, standard deviations and 95% confidence intervals to the supplementary online appendix.

Figure 4 presents the distributions of the simulated results using box and whisker diagrams with each scenario in a separate panel. For each model output value, the mode of the simulated distribution is represented in a thick solid line, the 50% percentile range (25% on each side of the mean) is

16 As a check, we performed sensitivity analysis allowing for variations in the shares and found no relevant difference with what we present here.

17 The choice of a beta distribution for almond demand elasticity requires explanation. Our almond demand elasticity, −0.27, was obtained from the only recent publicly-available source. This estimate is highly inelastic, so our primary interest is to examine the sensitivity of the results to more elastic values (as noted in note 14). A beta distribution with its skewness enables us to draw from an asymmetric distribution (Davis and Espinoza 1998). With the domain restriction, assigning the mean and mode provides the distributional parameters, α (≈2.015) and β (≈3.7375), which fully characterizes the beta distribution. For the other elasticity values, given we have no such a priori notion, we adopted a symmetric distribution. The distributions are restricted to the theoretically consistent regions by performing the symmetric truncation of the distribution when necessary.
represented by the box, and the 100% percentile range is represented by the dotted line (the whiskers).

The overwhelming finding of our sensitivity analysis is that our results are robust to uncertainty in parameter values over plausible ranges. The modes and means of output distributions are very close to each other and the simulation results presented in table 3. In addition, the two top quartiles are tightly and symmetrically gathered around these central tendencies. The full range of output distributions generally preserves the magnitude of scenario shocks. Scenario 3, the reduction in irrigation water supply, displays wider distributions for all variables. Note that the signs of the effects are preserved by construction, when we truncate parameter distributions to avoid negative supply elasticities and other anomalies. These truncations are also responsible for the asymmetries in the tails of the distributions. The very small asymmetries around central tendencies are due to the slight asymmetry in the beta distribution of the demand elasticity for almonds. Price implications tend to show larger ranges than their quantity counterparts in all scenarios and markets. This is the result of demand functions being inelastic. For instance, changes in the two prices for pollination (in periods 1 and 2) and the price of honey tend to have wider distributions than the corresponding quantity variables. Across scenarios, we observe that results for scenario 2, higher colony losses, are more robust and results for scenario 3, almond water cost, are less robust than those for other scenarios. These differences are driven by the particular market that is directly affected by the scenario shocks and how this market is connected to the rest of the model. For instance, scenario 2 represents a shock in the production of bees, which is one step removed from the almond market (refer to figure 3). As a result, the uncertainty in almond demand elasticity and other almond parameters does not transmit as much variation to the results represented for scenario 2.

An important step in sensitivity analysis is to trace the source of output variation to variations in individual parameters. For this purpose, we computed the matrixes of partial correlation coefficients and elasticities that trace the effect of variation in each parameter to variation in each price, quantity, revenue, or cost represented in the model output. Partial correlation coefficients indicate the correlation between a parameter and a variable, once the linear effect of all other parameters has been accounted for. Reported elasticities measure the percentage changes in the values of each variable for a one percent change in the parameter value. The full results are presented in the online supplementary appendix, and are summarized briefly here. Our partial correlation coefficient and response elasticity results reveal the central contribution of the demand elasticity for almonds to the uncertainty surrounding the impacts estimated. Under all scenarios, the response elasticities involving the almond demand parameter are close to 10% in absolute value for most variables, whereas the response elasticities involving other parameters are mostly below 1% in absolute value. The central role of almond demand elasticity is consistent with the fact that the almond industry is a key determinant of the economics of honey bees. Other parameters play major roles in specific scenarios. The results of scenario 1 are also sensitive to the demand elasticity for honey, while the results of scenario 3 (a shock in the supply of input z in almond production) are, as expected, sensitive to the elasticity of supply of input z.

One additional insight derived from our sensitivity analysis in the context of EDMs concerns the robustness of our structural model to alternative assumptions. By drawing from a multivariate distribution in which parameter draws are correlated, relationships that are not explicit in the structural model can be brought to bear on simulation results. For instance, one may argue that demand for almonds is related to demand for other tree nuts through consumer behavior, which, in turn, affects the markets for crop inputs. This would especially be the case for the inputs that are commonly used in almonds and other tree nuts, which in our case, is the composite input z. (Recall the pollination input is not used in other nut production.) We implement a set of multivariate Monte Carlo simulations to assess the significance of such relationships by correlating the almond demand elasticity with the supply elasticity of input z. As detailed in the supplementary online appendix, our results are not significantly altered by parameter correlations, which is an indication of the robustness of our structural model specifications.
Effects of Changes in the Price of Honey

Two recent studies, Rucker, Thurman, and Burgett (2012) and Champetier, Sumner, and Wilen (2015), motivate our exploration of the likely effects of changes in the price of honey on pollination markets. As Rucker, Thurman, and Burgett (2012) argue, a change in the price of honey has two opposing effects on pollination fees. A rise in the price of honey causes substitution from pollination toward more honey-producing foraging, which reduces the supply of pollination services and thus increases pollination fees. On the other hand, a rise in the price of honey means that the in-kind benefit a beekeeper gets from access to forage rises and the compensating differential means that pollination fees for pollinating honey-producing crops would fall. Rucker, Thurman, and Burgett (2012) find, using Pacific Northwest pollination data, that a higher honey price has no significant effect on almond pollination fees but has positive effects on fees of other crops, supporting the hypothesis that substitution of honey-specific foraging for pollination among non-almond crops plays an important role.

Champetier, Sumner, and Wilen (2015) examine potential impacts of the price of honey on pollination fees in a dynamic model that emphasizes the role of honey as feed for bees as well as a marketable output. Their model explicitly shows how a higher honey price causes an increase in the opportunity cost of feeding bees during the winter. Higher honey prices translate into higher winter feeding costs, leading to a contraction in the bee population managed during the winter. This effect, combined with an upward sloping supply function of forage during the active season for bees, is another reason for a higher honey price to increase in pollination fees in both periods.

We can explore this issue using our approach by simulating the impacts of an exogenous shock in the honey market that causes both a 20% increase in the market price of honey and a 10% increase in the cost of purchased inputs in beekeeping ($p^h$) (because these inputs are substitutes for retained honey in the hive). The relationship between the price of honey and beekeeper costs is derived from data on winter-feeding that show that feed supplements account for about half of the cost of the composite input $k$ per hive. Thus, the 20% increase in the price of honey applied to its 50% share in input $z$ implies a 10% increase in the unit cost of $z$.

In our simulations, an increase in feeding costs causes a negative output effect, and thus lowers pollination output $y^1$ in period 1. In period 2, the lower $y^1$ results in lower production of period 2 products. At the same time, a higher honey price induces a positive supply response for honey production ($y^h$) but a negative supply response for post-almond pollination ($y^p$) due to the substitution between honey production and post-almond pollination.

Using our base case parameters, we find that the number of hives in period 1 ($y^1$) falls by 0.3% and the price of almond pollination rises by 2.7%. In period 2, the quantity of honey produced rises by 1.4%, and quantity of post-almond pollination falls by 4.3%, with the post-almond pollination fee rising by 14.3%. Revenue and cost for beekeepers both increase by 8.6%.

Our finding of a negative impact (−0.3%) on almond pollination is consistent with the notion from Champetier, Sumner, and Wilen (2015) that when the cost of feeding bees in the winter is higher, bee population falls. However, the impact is small. Our simulations document that this supply impact on bee population is the result of two opposing forces: a negative impact due to higher cost of feeding bees when forage is not available and a positive impact due to higher demand for bees to create more marketable honey in period 2. Our simulations show that the marketable honey impact can dominate only if the revenue share of honey is sufficiently large (close to 60%), which has not been the case in recent years (and in our simulations).

The finding that a higher price of honey causes higher pollination fees, by 2.7% for almond pollination and by 14.3% for post-almond pollination, is consistent with the econometric evidence of Rucker, Thurman, and Burgett (2012) who found a significantly positive impact on post-almond pollination fees (their finding for almond pollination fee was statistically inconclusive). Of course, pollination fees across crops depend on many factors beyond bloom season, including impacts of nearby pesticides, availability of safe habitat, or a crop’s nectar richness and quality. We also note that, although conceptually clear, the economic importance of in-kind payments from lower pollination fees on honey-rich crops is quantitatively small, because such benefits apply only to post-almond...
pollination, which generates only 12% of average beekeeper revenue. Full simulation results and sensitivity analysis for impacts of honey price increases are available in the supplementary online appendix.

Conclusions

This study models and simulates the interdependency between crop industries and commercial beekeeping using an equilibrium displacement approach. Our work focuses on the seasonality of crop pollination, the symbiotic nature of the pollination relationship, and the revenue implications of marketable pollination services and honey sales. We demonstrate how shifts in almond supply and demand, as well as much discussed shifts in honey bee health and supply, drive substantial price and quantity adjustments in horizontally and vertically linked markets. We find that factors affecting the almond industry, its acreage, and its demand for pollination, are key determinants of the number of bee hives in the United States.

Our analysis has important implications for policies related to crops and honey bees. For example, if maintaining bee hive numbers is an important public policy goal, the role of the economic health of the almond industry must be considered. Policies that cause cost shifts, such as regulations on pesticide use, reductions in irrigation water availability, or restrictions of land conversion to perennial crops, may have unintended but significant consequences for colony numbers, as well as honey bee revenue.

Our model can be extended in several important and useful ways in order to explore further questions regarding the future of pollinators. To reflect more subtle variations in pollination fees, it may be useful to refine the representation of seasonality to include more than two pollination periods. The bee stock could also be allowed to change between seasons in order to represent net bee population growth and better link pollination markets and forage availability across periods. Champetier, Sumner, and Wilen (2015) provide a basis for a simulation exercise where within-year and multi-year dynamics can be modeled to capture the reality that beekeepers may start new hives to supplement existing hives and manage die-off and feeding over the winter season. Finally, one might formally include the value of safe foraging areas that help preserve hive health, allowing for a more direct analysis of pesticides and policies.

Supplementary Material

Supplementary material are available at American Journal of Agricultural Economics online.

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