Honey Bees, Almonds, and Colony Mortality: An Economic Simulation of the U.S. Pollination Market

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ABSTRACT *Motivated by increasing threats to pollinator health and increasing pollination contract fees, we develop a simulation model for the honey bee pollination and honey production market. The model, calibrated using 2015 and 2016 data, incorporates population dynamics, 15 crops, and transportation of managed honey bee colonies across several states. In our model, forage that bees need is particularly scarce, and further increases in almond acreage will have little effect on the fees paid for pollination services. However, increases in bees' winter mortality will lead to increases in early-season pollination fees and declines in late-season fees.* (JEL Q11)

1. Introduction

In the mid-2000s, commercial bee mortality increased, pollination contract fees more than doubled (Figure 1),[1] and demand for pollination services increased greatly with almonds (the largest pollination demander), experiencing an almost 50% increase in bearing acreage in less than a decade. These events resulted in many news reports and policy concerns in the United States, including the 2014 presidential memorandum "Creating a Federal Strategy to Promote the Health of Honey Bees and Other Pollinators" (White House 2014). Several studies also forecasted significant economic effects resulting from honey bee (*Apis mellifera*) and native pollinator population declines (Kevan and Phillips 2001; Southwick and Southwick 1992; Gallai et al. 2009; Hein 2009; Winfree, Gross and Kremen 2011).

Economic studies provide less dire predictions. Beekeepers have been modeled as profit-maximizing agents who adapt to changing environmental conditions to avoid severe detrimental outcomes (Champetier, Sumner, and Wilen 2015; Lee, Sumner, and Champetier 2018; Champetier and Sumner 2019). Furthermore, econometric analyses show that increased mortality affects pollination fees only slightly (Rucker, Thurman, and Burgett, 2012, 2019a).

In this study, we develop a multicrop, multiperiod, and multilocation beekeeping equilibrium model in the United States and use it to simulate changes in winter colony mortality and California almond acreage. Our model is more detailed than previous models because it represents spatially and temporally distributed pollination markets for 15 different crops plus bee activity in a major honey production region. Spatially, we include 14 distinct locations across 6 western states. The model represents movement of hives across these

[1] Data for Figure 1 are from the California State Beekeepers Association Pollination Survey (CSBA 2014) and the Pacific Northwest Pollination Survey (Burgett 1992–2010; Caron, Sagili, and Cooper 2012). Fees are deflated using the Agricultural Services Price Index (www.nass.usda.gov). The 2009 fee for early cherries in California was corrected based on the raw CSBA data.

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Appendix materials are freely available at http://le.uwpress.org and via the links in the electronic version of this article.

locations in 24 periods in a year as beekeepers respond to pollination demands, habitat suitability, and honey harvest possibilities. It also incorporates trade-offs between colony allocations to demanding crops, pollination fees, honey production potential, and bee health. Because honey bee populations vary seasonally and spatially, beekeeper management decisions directly influence the extent to which honey bee colony populations fluctuate and whether colonies are transported to fulfill pollination contracts around the country. In particular, our model endogenizes pollination and honey market prices. It is calibrated using 2015 and 2016 market data for honey and pollination services as well as beekeepers' major cost components, although our cost breakdown is not as detailed as Goodrich, Williams, and Goodhue (2019).

Our model includes substantial institutional detail on geographic, temporal, and economic forces that drive the U.S. pollination market. This yields more detailed and calibrated results than previous models (e.g., Lee, Sumner, and Champetier, 2018), provides qualitatively different results, and allows us to explore the economic forces behind the simulated values. We find that further increases in California almond acreage have little effect on pollination prices when there is ample bee forage. We also find that almond pollination is so dominant that additional almond pollination can be supplied in an essentially constant-returns-to-scale fashion. However, when we assume that limited forage availability reduces colony productivity, pollination fees become sensitive to a change in almond acreage. We also find that alterations in winter colony mortality affect pollination fees, as do Rucker, Thurman, and Burgett (2019b). Higher winter mortality causes increases in the total number of colonies to prepare for winter declines. This leads to higher early-season pollination fees but lower late-season fees.

2. The Pollination Market

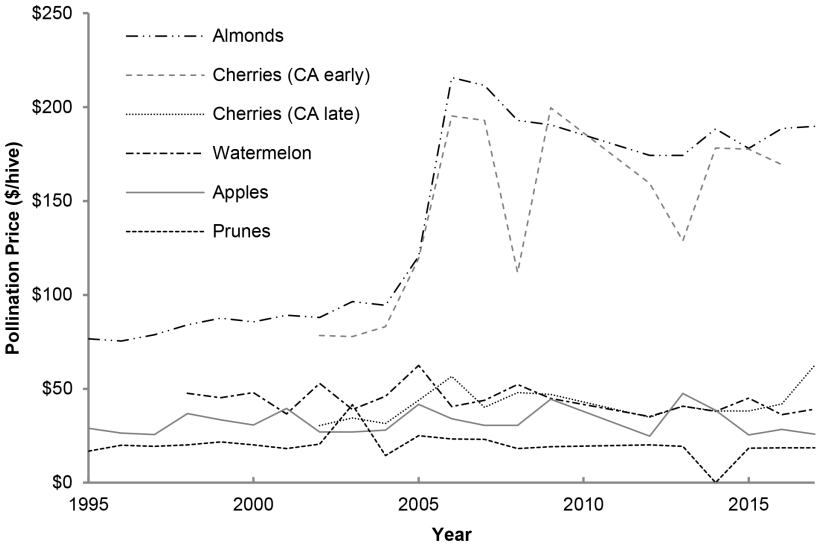
Many of the major crops produced in the United States depend on some form of animal-mediated pollination. In most cases, the populations of natural pollinators are not sufficient because pollination services are required at levels that are concentrated in both time and space, greatly exceeding what would be provided without human intervention (Morse and Calderone 2000; Calderone 2012). To meet the demand for managed honey bee pollination services, commercial beekeepers ship thousands of truckloads of honey bee colonies across the country.

In recent years, the honey bee pollination market has experienced an increase in pollination fees, particularly for almonds (Figure 1). The market has been affected by an expansion in almond acreage, from 480,000 acres in 1999 to 1.1 million acres in 2018 (USDA-NASS 2019). It has also suffered from an increase in honey bee winter colony mortality, which has roughly doubled from about 15% in 1999 to more than 30% in 2019 (Sumner and Boriss 2006; Kulhanek et al. 2017; Rucker, Thurman, and Burgett 2019b). In addition, wild bee populations declined by about 23% between 2008 and 2013 (Dicks et al. 2016; Koh et al. 2016; Potts et al. 2016).

Economists have long examined the honey and pollination markets as an instance of an apparent externality but for which markets arose naturally (Meade 1952; Cheung 1973). Recent work has analyzed various market aspects. Champetier (2010) and Champetier, Sumner, and Wilen (2015) focused on dynamic market variations showing the importance of bee forage.[2] Champetier (2010) showed that winter colony losses affect pollination fees for early-blooming crops such as almonds with a lower effect on fees later in the year. Ward, Whyte, and James (2010) showed that pollination fees are affected by the life cycle of a bee colony, particularly in the spring when populations are at their lowest. Sumner and Boriss (2006) indicated that beekeepers maintain additional colonies to meet early spring demand, and this results in excess pollination capacity after peak spring

[2] "Forage" refers to the dietary nectar and pollen available to honey bees. Depending on when and where beekeepers place colonies, there will be different forage supplies available. During some parts of the year, beekeepers place the colonies on sites exclusively for foraging; these sites may contain cultivated crops, wild plants, or both.

Figure 1
Pollination Fees per Colony for Selected Crops (2016 Dollars)



Source: Burgett (1992–2010); Caron, Sagili, and Cooper (2012); CBSA (2018).

demand lowers fees later in the year. Our model builds on these insights.

3. A Model of the Pollination Market

Following Rucker, Thurman, and Burgett (2012), and especially Lee, Sumner, and Champetier (2018), we model equilibrium U.S. pollination and honey markets. Our model is more disaggregate in time and space than those of our predecessors because we include varying seasonal pollination demands that are spread across $k = 1, \ldots, K = 24$ periods a year. It incorporates (1) joint production of pollination services and honey; (2) colony population growth and decline as influenced by crop, place, and time; (3) hive maintenance; (4) hive transportation; (5) honey production costs; and (6) regionally differing honey production rates. We model a single equilibrium year in which the number of colonies at the end of the final period become the initial colonies in the first period. Appendix Table A1 describes the parameters and variables used in the model.

Following Lee, Sumner, and Champetier (2018),[3] we simulate a perfectly competitive market equilibrium for pollination services and honey. Beekeepers are assumed to be profit-maximizing price takers facing demand curves for pollination services and honey. We allocate colonies and other inputs over 24 periods, not the 2-period representation in Lee, Sumner, and Champetier (2018). In each period, beekeepers choose whether and where to move colonies and the number of new colonies to create through splitting, provided that colony populations are growing.[4] Pollination demands vary across space and time. Thus, colony location at a point in time determines the type of crops that can be pollinated, the proximity to future pollination markets, the location-specific growth and mortality rates, the honey production rate, and the available forage potential and accompanying need for feeding. A typical commercial beekeeper's profit in each year consists of the revenue

[3] The structure of our model, however, is based on Williamson (2016).

[4] Splitting a colony involves turning one large colony into two smaller ones plus adding a new queen to the new split. This allows the bee populations in the two colonies to grow (Rucker, Thursman, and Burgett 2019a).

generated from pollination services and honey sales less the costs of splitting, transporting, feeding, and management.

Population Dynamics and Colony Management

In our model, honey bee populations grow and shrink in a discrete-time version of the continuous-growth process of Champetier, Sumner, and Wilen (2015). In each period, colonies are transported, honey production and pollination services are then provided, and the location and pollination targets determine population changes. The model represents the number of colonies at site j in period k before transportation $A_{k,j}$ and after movement, $B_{k,j}$.[5] The bee population in period k at site j increases or decreases by a factor expressed as $V_{k,j}$. When foraging and other environmental conditions at a location are unfavorable, especially in the fall and winter, $V_{k,j} < 1$, which means that colonies have to be combined to maintain sufficient bees for pollination. This has the same effect as the culling process in Champetier, Sumner, and Wilen (2015).[6] When environmental conditions are favorable, as in the spring and summer, $V_{k,j} > 1$, and beekeepers have the ability to increase their number of colonies through splitting. The number of splits, $N_{k,j}$, cannot exceed the natural rate of population growth:

$$N_{k,j} \leq B_{k,j}(V_{k,j} - 1) \text{ when } V_{k,j} > 1. \quad [1]$$

[5] As discussed below, there are 14 sites in our model, corresponding to the centroid of the production region for each of the crops or major honey-producing regions. The point in southwest Montana captures honey production in Idaho and Montana. Honey regions are aggregated for growth and honey production, but beekeepers are assumed to spread out their colonies geographically based on historical rates to each of the points indicated on Appendix Figure A1.

[6] Combining colonies is typically a very low-cost operation that can be done by stacking the colony hive bodies from two relative small bee colonies on top of one another, usually placing newspaper in between so that the combined colonies slowly get used to each other. Sometimes two weak colonies with queens can be combined, and both queens have a chance of surviving, which would then make it easy to split the colony once they are stronger. We abstract from these and other technical details of the beekeeping process in our aggregate model and assume that all splits are equally costly.

Hence, the number of colonies at the start of period k, $A_{k,j}$, is a function of the stock at the end of period $k - 1$ after splitting and population change as follows:

$$A_{k,j} = \begin{cases} V_{k-1,j} B_{k-1,j} & \text{if } V_{k-1,j} \leq 1 \\ B_{k-1,j} + N_{k-1,j} & \text{if } V_{k-1,j} > 1 \end{cases}. \quad [2]$$

The equilibrium year is imposed by requiring that the number of colonies in the first period, $A_{1,j}$, follow equation [2], with $B_{24,j}$, $V_{24,j}$, and $N_{24,j}$ on the right-hand side.

Champetier, Sumner, and Wilen (2015) emphasize that forage scarcity can have a significant effect. Such scarcity, however, is not captured in our base model specification. While growth factors, $V_{k,j}$, and honey production, $H_{k,j}$, vary across space and time based on forage abundance and quality, we do not represent forage adequacy as a function of the number of colonies currently present in a given region. To some extent, this is unrealistic. As the number of colonies in an area grows, eventually the quality of the forage and pollen that bees can access will diminish, and population growth rates and honey production will decline accordingly. We explore this in the scenario analysis section.

Transportation and Management

Our model contains a variable for the number of bee colonies transported from location i to location j in period k ($T_{k,i,j}$). When $i = j$, the colonies remain in the same location. The number of colonies that leave or remain in location i during period k must equal those ending period $k - 1$ in that location, that is,

$$A_{k,i} = \sum_j T_{k,i,j}. \quad [3]$$

Because a portion of the bees die during shipment ($L_{i,j}$), the number of colonies that arrive at site j and are then available for pollination is given by a loss correction of the transport variable

$$\sum_i (1 - L_{i,j}) T_{k,i,j} = B_{k,j}. \quad [4]$$

The loss rate, $L_{i,j}$, is computed as a function of the distance traveled. Transportation costs

are a linear function of the number of colonies moved, $\sum_i \sum_j D_{i,j} T_{k,i,j}$, where $D_{i,j}$ is the cost of transporting a colony over the distance from i to j. Transportation losses and costs both equal zero when $i = j$.

Colony management costs in a given time period k, C_k^M, include the costs of splitting colonies and maintenance, including labor, feeding, and medicating:

$$C_k^M = \sum_j (\sigma N_{k,j} + \gamma_{k,j} B_{k,j}), \quad [5]$$

where σ is the cost of a split and $\gamma_{k,j}$ is the cost of maintaining each colony for one period, which varies by time of year and location. Although we capture the major costs incurred by beekeepers, in reality there are other costs, some of which are fixed (Champetier and Sumner 2019).

Pollination and Honey Demand

Following Rucker, Thurman, and Burgett (2012), we assume a perfectly inelastic demand for pollination services. This is equivalent to assuming that the elasticity of substitution with other inputs is zero, and that the input is a vanishingly small share of the total cost of production. This simplification seems reasonable because, as Rucker, Thurman, and Burgett indicate (2012, 968), "the cost share of pollination is small in the production of most crops" and "advisors and farmers act as if they perceive their production processes to be fixed regarding proportions of land and bees."[7] Although the actual elasticity is certainly not zero, we believe such an assumption is reasonable, even though evidence to support this for crops other than almonds is lacking. Hence, pollination demand is modeled using a constraint requiring that the number of colonies present after transportation, $B_{k,j}$, exceeds the demand for pollination by location and time period, $\beta_{k,j}$:

$$B_{k,j} \geq \beta_{k,j}. \quad [6]$$

For honey, following Lee, Sumner, and Champetier (2018), we assume an annual downward-sloping demand curve for a single homogeneous honey, S. The total amount of honey produced during the year across all locations is

$$S = \sum_k \sum_j H_{k,j} B_{k,j}. \quad [7]$$

The price then arises from an inverse, constantly elastic demand function:

$$P^H = \eta S^{\frac{1}{\varepsilon}}. \quad [8]$$

Given this demand curve, the surplus generated directly by extracting and selling honey, H^S, equals the area under the demand curve less the cost of extracting and processing the honey for sale:

$$H^S = \eta S^{\frac{1}{\varepsilon}+1} / \left(\frac{1}{\varepsilon}+1\right) - \lambda S, \quad [9]$$

where λ is the cost per pound of extracting and processing honey for sale.

Surplus Maximization to Find Market Equilibrium Prices and Quantities

Assuming a perfectly competitive market, equilibrium prices and quantities can be simulated by maximizing consumers' surplus plus producers' surplus (as reviewed in McCarl and Spreen 1980). A quasi-welfare function is equal to the area below the inverse demand curves less the total costs to meet those demands.[8] Because we assume a perfectly inelastic demand for pollination services over the relevant range of prices, the area under the pollination demand curve is constant. Furthermore, pollination revenue is simply a transfer from crop producers to beekeepers, netting to zero. Hence, the aggregate welfare for a single equilibrium year for the pollination market is equal to the total surplus in the honey market less the costs of honey production and bee management/transport:

[7] Lee, Sumner, and Champetier (2018) relax this assumption, adopting a low elasticity of substitution (0.1), but they recognize the weak empirical foundation for this value and find that allowing pollination demand to be price sensitive does not significantly affect their results.

[8] Because we do not model the number of beekeepers directly, we ignore fixed costs in this calculation. To the extent that entry costs exist, beekeepers will be able to extract rents so that the assumption of a fully efficient market is not satisfied.

$$W = \underbrace{H^S}_{\substack{Honey\\Surplus}} - \sum_k \left(\underbrace{C_k^M}_{\substack{Mgmt.\\Costs}} + \underbrace{\sum_i \sum_j D_{i,j} T_{k,i,j}}_{\substack{Transportation\\Costs}} \right). \quad [10]$$

We solve the model, as given in equations [1]–[10], using the General Algebraic Modeling System (GAMS Development Corporation 2016). The pollination fees are recovered as the shadow prices on the pollination demand constraints [6] and the honey price is obtained from the inverse demand curve [8] or, equivalently, the shadow price on the honey market clearing constraint [7].

4. Parameterization and Calibration

We parameterize and calibrate the model to represent the pollination markets in 2015 and 2016 in California, Oregon, and Washington plus the honey-production region spanning Idaho, Montana, North Dakota, and South Dakota (Appendix Figure A1; Bond, Plattner. and Hunt 2014). Data were collected from a variety of sources, including the available economics literature, the U.S. Department of Agriculture (USDA), the National Agricultural Statistics Service (USDA-NASS 2015), USDA publications (USDA-NASS 2019), HoneyBeeNet (Nickeson and Esaias 2015), the Bee Informed Partnership (Bruckner et al., 2019), the California State Beekeepers Association Pollination Survey (CSBA 2018), the Pacific Northwest Pollination Survey (Burgett 1992–2010; Caron, Sagili, and Cooper 2012), and personal communication with beekeepers, growers, and industry experts.

Crop Choice and Pollination Demand

We model crop pollination demand as if it were located across space at the points that are shown in Appendix Figure A1. These points are the crop-production-weighted centroids in each pollination-demanding or honey-producing state. Transportation costs are estimated using Google Maps to compute driving distances between those points. Based on communications with commercial beekeepers, shipping costs are assumed to be $8.10 per 1,000 colonies per mile, and the bee population loss rate is assumed to be 5% per 1,000 miles traveled.[9]

Pollination of the modeled crops required more than two million colonies in 2016, representing more than 90% of all managed colonies in the study region (USDA's regions 5 and 6, Figure 2)[10]. We assume that each crop has a single location-dependent bloom period. The exceptions are sweet cherries, which are divided into three subcrops (Washington cherries and early and late California cherries) and plums, which are subdivided into plums and prunes (CSBA 2018). We approximate the acreage of subcrops by assuming that colony demand is broken up across the subcrops so that the weighted average fee for the crop is equal to that reported by USDA-NASS (2017a), while subcrop prices are those reported by CSBA (2018). Most crops have bloom periods that last one month, although there are several exceptions, as seen in Figure 2.

Beekeeping Costs

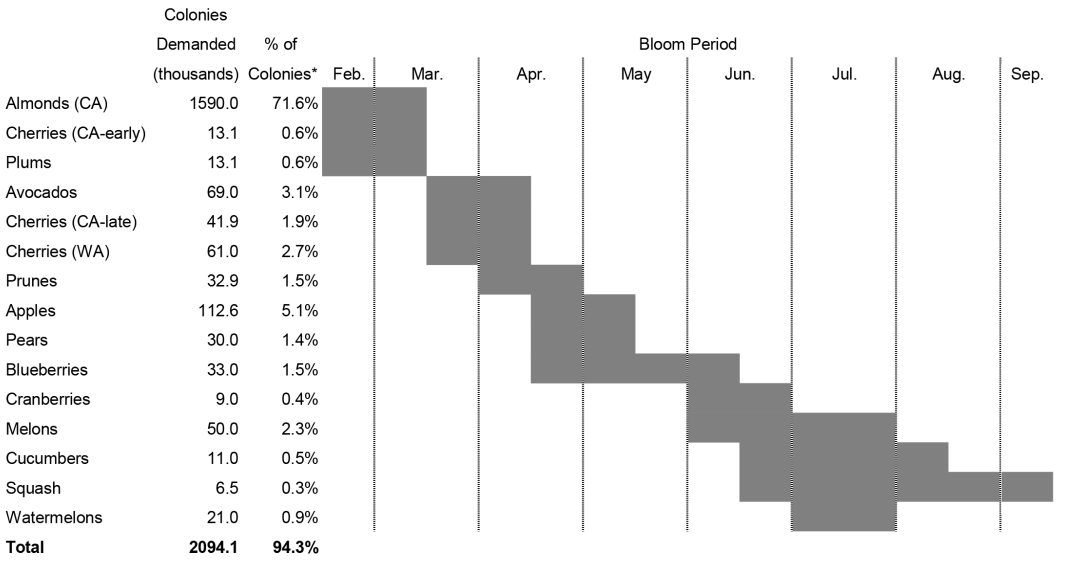
Nontransport-related beekeeping costs are those for colony maintenance, splitting, preventive medication, and feeding (Hofshi, Sherman, and Arpaia n.d.; Laate 2017; Champetier and Sumner 2019).[11] Maintenance costs

[9] The honey production areas in Idaho, Montana, North Dakota, and South Dakota are aggregated into a single composite region, and transportation costs are based on weighted average distance traveled to the three points indicated on the map in Appendix Figure A1, weighting based on the annual honey production in each state.

[10] Pollination "Colonies demanded" as shown in Figure 2 is for 2016 (USDA-NASS2017a). The "% of colonies" values are relative to totals for USDA regions 5 and 6. Blooming periods are from Morse and Calderone (2000), Sumner and Boriss (2006), Nickeson and Esaias (2015), and discussions with M. Mahoney, C. Moore, and T. Martin. Region 5 includes Alaska, Idaho, Oregon, and Washington. Region 6 includes California and Arizona. The majority of U.S. pollination services occurs in California, Oregon, and Washington. Data used to calibrate this model were included in the USDA's "Cost of Pollination" report, which was discontinued in 2018.

[11] Based on the dates of references, the undated report by Hofshi, Sherman, and Arpaia seems to have been created around 1999–2000. Hence, values were inflated to 2015 prices based on the consumer price index for 2000.

Figure 2
Pollination Demand, Percentage of All Pollination Demanded in California, Washington, and Oregon by Pollination Demand Timing



Source: Morse and Calderone (2000); Sumner and Boriss (2006); Nickeson and Esaias (2015); M. Mahoney, C. Moore, and T. Martin (pers. comm. 2016); USDA-NASS (2017a).

are assumed to be distributed evenly throughout the year. Laate (2017) provided estimates of beekeeping costs in Alberta, Canada. From that study, we assume an annual feeding cost of $16.50 per colony and nonfeed maintenance costs of $83.73, although this might be on the high end because such costs are likely higher in northern climates. We distribute feeding across the year in each state based on growth rate indices derived from NASA's Honey Bee Forage Map (Nickeson and Esaias 2015; shown in Appendix Figure A1) and the USDA's list of crops that are attractive to honey bees (USDA 2015). The cost of each split, including the cost of a new queen and labor, is set at $70 based on personal communication with beekeepers.

Honey Production and Sales

Honey production rates are taken from USDA state-level yearly production data and range from 35 to 36 pounds per colony in California, Washington, and Oregon to 71–78 pounds in South Dakota, North Dakota, and Montana (USDA-NASS 2018). A colony's honey production is then distributed throughout the year based on the species of plants being foraged and their blooming times (Nickeson and Esaias 2015). To account for crowding, task allocation, and reduced diversity in nectar sources, we assume that honey bee colonies produce less honey when pollinating cultivated crops. The final honey production rates parameters, $H_{k,j}$, are set in the calibration process, as we discuss below.

The honey demand elasticity, ε, is set at –0.765 based on Ward (2014). The constant term in the honey demand equation, η, is selected by passing the demand curve through the actual honey price and quantity in 2015 and 2016, $\widehat{P_t^H}$ and $\widehat{S_t^H}$. Therefore,

$$\eta_t = \widehat{P_t^H} / \widehat{S_t^H}^{\frac{1}{\varepsilon}}, \quad [11]$$

yielding $\eta_{2015} = 52.81$ and $\eta_{2016} = 54.93$ in our model.

Ideally, the colony population change parameters, $V_{k,j}$, would be based on area-specific scientific analyses of growth potential and death rates. Because such analyses are lacking, we develop the parameters in a two-step calibration process. First, we compute

initial values for these parameters by state using quarterly data on the maximum number of colonies present (**CM**), number of colonies added (**CA**), number of colonies renovated (**CR**), and number of colonies lost (**CL**) (USDA-NASS 2017b). The resultant base population change rate for each quarter is computed as $\mathbf{\Delta C} = (\mathbf{CA} + \mathbf{CR} - \mathbf{CL})/\mathbf{CM}$. The initial estimate of the **V** parameters for a half-month period that would be consistent with these reported values is $\mathbf{V} = (1 + \mathbf{\Delta C})^{\frac{1}{6}}$. These base rates are set for acreage in each state for the full quarter and are used as the initial values for our calibration process.

Second, we calibrate the model to closely match pollination fees, honey price, and honey production. In the calibration process, we vary three parameters: (1) colony growth rates in periods during pollination ($V_{\mathbf{k,j}}$), (2) honey production rates per colony during pollination ($H_{\mathrm{k,j}}$), and (3) a universal scaling factor that adjusts the costs of pollinating all crops, which reflects unobserved differences in feeding and maintenance costs. Our calibration approach is relatively new to models of this type. We calibrate so the model satisfies the Karush-Kuhn-Tucker conditions for optimality while matching to the extent possible (1) the pollination fees for each crop, (2) the honey price, and (3) the honey production quantity. Calibration is carried out using the Mathematical Program with Equilibrium Constraints (MPEC) model (Dirkse and Ferris 1998) that chooses parameter values to minimize the sum of the squared differences between the actual and simulated revenue from pollination and honey sales with the Karush-Kuhn-Tucker holding conditions simultaneously. Because colonies typically grow during the spring and summer, we constrain the growth parameters to be at least one through the first half of October ($V_{\mathrm{k,j}} \geq 1$). To avoid unrealistically high levels of mortality, we also constrain the model so that the lowest allowable value for $V_{\mathrm{k,j}}$ is 0.9. The model is independently calibrated for 2015 and 2016, the two years for which data are available.

After calibrating the model for 2015 and 2016, we average the calibration parameters to obtain a single model that predicts the situation in both years. The final calibrated version of the $V_{\mathrm{k,j}}$ matrix is presented in Appendix Table A2. The fees predicted by the calibrated model compared with the actual 2015 and 2016 fees are shown in Appendix Figure A2. As seen in the figure, the difference between the simulated and actual prices is negligible for almonds, but the differences grow as we move to crops where pollination demand is lower. The simulated 2016 honey quantity and price are 86.6 million pounds and \$1.846 per pound, each of which is less than 0.2% from the actual values for 2016 (USDA-NASS 2018). A range of specifications and starting values were explored.[12] Although we have strong confidence in our qualitative findings, the quantitative predictions of the simulation model should be viewed with caution. The GAMS code for all models is available through Github.[13]

5. Scenario Analysis

We now turn to our analysis. We look first at the effect of continued almond acreage expansion. We later examine increases in winter mortality rates. By also evaluating a reduction in almond pollination demand, we explore the potential effect of expanding self-pollinating almond varieties (Lee, Sumner, and Champetier 2018). All scenarios were created using the average 2015 and 2016 calibration, but we use only the 2016 pollination demand levels.

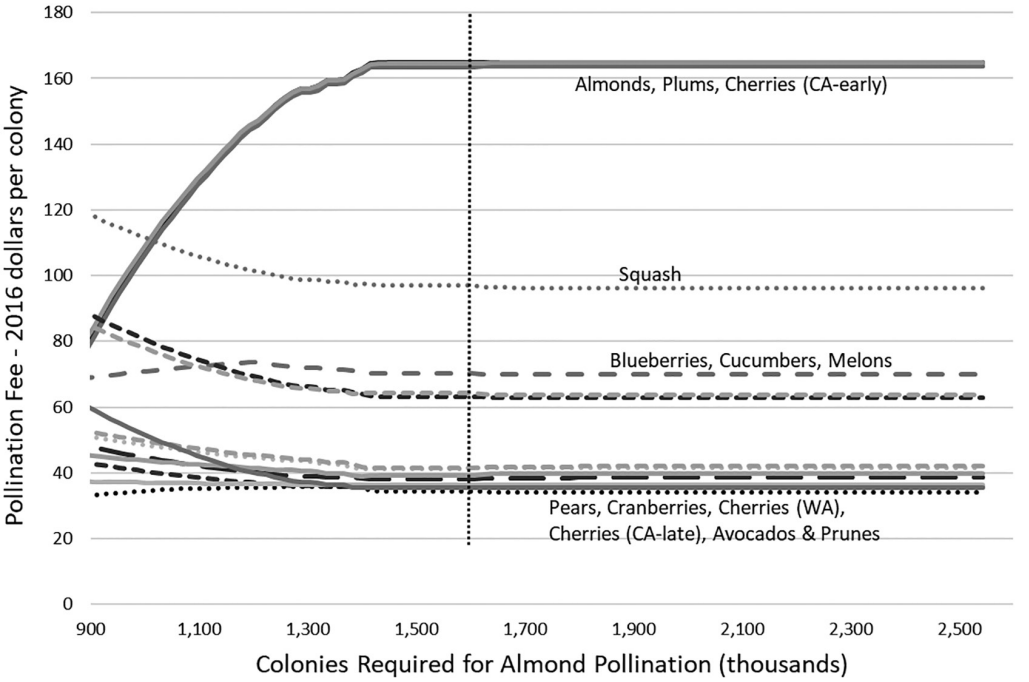
Change in the Number of Colonies Demanded for Almond Pollination

Figure 3 shows simulated pollination fees by crop for alternative almond pollination demand scenarios (note that the level of demand in 2016 is indicated by the vertical dotted line). The simulated pollination fees change significantly as the annual almond pollina-

[12] Limited by the method and solver we used for the calibration process, the solver frequently yielded corner solutions in which the simulated fees were accurate for 2015 or 2016 demand levels, but the resulting calibration was not able to reach an equilibrium as simulations were run for slight differences in pollination demand or winter mortality. Although the general trends were consistent across the calibrations, the simulated fees changed abruptly and unrealistically for modest increases in demand or mortality.

[13] See https://github.com/feiccheng/Bees.

Figure 3
Impact of Changes in Almond Demand on Pollination Fees



tion demand increases from 0.9 to 1.3 million colonies, but there are only slight changes as demand increases further. The pollination fees charged for early-season crops (almonds, plums, and California early cherries) increase, while most other fees fall slightly. This finding is consistent with Sumner and Boriss (2006), who argue that expanding early-season crops creates a situation with excess supply of bees later in the year.

To understand how almond acreage affects pollination fees, recall that our fees are equal to the shadow prices on the pollination constraints [6]. Relaxing or tightening this constraint will induce marginal changes across the elements of the objective function elements [10]. Because the pollination fee is positive, we know that a marginal increase in demand for almond pollination must lead to an increase in total costs with the overall value of the objective function value, *W*, declining. Nonetheless, some elements of *W* can increase, and a breakdown on this is shown in Table 1.

Consider first the case when almond pollination requires 1,113,000 colonies, which is about 30% below 2016 levels. At this level, one more colony for almond pollination results in $287 of extra costs, including $41 for shipping, $100 for splitting, and $139 for feeding. This requires more than one additional split to make up for additional transportation mortality. However, additional honey is also produced, leading to a honey surplus gain of $155. Therefore, the net marginal change in welfare is $131, which is the simulated equilibrium fee.

As the demand for almond pollination increases, there is a shift. At the 2016 level with 1.6 million colonies required, a one-colony increase in almond demand reduces shipping costs by $28 because the extra hive reduces the need to move colonies. As a result, transportation mortality falls, and only about half of an additional split ($25) is needed. Hence, the cost of a one-colony increase in almond pollination demand is $165.But this pushes the honey price down to $1.85 per pound. Although an additional colony could produce more honey, the model predicts that beekeepers will not manage that colony in a manner that produces more honey. Hence, there is no

Table 1
Decomposition of the Marginal Cost of Almond Pollination at Different Levels of Almond Acreage

Almond Pollination Demand (1,000 colonies)	1,113	1,352	1,590	1,829	2,067
% change relative to 2016	−30	−15	0	15	30
Marginal cost of one additional colony for almond pollination ($/colony)					
Shipping	32.5	15.2	−27.8	−27.8	−27.8
Splitting	60.0	52.5	24.9	24.9	24.9
Feeding	137.6	58.0	133.8	133.8	133.8
Other pollination costs	33.8	33.8	33.8	33.8	33.8
Honey extraction	23.6	0.0	0.0	0.0	0.0
Gross marginal costs	287.5	159.5	164.7	164.7	164.7
Increase in honey surplus	155.8	0.0	0.0	0.0	0.0
Net marginal decline in welfare = pollination fee	131.8	159.5	164.7	164.7	164.7
Honey price/lb.	2.34	1.93	1.85	1.84	1.84

Note: Equilibrium honey prices for each level of almond pollination levels are presented in the final row.

increase in honey surplus, and the pollination fee is $165. Similar values are found for almond acreage that is 15% and 30% above the base level.

In our base scenario, we find that once a sufficient number of colonies is available, almond pollination is a constant returns-to-scale process. This is true because of the surplus of honey bees after almond pollination ends. For instance, in 2016, 1.6 million colonies were needed for pollination in the second half of February and first half of March; in no other period did the demand exceed 10% of that level, leaving 90% of the colonies to produce honey or be idle. Hence, while a marginal increase in almond demand means added colonies, requiring a little more splitting and feeding but less shipping, there are no other associated benefits or costs. Because the splitting and feeding are provided at a constant cost, the pollination fee does not change, even if the almond demand expands substantially.[14] The constant pollination fee above 1.3 million colonies differs from that found by Lee, Sumner, and Champetier (2018), whose model has more imposed economic structure, which predicted that a 10.3% decline in demand for almond pollination will cause a 13.3% decline in the almond pollination.

[14] The assumptions regarding constant cost of feeding and splitting are discussed where we evaluate key assumptions in the model.

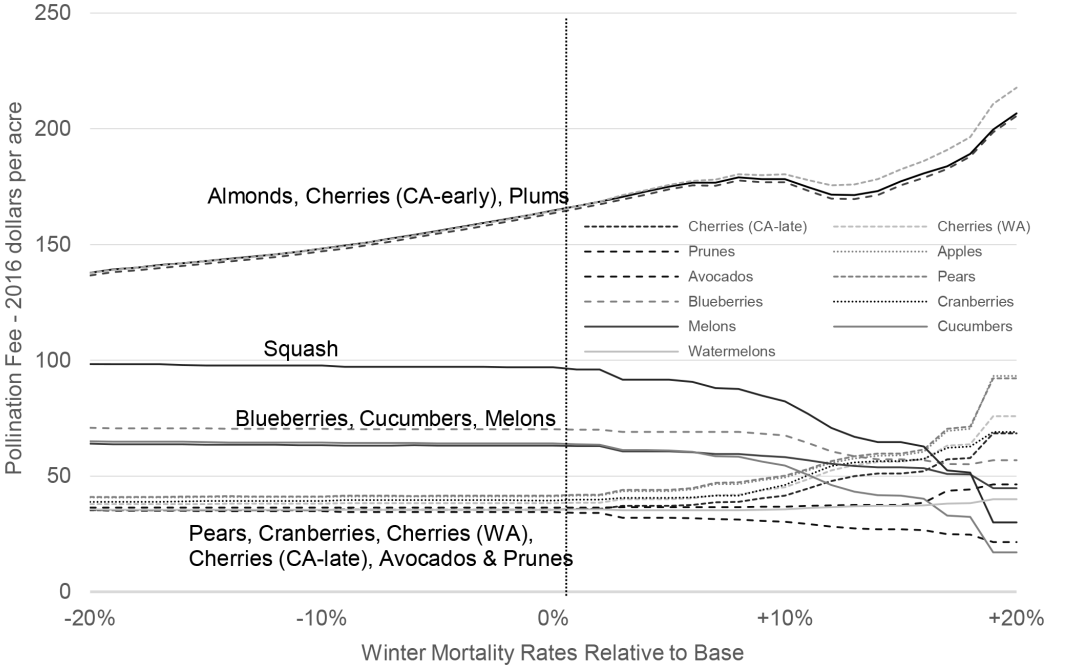
Change in Winter Colony Loss Rates

We now evaluate the effect of increased winter mortality. We simulate this by reducing the population change parameters, $V_{k,j}$, for the time periods beginning with the second half of October and continuing through the first half of February. The total change in winter mortality that we report is the cumulative reduction over these periods.

We modify the loss rate from 20% below the base level to 20% above it. We find that as the mortality rate increases, the pollination fees tend to increase for early season crops, while they decline slightly for some late season crops and increase for others (Figure 4; note that the change in winter mortality is the cumulative increase in mortality from the second half of October to the first half of February).[15] Figure 5 shows the resulting total number of colonies throughout the year, providing the intuition for why mortality rates exert different effects on early- and late-season fees. Bars indicate the number of colonies required for pollination. The lines give the total number of colonies by three mortality levels: the top dashed line is for 20% higher mortality, the middle line is the base scenario, and the lower dotted line is for 20% lower mortality.

[15] The simulated effect on early season crop is robust to model calibration; consistently, we found that prices for those crops were simulated to increase for higher levels of winter mortality. We have less confidence in the simulated effects on late-season crops, as these changes varied significantly for alternative model specifications.

Figure 4
Impact of Increasing Winter Mortality on Pollination Fees



Therein, except during the first two periods (February 2 and March 1), the number of colonies available far exceeds that required for pollination. However, because of spring and summer colony growth, the number of colonies increases until early in the fall. Consequently, the number of colonies available in October exceeds those required to pollinate early crops by more than 80%. If winter mortality increases, this gap grows because beekeepers must build up a larger bee stock during the year to ensure there are enough colonies to meet the peak February almond demand. Hence, higher winter mortality rates lead to more colonies throughout most of the year. In our simulations, if the colony mortality rate is 20% higher than the base level, beekeepers will need to have nearly one million more colonies present at the end of the summer.

In contrast, when mortality is reduced, fewer colonies are needed. In that case, beekeepers have fewer surplus colonies available for late-season crops, and this requires greater opportunity costs in terms of forgone honey, leading to fee increases as seen in Figure 4.

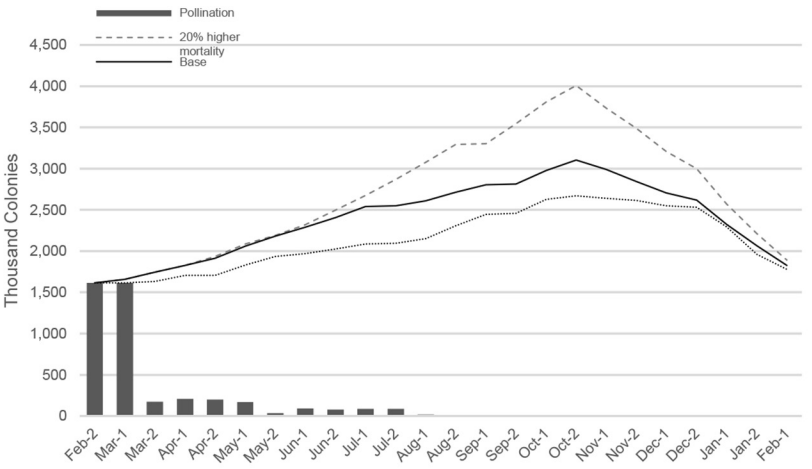
The mechanism through which changing mortality rates impact pollination fees can also be seen by looking at changes in components of the objective function (Appendix Table A3). When mortality rates are high, to have one more colony ready to pollinate in February requires more splitting and feeding costs and therefore a higher equilibrium fee.

Key Assumptions and Forage Scarcity

We now discuss key assumptions on which our findings rest. First, we assume bee management inputs are supplied at a fixed price, that is, from a perfectly elastic supply curve. For labor, transportation, and most other inputs, this is reasonable owing to tiny market share.[16] For other inputs, the supply may not be perfectly elastic. In particular, queen

[16]There is, however, the possibility that timely transportation could be scarce, especially since bee transportation is a specialized service (S. D. Aurell, pers. comm. 2016). We believe that although such scarcity may affect the market in the short run, in the long-term equilibrium framework used here, the supply would be able to be provided with little increase in cost.

Figure 5
Simulated Number of Colonies as Mortality Rates Vary



bees, which are needed when a colony is split, will likely exhibit an upward-sloping supply curve. However, Rucker, Thurman, and Burgett (2019a) found that the short-run supply curve for queens is highly elastic. Furthermore, in the long term, all inputs will be highly elastic, and our model is one of a long-term equilibrium. Hence, we believe that the assumption that input costs are exogenously fixed is reasonable.

Another important assumption in our base model is that forage supply is ample and does not affect colony growth/mortality rates and honey production. Champetier, Sumner, and Wilen (2015) indicate that forage limitations can play a critical role in the pollination market. This is unlikely to be a problem at the level of a parcel of land because the number of colonies used to pollinate a specific crop varies little. However, if the number of bee colonies in a region increases significantly, competition may lead to a decline in honey production and bee survival due to use of lower quality forage and greater travel distance.

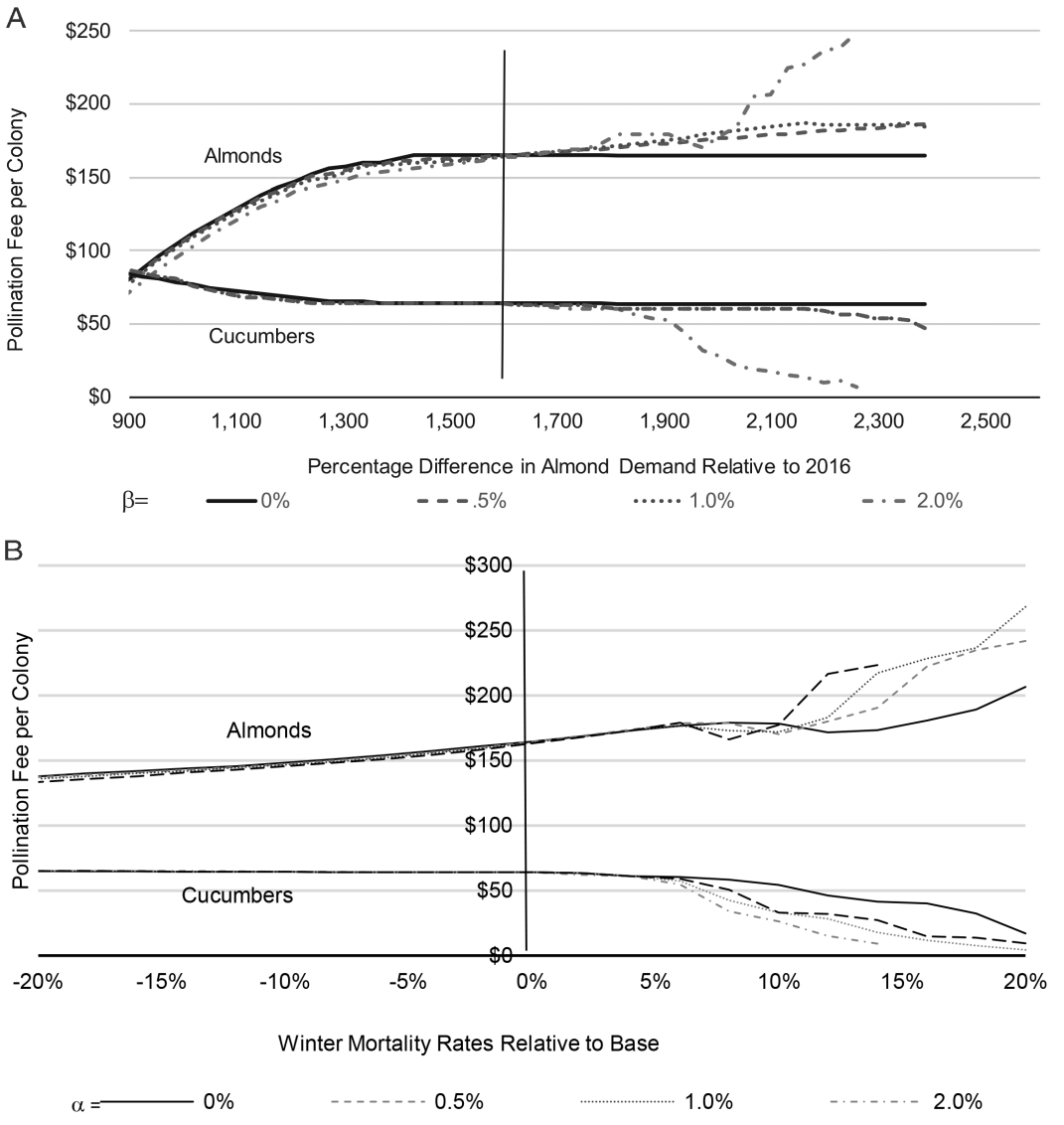
Because we are unaware of broad-scale empirical estimates on how forage scarcity affects bee productivity and survival, we carried out a sensitivity analysis on this effect. We simulated forage scarcity by reducing colony growth rates when the total number of bees in a region exceeded base levels (Nickeson and Esaias 2015). First, we aggregated the total number of bees in a forage region following Nickeson and Esaias (2015) (see Appendix Figure A1). If the number of colonies in a region (R) exceeds that in the base year, that is, if $\sum_{j\in R} B_{k,j} > \sum_{j\in R} \bar{B}_{k,j}$, the growth rate is adjusted downward, specifically, $V_{k,j} = \delta_R \bar{V}_{k,j}$, where $\delta_R = 1 - \alpha\left(\frac{\sum_{j\in R} B_{k,j} - \sum_{j\in R} \bar{B}_{k,j}}{\sum_{j\in R} \bar{B}_{k,j}}\right)$.[17] Hence, for every 1% increase in the number of colonies, the population growth factor falls by $\alpha/100$ and vice versa if fewer colonies are present.

The effects of including this forage scarcity adjustment on pollination fees for changes in almond demand and winter mortality are shown in Figure 6. Panel A presents the simulated pollination fees for almonds (an early-season crop) and cucumbers (a late-season crop) for different levels of almond acreage and four values of the bee forage scarcity parameter (α), which affects bee colony growth. Panel B presents fee sensitivity to varying winter mortality rates and forage scarcity effects.

If forage scarcity does not affect bee productivity ($\alpha = 0\%$), we see in Panel A that almond expansion past base levels has no discernible effect on the pollination fee for

[17] Because we aggregate the colonies in the honey-production regions in Idaho, Montana, North Dakota, and South Dakota, these regions are also aggregated for calculating the bee forage scarcity adjustment.

Figure 6
Pollination Fees with Forage Scarcity



either almonds or cucumbers (a representative late-season crop). As the forage scarcity factor grows, however, rising almond demand increases almond pollination fees.

However, the cucumber pollination fee falls again, reflecting increased numbers of colonies. For the highest forage scarcity adjustment fees change abruptly, which probably suggests our model is not well calibrated for such conditions.

Similar effects arise in Figure 6, Panel B, which displays results when winter mortality rates are varied. Without a forage scarcity effect, a 20% increase in mortality causes a $40 increase in almond pollination fees and a similar decline in cucumber fees. When forage scarcity is introduced, the simulated effects on the pollination fees are more pronounced.

There is significant uncertainty around these forage scarcity results. However, we lack

data with which we can calibrate α, and we assumed a closed bee market, excluding bee imports from other regions. As simulated winter mortality increases, more bees are required to achieve an equilibrium and, in some cases, our model ultimately is unable to converge to an equilibrium. In reality, this will probably lead to bees being imported. Nonetheless, our results suggest that if forage scarcity effects are substantial, almond pollination fees will increase more and late-season fees will drop.

6. Conclusion

We investigate bee pollination market implications of increases in colony mortality and almond pollination demands plus forage scarcity effects. We use a western U.S. regional, multicrop, multitime period, multilocation model that represents bee population dynamics, spatial and temporal pollination demand, bee allocation, honey production, and interregional bee movement. When demand for almond pollination is low, a marginal increase in almond pollination demand reduces honey production, increases bee stocks, requires additional transportation and maintenance, and changes how bees are moved throughout the year. Up to a critical point (1.3 million colonies per year for almond pollination), early-season pollination fees increase and late-season fees decrease. Beyond that, simulated pollination fees change very little assuming adequate forage. Unless forage scarcity is important, increases in almond pollination beyond 2016 levels requires relatively constant expenses for splitting and maintaining hives with the pollination fee being changed. However, if forage scarcity effects on productivity and survival are important, opportunity costs are nonlinear and increasing, so that pollination fees continue to change as almond acreage expands.

Increasing winter mortality affects pollination fees and bee populations. However, contrary to dire popular press predictions, increased mortality has not pushed and will not push the market to the cusp of collapse. Instead, increased winter mortality stimulates beekeepers to hold more colonies and take other actions to respond, leading to higher almond pollination fees but slight declines in fees for other crops. Recently, there has also been growing concern about changes in summer mortality (Kulhanek et al. 2017). Research on that topic is part of an ongoing project that extends the work reported here.

We also explore the effects of forage scarcity. As the number of colonies in a region grows, bees may be forced to use lower quality forage or travel farther to find satisfactory forage. We simulate these effects by adjusting the population growth/mortality parameter as densities increase and find that forage scarcity has significant consequences. This is an important factor for future study and should be considered when carrying out similar analyses.

The model developed here captures additional spatial and temporal aspects of the situation relative to previous efforts. We also use a unique calibration process that helps estimate parameters that were otherwise unobtainable. Our model allows for a more complete evaluation of the spatial and temporal trade-offs between bee mortality, bee growth, honey production, and pollination. The model shows those trade-offs can have important effects on pollination fees while also revealing cases where they have little effect. There are a number of other trends affecting the honey bee pollination market that deserve attention, including changes in summer mortality and international trade forces affecting the honey market. Future research can extend the modeling structure provided here to study these economic forces.

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