

HONEY BEE POLLINATION MARKETS AND THE INTERNALIZATION OF RECIPROCAL BENEFITS

RANDAL R. RUCKER, WALTER N. THURMAN, AND MICHAEL BURGETT

The world's most extensive markets for pollination services are those for honey bee pollination in the United States. These markets play important roles in coordinating the behavior of migratory beekeepers, who both produce honey and provide substitutes for ecosystem pollination services. We analyze the economic forces that drive migratory beekeeping and theoretically and empirically analyze the determinants of pollination fees in a larger and richer data set than has been studied before. Our empirical results expand our understanding of pollination markets and market-supporting institutions that internalize external effects.

Key words: bees, ecosystem services, markets, pollination.

JEL codes: Q13, Q12, Q57.

Introduction

Pollination is essential for seed plant reproduction. The transfer of pollen from stamen to pistil is accomplished in different plants by wind, water, insects, birds, and bats. Pollination by some insects can be economically manipulated by man, and the services of these insect pollinators have become vital agricultural inputs. In particular, the well-known European honey bee (*Apis mellifera*) is widely used to enhance yields and promote uniform quality in nuts, fruits, and vegetables—notably almonds, kiwifruit, apples, cherries, pears, blueberries, and cucumbers.¹

While managed honey bees have provided pollination services in American agriculture since colonial days, their importance has grown in recent years, and for at least two reasons. First, as modern agricultural production has come to employ large monocropped

farms, pollination by wild insects living on the periphery of fields has become less reliable. Second, feral honey bees were decimated in the mid- to late-1980s by *Varroa* and tracheal mites—both of which are acarine parasites that attack bee colonies. While both pests can be controlled (at a cost) in managed colonies, feral honey bee populations were hit hard. Although these populations have slowly recovered, there are no good data available on the extent of the recovery. Experts agree, however, that across North America there is now much less “natural” pollination to be relied upon than in the past.²

The decline in wild pollinators has been taken up as a *cause celebre* by those concerned with wildlife preservation and biodiversity.³ Concern over the loss of wild pollinators has been accompanied in the past few years by concern over the numbers of managed bees, as parasites and disease have been joined by a phenomenon dubbed Colony Collapse Disorder. Virtually the entire bee populations of large numbers of overwintered colonies have disappeared in various parts of the United States, and no single cause to explain the disappearances has been identified. To some, Colony Collapse Disorder symbolizes the deleterious

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¹ See Hoopinger and Waller (1992) and Robinson et al. (1989). Although honey bees are the best known commercial pollinators, other bees are used as well. Non-colonial bees are important for some commodities. For example, alfalfa leafcutting bees are used for alfalfa seed crops (Mayer and Johansen 2003), as well as for hybrid canola seed crops in Canada, and bumblebees are used for greenhouse tomatoes (Thorp 2003).

² See National Research Council (2007).

³ See, for example, the web page sponsored by the Ecological Society of America and the Union of Concerned Scientists: www.esa.org/ecoservices and the National Academy of Sciences study (National Research Council 2007).

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environmental consequences of industrialized agriculture, which takes widespread advantage of specialization, exchange, and economies of scale, and that in the process may be compromising the health of managed honey bees. To other (commercial agricultural) interests, Colony Collapse Disorder represents a new source of concern regarding their livelihoods, highlights the economic contribution of honey bees, and provides justification for government-funded research.⁴

What is usually missing from discussions of honey bees and their plight is an appreciation of the role of markets for pollination services. Pollination markets are also largely missing from the large and growing body of literature on the economic value of ecosystem services.⁵ Where they do exist, these markets provide readily available and relatively inexpensive substitutes for the ecosystem services provided by wild pollinators.

The world's most extensive and active market for pollination services is for honey bees in the United States. A large-scale annual migration of beekeepers moves hives from farm to farm, charging pollination fees as the crops bloom. In recent years, fees paid to U.S. beekeepers were approximately \$350 million.⁶ Given the current and potential future importance of pollination services, as well as the public's interest in honey bees, there has been surprisingly little economic analysis of pollination markets.

Cheung (1973) was the first to take seriously the role of markets in allocating honey bee services. Cheung challenged earlier theoretical

literature on externalities (Meade 1952, Bator 1958, and precursors by Pigou 1912 and 1920) that used honey bees and apples as an illustration of reciprocal externality. The earlier literature argued that apple trees provide uncompensated benefits to beekeepers (nectar for bees and honey production), and bees provide uncompensated benefits to orchard owners (pollen transfer for apple production). From their assertion that apple farmers and beekeepers do not transact, the writers inferred an underprovision of both apples and bees. Cheung responded with an examination of 1971 data from a small number of beekeepers, arguing that (1) the existence of markets for pollination services rebutted the presumption of externality, and (2) variation in the observed fees was consistent with differences across crops in the relative values of pollination and honey.⁷

Pollination markets have developed considerably in the 40 years since Cheung wrote, and the policy issues surrounding pollination agriculture have changed considerably as well. In the current paper we theoretically and empirically analyze the determinants of pollination fees with a much larger and richer data set than has been studied before. Our data come from an annual survey of Pacific Northwest (PNW) beekeepers that has been conducted by Michael Burgett at Oregon State University since the late 1980s. In addition to reinforcing Cheung's refutation of the externality myth, our empirical results expand our understanding of pollination markets and market-supporting institutions that internalize external effects.

⁴ Arguments made in Congressional subcommittee hearings in the past two decades assert the annual value of pollination services to be \$9 billion (see Robinson, Nowogrodzki, and Morse 1989). Updates to that figure (see Morse and Calderone 2000) peg the value at \$14.6 billion in 1999 dollars, a number that has been referenced by policy-makers. The accuracy of these estimates is an issue of active research and debate (see for example, Muth and Thurman 1995, Gallai et al. 2009, and National Research Council 2007). Regarding the magnitude of the economic effects of CCD, little research has been conducted. In 2007, U.S. Secretary of Agriculture Johanns warned that, "if left unchecked, CCD has the potential to cause a \$15 billion direct loss of crop production and \$75 billion in indirect losses;" (USDA 2007). Rucker, Thurman, and Burgett (2012), however, estimate the economic impacts of CCD to be relatively small, a result attributed by Rucker and Thurman (2011) to "the resilience of honey bees and to the business acumen and perseverance of commercial beekeepers."

⁵ For a review of recent literature on the economics of ecosystem services, see Swinton et al. (2007).

⁶ The \$350 million estimate is based on assigning an annual pollination rental income figure of \$145 per colony to the number of bee colonies reported by the U.S. Department of Agriculture in 2009. For comparison, the USDA reports the 2009 value of honey produced in the United States (the other output of managed honey bees) as \$208 million.

⁷ To our knowledge, other than Cheung's 1973 paper, refereed publications on the workings of pollination markets are the following: Johnson (1973), Olmstead and Wooten (1987), Muth, Rucker, Thurman, and Chuang (2003), Ward, Whyte, and James (2010). Of these, only Cheung, Muth et al. and Ward et al. statistically examine pollination market data. The differences between the current work and the three empirical studies—and the advances we offer beyond them—are as follows. Cheung's 1973 study analyzed detailed data on one year of activity from eight beekeepers, all of whom lived in Washington. All of his statistical tests are relatively simple, and several of them are calculated using data obtained from only four beekeepers. An important finding was that pollination fees varied inversely with the honey value of the crop. The focus in Muth et al. is the honey support program. For pollination, they study an earlier data set (through 1995) in a simpler econometric setting that does not take into account several potentially important covariates. Ward et al.'s 2010 study focuses only on almond and cherry pollination fees, and fails to take into account changes in the purchasing power of the U.S. dollar over a twenty-year sample period. Our analysis examines in a panel data setting a substantially more extensive set of pollination market data than has heretofore been studied.

Pollination and Markets

A typical large-scale North American commercial pollinator drives a tractor-trailer combination that carries 400 to 500 bee hives, each of which contains a single colony with a queen and between 15,000 and 30,000 workers.⁸ Transportation of the bees is facilitated by traveling at night with nets covering the hives—bees fly out of their hives only during the day. Once the truck arrives at a field or orchard for pollination, forklifts are used to move the hives to strategic points to spread bees throughout the flowering area. Bees typically stay close to home when placed in a pollen and nectar-rich flowering field. They will, however, fly considerable distances when pollen and nectar sources are more difficult to find.⁹ As bees forage across flowers, they pick up pollen (which contain the male gamete, or sperm) on their bodies and transfer it to the pistils (the female reproductive organs) of other flowers. In the case of nuts and tree fruit, an important role played by bees is cross-pollination: the transfer of pollen between trees of one variety and those of another variety, strategically planted in adjacent rows.¹⁰ The hybrid vigor that results from inter-variety pollen transfer promotes fruit sets and ultimately fruit quality and uniformity.

Bees are typically moved into an orchard or field for just the flowering period. This period is roughly three weeks for almonds and most tree crops, but can vary with the weather, with higher temperatures condensing the bloom period and lower temperatures extending it. The placement period for some crops is longer—cranberries can require four to five weeks. After pollination of a particular orchard, field, or bog, many beekeepers move their colonies by truck to the next pollinating site, usually a later blooming crop or possibly the same crop farther north or at a higher altitude. At some point during the summer most beekeepers move their colonies to a location where the

focus of the bees' efforts is commercial honey production.

That pollination has been used as an example of a positive externality is understandable. The physical facts of crop pollination imply that transactions are difficult to monitor and agreements costly to enforce. Crops require pollination for only a brief period each year, and crops at different latitudes and altitudes require pollination at different times. Thus, there are large economies of scale available to mobile beekeepers, who use the same bees to pollinate several crops in a season. But mobility also makes market transactions costly. Delivering pollination services must be coordinated across multiple crops during their blooming seasons, and in the face of substantial uncertainty regarding the precise timing of the blooms. Further, markets must coordinate the joint production of pollination and honey against a backdrop of continually evolving scientific views of the efficacy of honey bee pollination.

Pollination markets today consist of contracts between farmers and migratory beekeepers. There are several large-scale migration routes traveled by these beekeepers and their bees, including the route traveled by Washington and Oregon beekeepers, who are the focus of our empirical analysis. Their pollination season begins each year in February in the almond groves of California.

Following almond pollination, California-based bee colonies are often put into nearby citrus orchards. Although there are no pollination benefits to citrus farmers and no fees received by beekeepers, the nectar is plentiful and valuable honey is produced. The migratory PNW beekeepers, on the other hand, typically move their colonies north to their home bases in Oregon and Washington. From there, they distribute their colonies among local apple, pear, and cherry orchards. Following that, the majority of the beekeepers with home bases west of the Cascade Mountains rent their colonies out to pollinate additional crops—typically soft fruits (strawberries, raspberries, and blueberries) in May and June, followed by seed crops (especially vegetables such as onions and carrots), then cucumbers, pumpkins, squash and some legume seeds (e.g. clovers) and occasionally alfalfa seed.¹¹

⁸ Historical and contemporary accounts of beekeeping can be found in Nordhaus (2011), Horn (2005), Crane (1999), Mairson (1993), and Pellett (1938).

⁹ Seeley (1995, pp. 46–50) discusses the results of studies of the foraging range of honey bee colonies. He states that, "... the median distance was 1.6 km, the mean distance was 2.2 km, and the maximum distance was 10.9 km. Perhaps the most important property of this distribution is the location of the 95th percentile, which falls at 6.0 km. This indicates that a circle large enough to enclose 95 percent of the colony's forage sites would have a radius of 6 km, hence an area greater than 100 km²."

¹⁰ See, for example, Degrandi-Hoffman et al. (1992) on bee foraging behavior in almond orchards and its implications for optimal planting of trees and varieties.

¹¹ It is noteworthy that most alfalfa seed in the Pacific Northwest is pollinated by two species of "managed wild bees," the alfalfa leaf-cutting bee and the alkali bee. Further, survey data from the PNW survey suggest that PNW beekeepers engage in substantially more

Not only does the timing of colony placement vary across crops, but the pollination fees collected by the beekeepers also differ. These differences are a focus of our theoretical model and empirical analysis below.

The east side of the Cascades is much richer in honey sources than the west side. As a result, beekeepers whose home bases are on the east side of the Cascades typically pollinate California almonds and then tree fruits in eastern Washington and Oregon. After that, they spend the rest of the season using their bee colonies to produce honey.¹² Many of the colonies remain in eastern Oregon and Washington, with a minority of them being moved to summer honey locations in Montana and other Northern Plains states. There, they join large numbers of other U.S. beekeepers, who also find summer ranges for their colonies in the region. For the rest of the summer, the hives remain at these sites, and the bees visit sunflowers, clover, basswood trees, and other nectar sources, producing honey for consumption by the hive and extraction for sale by the beekeeper.

In the fall, many U.S. beekeepers move their bees again, this time to winter in the south or in the Central Valley of California. Some Washington and Oregon beekeepers move their bees to California in December and find locations to hold their bees until the following year's almond bloom. The majority of PNW beekeepers wait until January or early February, however, to move their bees to California, where they often are placed in temporary holding yards (apiaries) until it is time to move into almond orchards for pollination.

Parallel migratory routes move up the Atlantic coast, from fruit and vegetable crops in Florida to blueberry bushes in Maine. Although surveys of eastern beekeepers have been initiated recently, there is no survey whose longevity comes close to approaching that of the PNW surveys we analyze below.

The markets that connect beekeepers with contracting farmers range across the United States, addressing complex problems of information gathering and processing. To gain a

quantitative understanding of these markets, we develop a formal model of price relationships in pollination markets, and derive and test its predictions.

A Competitive Model of Pollination Fees

Honey and fruit (representing here also nuts and seeds) are the joint outputs of a production process that employs both land and bees. The typical organization of production involves farmers who hire beekeepers to provide bee colonies to pollinate their crops. Farmers receive the output of fruit while beekeepers receive the honey (and the nutritional value of the nectar for their bees). In equilibrium, there is a side payment from farmers to beekeepers.¹³

To determine the equilibrium pollination payment, we first consider an equilibrium that would result in a fictional market where multi-output firms hire the services of land and bees in order to produce fruit and honey, which the firms sell in competitive markets. We then derive the implications for an equilibrium payment from crop growers to beekeepers in the real world, where farmers retain ownership of the fruit and pay pollination fees to beekeepers, who retain ownership of the honey.

Optimal Stocking of Bees on Land

The two-output production function is described by a pair of constant-returns-to-scale production functions:

$$(1) \quad H = G_H(A, B) \quad \text{and} \quad F = G_F(A, B)$$

where H and F are the quantities of honey and fruit produced, and A and B are the numbers of acres and bee colonies employed. Because the honey and fruit production functions are constant returns to scale, they can be written in per-acre terms:

$$G_H(A, B) = A \cdot g_H(b) \quad \text{and} \\ G_F(A, B) = A \cdot g_F(b),$$

where $b \equiv B/A$ is the stocking density, which is the sole determinant of the per-acre outputs of both honey and fruit.

pollination activities than their California counterparts. On average, PNW respondents reported that each colony pollinates almost 1.5 additional crops after almonds. This number masks to some degree the extent of beekeeper (as distinct from bee) activities. For example, on average, individual beekeepers reported taking bees to pollinate 5.5 different crops in 6.8 counties each year. See table 1 in Burgett et al. (2010).

¹² West-side beekeepers produce honey, but the quantity is small relative to east-side production. The primary source of west-side production is blackberries.

¹³ In the model we develop below, situations can arise where side payments flow from beekeepers to farmers. From our study of actual market arrangements, it is clear that such situations are rare when bees provide pollination services.

An owner of a fixed quantity of acres solves the per-acre profit maximization problem:

$$(2) \quad \max_{(b)} \pi(b) = P_H \cdot g_H(b) + P_F \cdot g_F(b) - w \cdot b,$$

where P_H and P_F are the market prices of honey and fruit, and w is the market wage of bees. The bee wage is the market price of pollination services, a parameter from the perspective of the individual beekeeper. Determination of the equilibrium bee wage is discussed below.

The first and second-order conditions for the profit-maximization problem are:

$$(3) \quad \text{FOC: } \frac{d\pi}{db} = P_H \cdot g'_H(b) + P_F \cdot g'_F(b) - w = 0$$

$$(4) \quad \text{SOC: } \frac{d^2\pi}{db^2} = P_H \cdot g''_H(b) + P_F \cdot g''_F(b) < 0.$$

Note that (4) is not a global restriction on the shapes of the individual production functions, g_H and g_F . At the optimum, a linear combination of the two production functions must be concave.

The first-order condition in (3) can be interpreted as setting the total value marginal product of bees (TVMP_B) equal to the bee wage, where TVMP_B is the sum of the VMPs for honey and fruit. Solving (3) for b as a function of w , P_F , and P_H , and substituting that function [$b^* = b^*(w, P_F, P_H)$] back into (3) yields

$$(5) \quad \text{TVMP}_B \equiv P_H \cdot g'_H(b^*) + P_F \cdot g'_F(b^*) \equiv \text{VMP}_B^H(b^*) + \text{VMP}_B^F(b^*) = w.$$

The left-hand panel of figure 1 displays the optimal choice.

Log-differentiating (5) results in

$$(6) \quad [\varphi\eta_H + (1 - \varphi)\eta_F] d \ln b^* + \varphi d \ln P_H + (1 - \varphi) d \ln P_F = d \ln w,$$

where $\eta_H \equiv \frac{d \ln g'_H}{d \ln b}$, $\eta_F \equiv \frac{d \ln g'_F}{d \ln b}$, and $\varphi \equiv \frac{P_H g'_H}{P_H g'_H + P_F g'_F}$. Note that the parameter φ is the honey share of the total VMP of bees and is represented as the ratio cd to ce in figure 1. Solving for the comparative static responses of b^* to changes in w , P_H and P_F

gives

$$(7) \quad d \ln b^* = \frac{1}{\varphi\eta_H + (1 - \varphi)\eta_F} \times [d \ln w - \varphi d \ln P_H - (1 - \varphi) d \ln P_F].$$

Note that the own-price elasticity of the optimal stocking density is

$$(8) \quad \eta^b \equiv \frac{\partial \ln b^*}{\partial \ln w} = \frac{1}{\varphi\eta_H + (1 - \varphi)\eta_F} \leq 0 \text{ by the SOC.}$$

Substituting the expression for η^b into (7) results in

$$(9) \quad d \ln b^* = \eta^b d \ln w - \varphi \eta^b d \ln P_H - (1 - \varphi) \eta^b d \ln P_F.$$

From (9) one can see that the comparative static effects of P_H and P_F on b^* are of the same signs as φ and $(1 - \varphi)$. Both φ and $(1 - \varphi)$ are positive if, at the optimum, the marginal products of bees in fruit and honey are positive. If such is the case, then bee stocking density increases from increases in either output price.¹⁴

Equilibrium in the Market for Pollination Services

Equilibrium is characterized by an aggregate demand, which is the sum of the optimal stocking density function (b^*) across A (assumed identical) acres on which bees are employed as described above, and an aggregate supply of bee services for pollination.

Supply depends upon the bee wage (w), various factors that affect the costs of beekeeping (k), and the price of honey (P_H). The aggregate equilibrium appears as:

$$(10) \quad A^* \cdot b^*(w, P_F, P_H) = Q_S(w, P_H, k),$$

where A^* is the aggregate equilibrium number of acres pollinated. While we analyze the

¹⁴ Note that one of φ and $(1 - \varphi)$ (but not both) can be negative at the optimum, implying that the marginal product of bees in, say, honey could be negative. Expression (9) then implies that an increase in the price of honey would increase the opportunity cost of a negative marginal product of bees in honey, and result in a decrease in stocking density (and an increase in the marginal product of bees in honey).

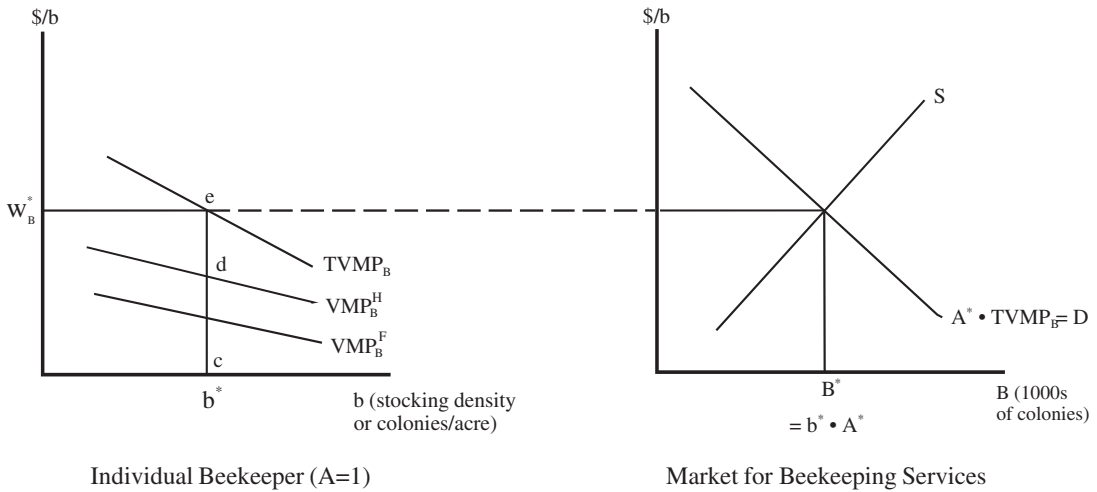


Figure 1. The optimal bee stocking rate

effects of changes in A^* , we take those changes to be exogenous with respect to changes in market prices in the length of run considered, which is most reasonable for long-lived perennials such as almonds and tree fruit. On the right-hand side of (10), $Q_S(\cdot)$ represents the aggregate pollination supply function, which is assumed to be increasing in w and decreasing in k . The equilibrium in equation (10) is depicted in the right-hand panel of figure 1.

Log differentiate (10) to determine the equilibrium response of w to exogenous changes in A , P_F , P_H , and k :

$$(11) \quad d \ln A + d \ln b^* = \varepsilon d \ln w + \beta d \ln P_H + \gamma d \ln k,$$

where $\varepsilon \equiv \frac{\partial \ln Q_S}{\partial \ln w} > 0$, $\beta \equiv \frac{\partial \ln Q_S}{\partial \ln P_H} < 0$ and $\gamma \equiv \frac{\partial \ln Q_S}{\partial \ln k} < 0$.

Substitute into (11) from (9) and collect terms to obtain

$$(12) \quad d \ln w = \frac{1}{\varepsilon - \eta^b} d \ln A - \frac{\varphi \eta^b + \beta}{\varepsilon - \eta^b} d \ln P_H - \frac{(1 - \varphi) \eta^b}{\varepsilon - \eta^b} d \ln P_F - \frac{\gamma}{\varepsilon - \eta^b} d \ln k.$$

Equation (12) gives the equilibrium response in the bee wage to exogenous changes in A , P_H , P_F , and k . Substitute from (12) back into (9) to derive the equilibrium change in b^* induced directly by exogenous changes in P_H and P_F , and indirectly by induced changes in equilibrium w :

$$(13) \quad d \ln b^* = \frac{\eta^b}{\varepsilon - \eta^b} d \ln A - \frac{\eta^b(\varphi \varepsilon + \beta)}{\varepsilon - \eta^b} d \ln P_H - \frac{\eta^b(1 - \varphi)\varepsilon}{\varepsilon - \eta^b} d \ln P_F - \frac{\eta^b \gamma}{\varepsilon - \eta^b} d \ln k.$$

Equations (12) and (13) comprise a reduced form for equilibrium changes in w and b^* that result from exogenous changes in A , P_H , P_F , and k . The coefficients on $d \ln A$, $d \ln P_H$, $d \ln P_F$, and $d \ln k$ in (12) and (13) are the comparative static effects of changes in those variables on the (unobservable) bee wage (equation 12) and stocking density (equation 13). Their signs can be summarized as follows.

Each of the terms in (13) involves a multiplicative coefficient of η^b , the field-level own-price elasticity of bee stocking density. By the second-order condition $\eta^b \leq 0$. If $\eta^b < 0$, we can say the following. First, referring to figure 1, an increase in A shifts aggregate demand for bee services to the right, increasing w , and inducing an upward movement along the $TVMP_B$ curve,

which decreases b^* . Second, an increase in P_F shifts to the right the $TVMP_B$ curve, inducing an increase in equilibrium b^* , a rightward shift in the aggregate demand for bee services, and an increase in w assuming that $(1 - \varphi) > 0$. This latter condition is equivalent to the VMP of bees in fruit production being positive at the equilibrium b^* . We consider $1 - \varphi > 0$ to be the normal case: at the margin, higher stocking densities of bees produce more fruit, but may result in less honey due to bees' own consumption and competition among bees for nectar.

Third, an increase in P_H shifts the $TVMP_B$ curve to the right, thereby shifting the aggregate demand for bee services to the right. An increase in P_H also shifts the aggregate supply of bee services, either leftward or rightward depending on whether or not pollination and honey production are net substitute or complementary outputs. Fourth, an increase in k —the costs of beekeeping—shifts the supply curve of bee services upwards, resulting in an increase in the bee wage (w), and a decrease in the stocking density (b^*).

Comparative Statics of Pollination Fees

Now consider the real-world situation where farmers own or rent the orchards and rent the services of beekeepers. Beekeepers are paid partly in kind by the honey, which they keep, and partly by a pollination fee paid by farmers. Farmers retain their claim to the fruit produced by the joint efforts of bees and land.

The fact that the standard contractual agreement for pollination services assigns property rights to the beekeeper to all honey produced is a result of measurement and monitoring costs, and an optimal allocation of price and output risk. A contract in which the farmer was due the honey would be more difficult to monitor than one in which the farmer was due only the pollination services of a fixed number of easily observed bee colonies.¹⁵ Such a contract would require the extraction, or at least the accurate estimation, of honey reserves after each crop was pollinated. Given that

¹⁵ This is not to suggest that monitoring pollination services is without cost. The issue of hive quality is of great concern to farmers. The strength of hives is assessed partly by the inspection of hives by farmers, partly by third party inspectors and, in some cases, by the assurances of bee brokers who guarantee colony strength in rented colonies. Reputation effects provide an incentive for beekeepers to provide full strength hives, especially in instances where hives are placed with a particular farmer year after year (see Klein and Leffler 1981). Some almond growers specify a sliding pollination fee based on hive strength, which is assessed by third party inspectors.

extraction equipment is typically located at a beekeeper's home base, extraction after each pollination set would be costly, and it is difficult to imagine how a farmer might validate estimates of honey reserves accumulated while colonies were located on their land. Moreover, as argued by Barzel (1997, chapter 1), production and price risk will tend to be borne by the transacting party who has the most influence over those sources of income variability.

Thus, the allocation of honey price and yield risk to beekeepers, and fruit price and yield risk to orchard owners, is in accord with their relative abilities to maximize economic value in response to those sources of income variability. See Knoeber and Thurman (1994) regarding a similar contractual allocation of price and production risk to enhance value in contract broiler production.

The bee wage, w , is comprised (in different proportions across crops) of a per colony pollination fee (P_P) and an in-kind honey payment, or $w = P_P + g_H P_H / b$.¹⁶

Equivalently, the equilibrium pollination fee is

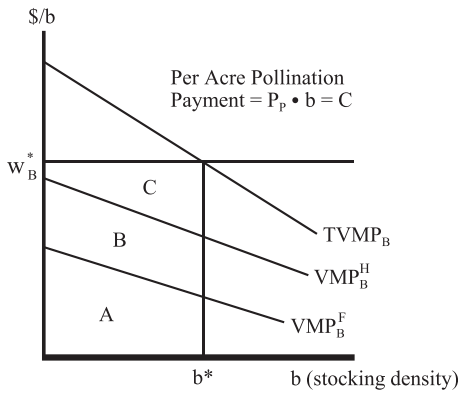
$$(14) \quad P_P = w - \frac{g_H \cdot P_H}{b}.$$

Log differentiate (14) to obtain

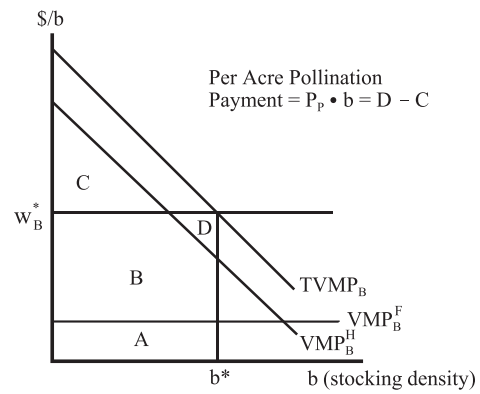
$$(15) \quad d \ln P_P = \frac{1}{1 - \alpha} d \ln w - \frac{\alpha}{1 - \alpha} [d \ln g_H + d \ln P_H - d \ln b],$$

where $\alpha = \frac{P_H \cdot g_H}{w \cdot b}$, the honey share of compensation. Denoting the elasticity of honey output with respect to b as $\eta_b^H = \frac{d \ln g_H(b)}{d \ln b}$, (15)

¹⁶ Figure 2 shows the equilibrium payment to beekeepers per acre of land, $P_P b$, in two situations. The first panel shows the situation where the per-acre pollination payment (which will equal the difference between the product of the bee wage and the number of colonies, and the total value of the honey produced at the optimal stocking density) is positive and equal to area C. The second panel shows the uncommon case in which the equilibrium payment is negative (and equal to area D-C), that is, beekeepers pay farmers for the privilege of placing their bees on the cultivated land. The possibility of zero or negative pollination fees can most easily be imagined for a crop that yields substantial marketable honey output, or little or no marginal fruit product at the equilibrium stocking rate, such as oranges in California and, in Oregon's Willamette Valley, crimson clover and hairy vetch (both of which are legumes grown for seed).



Positive Pollination Fees
(Individual Beekeeper, $A = 1$)



Negative Pollination Fees
(Individual Beekeeper, $A = 1$)

Figure 2. Pollination fees

reduces to

$$(16) \quad d \ln P_P = \frac{1}{1 - \alpha} d \ln w - \frac{\alpha}{1 - \alpha} [d \ln P_H + (\eta_b^H - 1) d \ln b].$$

To determine the effect on P_P from exogenous changes in A , P_H , P_F , and k , substitute for $d \ln w$ from (12), and for $d \ln b$ from (13), into (16). This results in

$$(17) \quad d \ln P_P = \frac{1}{(1 - \alpha)} \frac{[1 - \alpha \eta_b^b (\eta_b^H - 1)]}{(\varepsilon - \eta^b)} d \ln A - \frac{\gamma}{(1 - \alpha)} \frac{[1 - \alpha \eta_b^b (\eta_b^H - 1)]}{(\varepsilon - \eta^b)} d \ln k + \frac{(1 - \varphi) \eta^b [\alpha \varepsilon (\eta_b^H - 1) - 1]}{(1 - \alpha) (\varepsilon - \eta^b)} \times d \ln P_F + \frac{1}{(1 - \alpha)} \times \left\{ \frac{\eta^b \alpha (\eta_b^H - 1) (\varphi \varepsilon + \beta) - (\varphi \eta^b + \beta)}{(\varepsilon - \eta^b)} - \alpha \right\} \times d \ln P_H.$$

The comparative static effects from (17) cannot be signed in general. However, if stocking densities are constant with respect to changes

in w ($\eta^b = 0$) then all but one of the effects in (17) can be signed. In this important and—as argued below—empirically relevant case, we have the following:

$$(18) \quad \text{If } \eta^b = 0, \frac{\partial \ln P_P}{\partial \ln A} = \frac{\varepsilon}{(1 - \alpha)} > 0.$$

$$(19) \quad \text{If } \eta^b = 0, \frac{\partial \ln P_P}{\partial \ln k} = \frac{\gamma}{(1 - \alpha) \varepsilon} > 0.$$

$$(20) \quad \text{If } \eta^b = 0, \frac{\partial \ln P_P}{\partial \ln P_F} = 0.$$

The sign of the comparative static effect of a change in P_H remains ambiguous, but reduces to:

$$(21) \quad \text{If } \eta^b = 0, \frac{\partial \ln P_P}{\partial \ln P_H} = \frac{1}{(1 - \alpha)} \left(\frac{-\beta}{\varepsilon} - \alpha \right).$$

The effect of an increase in P_H can be seen to be positive if $-\beta > \alpha \varepsilon$: the substitution effect away from pollination supply due to a honey price increase must be larger than the share-weighted own-price elasticity of pollination services supply.

Testing the Model of Pollination Fees

In this section we test the implications of the economic model of equilibrium pollination fees developed above. We relate time series and cross-sectional variation in pollination fees to variations in the price of honey, the price of the pollinated crop, factors influencing the costs of beekeeping, and observable characteristics of the crop, such as its honey yield.

For data on pollination fees, we exploit a detailed annual survey of Oregon and Washington beekeepers that has been conducted annually by one of the authors over a 23-year period (see Burgett, various years, also Burgett, Rucker, and Thurman 2004.) The data set we have constructed includes information aggregated from the survey respondents on average annual pollination fees by crop from 1987–2009. We augment the survey data with annual data from other sources on Oregon crop and honey prices, and on factors that affect the costs of beekeeping.

Empirical Predictions

Equation (14) relates the equilibrium pollination fee to the unobserved equilibrium bee wage and the value of the in-kind payment of honey. The equation's most direct implication concerns variation in pollination fees across crops.

Prediction 1: Pollination fees will be lower for crops that yield more honey.

That this is true in theory can be seen from the fact that the bee wage, w (the sum of in-kind and pecuniary payments), is constant across crops. Therefore, from equation (14), an increase in the per colony honey yield, $g_H(b)/b$, reduces the pollination fee, P_P .

Our next three empirical predictions follow from the comparative static effects in (17) coupled with the auxiliary empirical assertion that stocking densities for a given crop are fixed as a matter of agronomic practice, and do not vary year-by-year with crop prices, beekeeper costs, or the price of honey. We support this empirical claim below.

Prediction 2: If stocking densities are fixed, pollination fees will vary directly over time with beekeeper costs. (Follows from equation 19.)

Prediction 3: If stocking densities are fixed, pollination fees will rise with increases in the acreage of pollinated crops. (Follows from equation 18.)

Prediction 4: If stocking densities are fixed, pollination fees will not change in response to crop price changes. (Follows from equation 20.)

Another potentially important determinant of pollination fees is the price of honey, the effect of which is theoretically ambiguous. Even if stocking densities are fixed, an increase in P_H will increase P_P if the elasticity of the

bee wage with respect to the price of honey exceeds the in-kind share of beekeeper compensation. This follows from equation 21. Intuitively, one reason why the effect of P_H on P_P might be large is that an increase in P_H could induce a large shift in bees away from pollinated crops and toward nectar-and-honey employments, such as uncultivated areas and the sunflower fields of North Dakota. This increase in the opportunity cost of placing bees on crops for pollination could raise w to such an extent that an increase in the price of honey results in an overall increase in pollination fees, despite the increased value to beekeepers of the in-kind payment.

The Importance of Almonds

Any analysis of contemporary U.S. pollination markets is incomplete without considering the role played by California almond pollination during February and March. Almonds as currently grown are highly dependent on honey bee pollination; figure 3 provides insights into how almond pollination has expanded over time. The two lines show almond pollination demand relative to the number of honey bee colonies available for pollination in (1) California, and (2) California plus the PNW (Oregon and Washington).

The quantity of almond pollination demanded in a given year is estimated as the number of bearing acres of almonds in California multiplied by the number of hives per acre used for pollinating almonds—for the purposes of figure 3, we use the average density of 2.1 hives per acre reported by PNW beekeepers.

The first series, titled “90% of California colonies,” provides an indication of when the quantity demanded for almond pollination services might have exceeded the quantity supplied by California beekeepers. If one estimates that 90% of the colonies in California are owned by beekeepers willing to provide commercial almond pollination services, then the approximate point at which out-of-state pollination services would have been imported was 1973.¹⁷ Two obvious sources of

¹⁷ Data from the 2002 Agricultural Census indicate that about 88% of the colonies in the United States are on commercial operations with 300 or more colonies, and another 10% are on semi-commercial operations with 25 to 299 colonies; see table 1 in Daberkow et al. (2009). Assuming that virtually all of the beekeepers with 300 or more colonies pollinate some crops and that a fraction of the smaller operations are also involved in pollination, our use of the 90% estimate in the text seems reasonable.

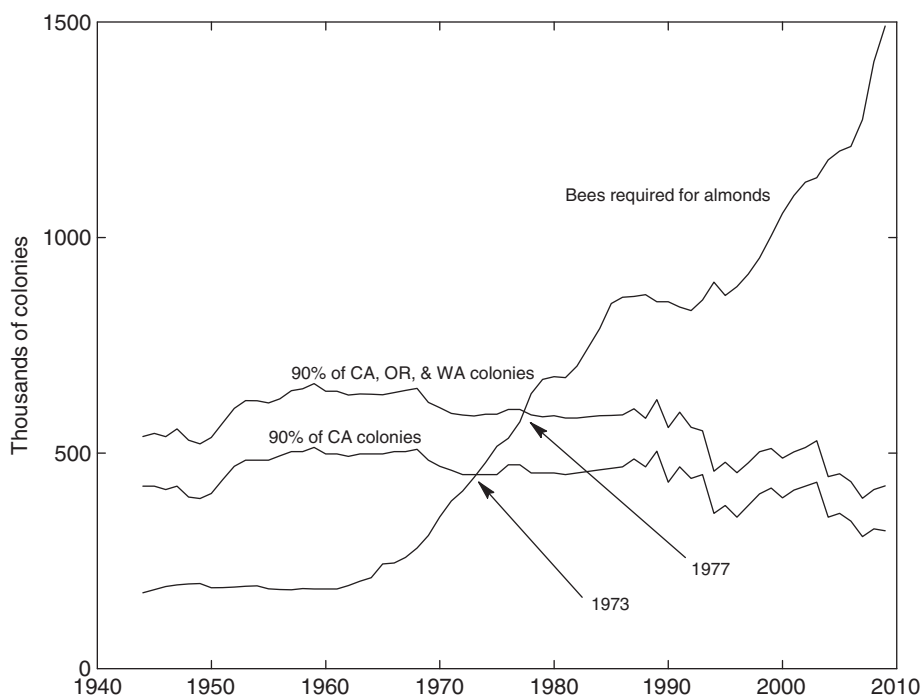


Figure 3. Almond bee requirements rise beyond regional colony numbers

outside pollination services are Washington and Oregon beekeepers. If one again assumes that about 90% of the colonies in California and the PNW are available for commercial pollination services, the second series in figure 3 suggests that the quantity demanded for almond pollination services exceeded the regional quantity supplied in the mid-to-late 1970s. Not shown in the figure is the substantial rise in the demand for almond pollination services relative to total U.S. honey bee colony numbers. Whereas almond producers employed less than 5% of U.S. colonies prior to the mid-1960s, they employed about 15% by the late 1970s, and currently employ 60%.

Today, many beekeepers are paid substantial premia to bring their colonies to California and place their bees in almond orchards during the bloom. In recent years, almond pollination fees reported by PNW beekeepers have increased dramatically—from an average of about \$66 per colony in 2004 to almost \$157 in 2006, in 2009 dollars.¹⁸

One response to increased almond pollination fees has been the attraction of beekeepers

from greater distances, some from as far away as the East Coast. The fee increases have been attributed to increases in almond acres and expectations of further future increases in almond acres. Some sources have suggested that the onset of Colony Collapse Disorder has resulted in increased pollination fees.¹⁹ In our empirical analysis, we examine the impact of these and other factors.

In light of the importance of almonds, it is useful to explicitly link our theoretical model with actual pollination markets. Three special cases in the model describe three distinct phases of the pollination calendar: almonds, post-almond pollination activity, and post-pollination honey production. While pollinating almonds, bee colonies run an energy deficit, and beekeepers typically feed their colonies supplemental calories—usually a sucrose solution. Bees produce no surplus honey while pollinating almonds. Further, honey from almond nectar has a bitter taste and so is undesirable if produced. In this situation, the theoretical model of the previous section applies, but the value, or effective price, of honey is zero. While

¹⁸ For California beekeepers, reported almond pollination fees increased from about \$73 in 2004 to \$166 in 2006. See Burgett et al. (2010), tables 3 and 4.

¹⁹ See Sumner and Borriess (2006), who cite almond acres as important drivers. Ward et al. (2010) and Carman (2011) add CCD to the list of factors they believe to have increased almond fees.

Table 1. Bee Stocking Density Summary Statistics by Crop

(1) Crop	(2) Years of Density Data	(3) Average Observations per Year	(4) Mean Annual Average Density	(5) Minimum Annual Average Density	(6) Maximum Annual Average Density
Almonds	15	8.53	2.08	1.51	2.61
Apples	17	8.94	1.34	0.97	1.87
Blueberries	17	6.82	2.07	1.16	3.00
Cherries	17	12.12	1.54	0.89	2.31
Red and White Clover Seed	17	4.76	1.30	0.90	2.31
Cranberries	7	1.57	1.59	1.24	2.20
Crimson Clover Seed	16	3.81	1.07	0.74	1.87
Cucumbers	16	2.25	0.98	0.20	1.60
Pears	17	8.76	1.40	0.89	2.29
Radish Seed	17	3.65	1.60	1.00	2.88
Squash and Pumpkins	17	5.23	0.86	0.49	1.33
Vetch Seed	7	2.29	0.97	0.60	1.30

pollinating almonds, beekeepers are paid by fee the value of their marginal product in producing almonds, which is unadjusted for honey value.

After the almonds bloom, beekeepers move their colonies to a variety of locations and crops. During this post-almond spring period, the full model is descriptive, with pollination fees taking into account both pollination value and the value of any honey produced. Finally, in late spring, commercial crops are through blooming and the value of bees' marginal product in the production of crops is zero; all commercial bee activity is directed toward honey production (and the buildup and maintenance of colony health).

Our survey data on pollination fees refer to transactions during the first two phases of the seasonal cycle: almonds and post-almond crops. During the third phase, pollination fees are zero or negative—they are considered as costs by beekeepers, not as sources of revenue. The PNW surveys include no observations from this period. In terms of our model, this portion of the beekeeping season corresponds to the situation where the value of the marginal product of bees in the production of fruit is zero (imagine any of the graphs in figures 1, 2, or 4 with the entire VMP of bees coming from the production of honey). While the bee wage in our model is constant across crops within any of the three sub-seasons, it may differ across the sub-seasons.

The Relative Constancy of Bee Stocking Densities

One potential influence in the theoretical model developed above is the responsiveness of stocking density (*b*) to changes in exogenous factors. Here we examine the issue empirically.

Beekeeper respondents to the annual PNW surveys were asked to report, for each crop, the number of colonies rented and the number of acres pollinated. Although responses to these questions are missing on many surveys, we have sufficient colony density data to estimate an empirical model that corresponds to equation (13): the comparative static result for how stocking density responds to changes in crop acreage, the (expected) prices of honey and crops, and economically significant cost factors—including the appearance of the *Varroa* mite in the PNW and the onset of Colony Collapse Disorder.

To empirically estimate (13) we constructed a data set of annual average stocking densities by crop for each year over 1989–2009. Table 1 presents summary information. For ten of the twelve crops, we have 15 to 17 observations. For cranberries and vetch seed, we are only able to determine average densities for seven years. With regard to the number of useable questionnaire responses per year, almonds, apples, cherries and pears all have averages of more than eight annual observations. Five of the other crops have averages of at least 3.5. Densities for cranberries, cucumbers, and vetch seed

are the least frequently reported, with the average number of responses for all three of these being less than 2.5.

Column (4) of table 1 shows notable variability in these densities across crops, with the means for almonds and blueberries being greater than two colonies per acre and the mean densities for vetch, cucumbers, and squash and pumpkins being less than one.

Further, columns (5) and (6) imply year-to-year variation in stocking densities for each of the crops.

The data summarized in table 1 comprise an unbalanced panel of stocking densities by crop (180 observations in total), which we use to estimate the following model:

$$(22) \quad \text{Density}_{it} = b_{0i} + b_1 \text{Crop Price}_{it} \\ + b_2 \text{Honey Price}_t \\ + b_3 \text{Almond Acres}_t \\ + b_4 \text{Varroa}_t + b_5 \text{CCD}_t \\ + e_{it},$$

where for crop i in year t , Density_{it} is the average annual hive stocking density; Crop Price_{it} and Honey Price_t are measures of expected crop and honey prices constructed from AR(2) time series models; Almond Acres_t measures bearing almond acres in California;²⁰ Varroa_t is a dichotomous variable equal to one for observations after 1990 (when *Varroa* first appeared in the PNW), and zero otherwise; and CCD_t is a dichotomous variable equal to one for observations after 2006 (when CCD first appeared), and zero otherwise. In addition to the linear specification shown, we also examine log-log, semi-log, and inverse semi-log versions of (21). All specifications include crop fixed effects, denoted as b_{0i} .

Ordinary least squares estimates of (22) are reported as specification (1) in table 2. The only statistically significant coefficients are the crop fixed effects, which are highly significant. We conclude that crops vary significantly in their typical stocking densities. But despite the evident variation over time seen in table 1, the variation is not explained by time series variation in almond acres, crop price, honey price, and cost-of-beekeeping factors. This conclusion is not affected by including a linear time trend (results not shown here).

A natural interpretation of this non-significance is that η^b —the factor common to all the comparative static effects—is zero. Unfortunately, the parameter η^b is not identified in the specification of equation (22); but one can come close. The ratio η^b/ε is identified from the elasticity of stocking density with respect to acres—see equation (13)—using variation in almond acres as the empirically important variation in acres. The parameter ε is the elasticity of the pollination services supply curve. Using equation (13), and the estimate of the elasticity of stocking density with respect to acres from specification (2), one can use the delta method to construct the following 99% confidence interval for η^b/ε : $(-0.079, 0.535)$. If η^b is non-zero, theory tells us it is negative. Further, the most negative value for η^b/ε supported by the data is -0.079 . Thus, if η^b is negative, the confidence interval tells us that it is smaller in magnitude than one-tenth the supply elasticity of bee services. By this comparison, η^b is economically insignificant.

To further examine the determinants of hive density, we supplement the regressions in table 2 with separate OLS time series regressions on each of the twelve crops in our data set. We estimate these regressions for each of the four specifications reported in table 2, and the results of these by-crop regressions are consistent with those for the full stocking data set. For each of the specifications, estimation of the twelve by-crop regressions yields 58 estimated coefficients.²¹ In none of the four specifications are more than four of the 58 (6.9%) estimated coefficients statistically significant at the 5% level. Moreover, for the four specifications in table 2, the estimated coefficients are jointly significant in, at most, two of the twelve by-crop regressions.²²

The results of this empirical exercise are easy to summarize by making two points. First, the analysis of the full data set indicates that there are significant differences in stocking densities

²⁰ We include almond acres as an explanatory variable for stocking densities for all crops due to the aforementioned importance of almonds in pollination markets.

²¹ This number excludes the estimated intercepts, which are not of interest. Ten of the twelve regressions include five explanatory variables. The almond regression excludes the *Varroa* variable because our almond data start in 1991, so all values of this variable are one for that crop. The vetch data set ends before CCD appeared, so that regression excludes the CCD variable.

²² A more detailed presentation of the by-crop regression results is available upon request. A number of other specifications were also estimated. In all cases, the number of significant coefficients is small, and the estimated coefficients are not jointly significant in the vast majority of the individual by-crop regressions.

Table 2. Determinants of Bee Stocking Densities

Dependent Variable	(1) Linear Density	(2) Log-linear ^a ln(Density)	(3) Semi-log ln(Density)	(4) Inverse Semi-log ^a Density
Independent Variable				
Crop Price	0.024 (0.203)	0.142 (0.118)	0.051 (0.155)	0.07 (0.155)
Honey Price	-0.002 (0.151)	-0.267 (0.144)	0.012 (0.116)	-0.037 (0.189)
Almond Acres	1.14 (0.515)	0.295 (0.200)	0.562 (0.393)	0.596 (0.262)
Varroa	-0.019 (0.121)	-0.011 (0.095)	-0.026 (0.092)	-0.013 (0.124)
CCD	-0.091 (0.112)	-0.054 (0.079)	-0.058 (0.086)	-0.074 (0.104)
Crop Fixed Effects Included	Yes***	Yes***	Yes***	Yes***
Adjusted R ²	0.548	0.522	0.519	0.549

Number of observations = 180. Standard errors appear in parentheses. Asterisks *, **, and *** indicate one-tailed significance at the 0.10, 0.05, and 0.01 levels, respectively.

^aDenotes that the natural logarithms of Crop Price, Honey Price, and Almond Acres (i.e., all non-binary variables) are used as regressors.

across crops. Second, there is virtually no evidence that colony density is related to annual changes in crop or honey prices, almond acres, the advent of *Varroa*, or the onset of CCD. We attribute this lack of relationship to two factors.

The first is that the cost share of pollination is small in the production of most crops. For example, apple yields in recent years have been roughly 10 tons per acre and prices have been roughly 17 cents/lb, for per acre revenues of about \$3,600. Recent (nominal) apple pollination fees are roughly \$45 per hive and the surveys suggest that 1.34 hives per acre is typical. The fraction of total revenue accounted for by pollination fees for apples is, then, $\$60.30/\$3,600 = .0168$, or 1.7 percent. One of Marshall's laws posits that when the cost share of an input is small, the derived demand elasticity is small as well. (See Marshall 1920, and Muth 1964.) While there may be non-zero effects of temporal variation in crop prices, almond acres, honey prices, and cost factors on hive density, they are small enough to not be identifiable empirically.

The second reason that the derived demand for pollination services is likely to be inelastic is due to the state of knowledge regarding the benefits of bee pollination to crops. Although crop science advisors make recommendations to farmers regarding the proper number of colonies to put on an acre of, say, almonds, we have never seen such advice conditioned on economic factors. This observation, combined with our estimation results discussed

above, suggests that advisors and farmers act as if they perceive their production processes to be fixed regarding proportions of land and bees.

Figure 4 shows the situation described above in which the value of marginal product of bees in fruit production has a vertical section, as it does for a fixed-proportion production function. This figure is heuristically useful for understanding the predictions of our model, given our empirical finding that hive stocking density is generally insensitive to the factors in our empirical analysis of the determinants of pollination fees.

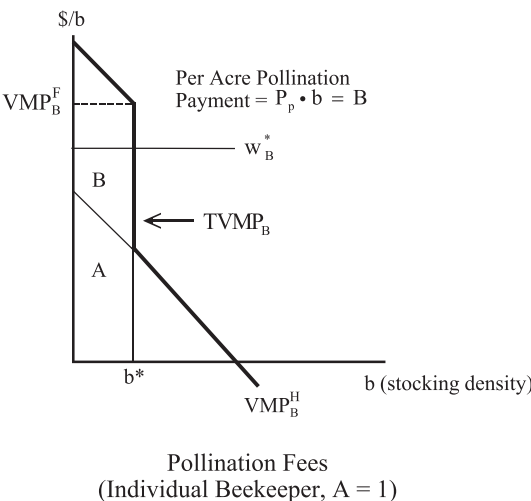


Figure 4. Pollination fees with fixed stocking density

Table 3. Pacific Northwest Pollination Fees by Crop, 1987–2009
(2009 dollars per colony rental)

	N	Mean	Min	Max
Honey Crops				
Blueberries	23	33.18	21.34	43.44
Crimson Clover	21	8.95	0.00	36.84
Radishes	23	31.42	15.92	49.23
Red Clover	22	27.07	9.93	46.47
Vetch	15	3.11	0.00	11.86
Group statistics	104	22.27	0.00	49.23
Non-honey crops				
Apples	23	38.80	22.67	49.68
Cherries	23	38.70	27.08	53.71
Cranberries	20	45.48	29.05	60.00
Cucumbers	21	39.46	23.47	71.04
Pears	23	38.23	24.01	51.41
Squash	21	40.64	26.20	60.78
Group statistics	131	40.10	22.67	71.04
Almonds	17	75.61	46.94	150.27
All crops	252	35.14	0.00	150.27

An Econometric Model of Pollination Fees

We now turn to panel regression analysis of 252 observations on crop-average per-colony pollination fees from the PNW beekeeper surveys. The data span the years 1987–2009, and include information on 12 crops. Table 3 displays sample-period averages of fees, divided into three categories: almonds, non-almond crops from which bee pollination produces no marketable honey (non-honey crops), and non-almond crops from which bee pollination produces marketable honey (honey crops).

Standard economic theory suggests that both cost and demand factors explain pollination fees. The theory developed in the previous section also suggests that the value of the in-kind payment of honey to beekeepers influences the equilibrium monetary payment, which in turn implies the importance of the honey output of the pollinated crop and the price of honey.

Strong evidence for the importance of the honey output of the pollinated crop is found in figure 5, which shows the annual real (2009 dollar) averages of pollination fees per colony for almonds, non-honey crops other than almonds, and honey crops. Almonds could be included in the non-honey crop

category, but due to the previously discussed importance of almonds and the fact that almond fee behavior departed from previous norms after 2004, we consider it separately.

The first thing to note from figure 5 is that the pollination fees for non-honey crops are consistently higher than those for honey crops. The difference between the sample average of honey-crop fees and non-honey-crop fees is \$17.84 in 2009 dollars (we consider a more formal test of this difference in the regressions to come). If almonds were included in the non-honey crop group, the difference between honey and non-honey crop fees would be larger. This corroborates the prediction that the higher the value of the honey payment to beekeepers, the lower is the monetary payment.

The second issue to note from figure 5 is the unprecedented increase in almond fees that occurred after 2004—behavior not seen for other surveyed crops. Almond pollination fees rose from \$59 to \$89 between 2004 and 2005, and increased again to close to \$140 in inflation-adjusted terms from 2006–2009. It is tempting to attribute these fees to Colony Collapse Disorder, and CCD may be partly to blame, but the timing is not right. The first reported instance of CCD was during the fall of 2006, which could only have affected fees beginning in spring 2007. But as figure 5 shows, almond fees rose earlier, in 2005 and 2006.²³

Because recent changes in almond fees are a prominent part of the data we analyze, we consider the time patterns of other possible explanations of recent high almond fees. Figure 6 displays two of them: the real price of diesel fuel (an important input into migratory beekeeping) and the numbers of nut-bearing almond acres. It is clear from figure 6 that there is a high degree of collinearity between these two series (the correlation coefficient between the two is 0.86). Coupling that fact with the limited duration of the recent period of high almond fees should cause one from the outset to not be optimistic about the ability of a few annual observations to definitively disentangle these effects.

Our empirical analysis is based on the following crop-wise heteroskedastic linear

²³ A comprehensive study of the economic consequences of CCD can be found in Rucker, Thurman, and Burgett (2012).

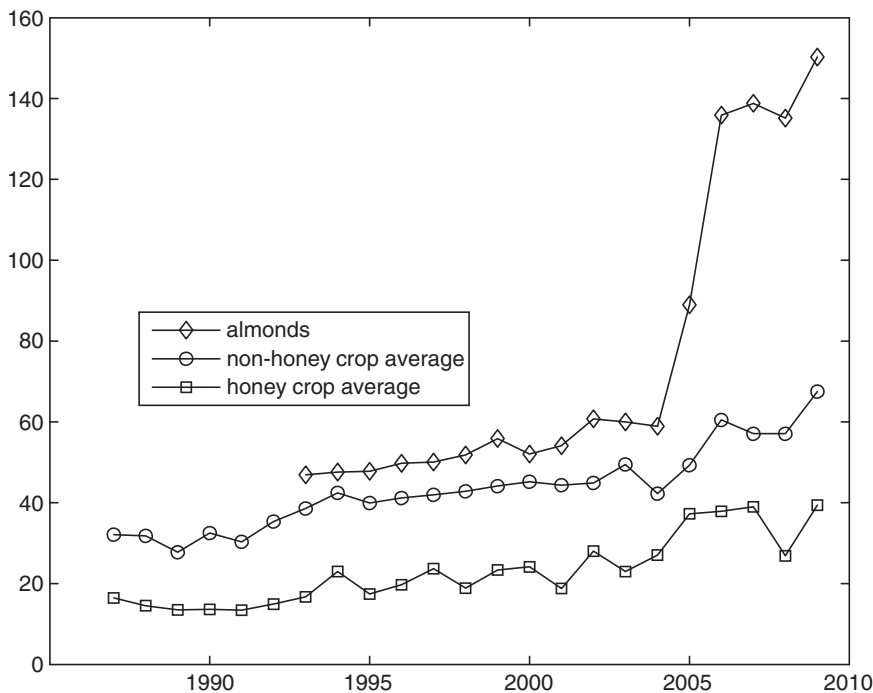


Figure 5. Real pollination fees per colony (2009 dollars)

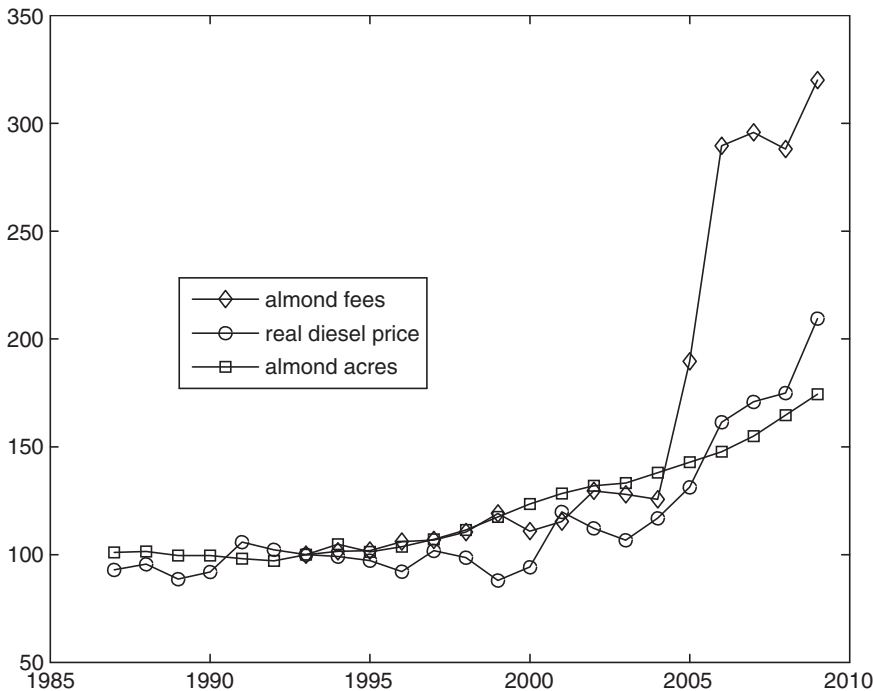


Figure 6. Index numbers (1993 = 100)

panel model:

$$(23) \quad y_{it} = \sum_{j=1}^{12} \mu_j d_{it}^j + \varphi V_{it} + x'_{it} d_{it}^A \beta_A \\ + x'_{it} (1 - d_{it}^A) \beta_N + \varepsilon_{it}, \\ \text{for } i = 1, \dots, 12 \\ \text{and } t = 1987, \dots, 2009$$

The variables are defined as follows:

y_{it} = real pollination fee for crop i in year t , measured by the average of responses across beekeepers,

d_{it}^j = crop dummy variables equaling 1 when $i = j$,

V_{it} = a dummy variable equaling 1 when $t \geq 1991$, the year in which *Varroa* began to cause large-scale losses in the Pacific Northwest,

x_{it} = a vector of explanatory variables, including subsets of the following: the log of one-step-ahead forecast honey price, the log of one-step-ahead forecast crop price, the log of diesel fuel price, the log of almond-bearing acres, a post-2004 dummy variable, and a post-2006 dummy variable,

d_{it}^A = a dummy variable equaling 1 for observations on almond fees.

The disturbance terms are assumed to be heteroskedastic but uncorrelated across crops and over time:

$$\text{Var}(\varepsilon_{it}) = \sigma_i^2, \text{Cov}(\varepsilon_{it}, \varepsilon_{is}) = 0 \text{ for } t \neq s, \\ \text{and } \text{Cov}(\varepsilon_{it}, \varepsilon_{jt}) = 0 \text{ for } i \neq j.$$

The semi-log specification in (22) allows for sensible aggregation across crops. For all crops, the left-hand side variable is measured in real dollars per colony of bees. On the right-hand side, prices of crops refer to different commodities and taking logarithms converts their changes into comparable percentage change magnitudes. Notice that in (22), crops are distinguished from one another by crop-specific intercepts and crop-specific variances. Almonds are further distinguished from non-almond crops by the almond dummy interaction terms.

The panel is nearly complete but contains holes due to survey non-response. Compared to a total potential number of observations of

12 crops \times 23 years = 276, our data set comprises 252 usable observations. We have no reason to suspect that the pattern of non-response is correlated with any of the covariates in our model. In table 4 we report Weighted Least Squares (WLS) estimates of equation 22, where first-stage Ordinary Least Squares residuals are used to estimate the crop-specific variances used in the second stage.

A summary of the expected effects in equation (22) is as follows: (1) We predict that growers of crops that provide valuable nectar to the bees (honey crops) will pay less in pollination fees than do growers of non-honey crops. (2) We predict that cost factors influence pollination fees. Specifically, we predict that the arrival of *Varroa* shifted upward the supply of pollination and, hence, increased pollination fees. Similarly, the price of diesel fuel represents a more continuously-varying cost factor, which we predict has a positive influence on prices. (3) We predict that to the extent that the supply of pollination services is upward sloping, almond pollination fees will vary directly with almond acres (although possibly only for almond pollination fees and not for later-pollinated crops). (4) We predict that higher expected prices of crops will have no effect on pollination fees to the extent that bee stocking rates are unaffected by crop prices (which we argued in the previous section to be the case). (5) A change in the honey price has a theoretically ambiguous effect and is to be determined empirically.

Empirical results are reported in table 4. The six specifications in table 4 all include effects for *Varroa*, honey price, and crop price. The specifications differ in their inclusion of effects for diesel fuel price, almond acreage, and CCD. Further, all regressions in table 4 include a post-2004 dummy variable, motivated by the substantial increase in almond fees after 2004, displayed in figure 5. While not so visually obvious, the post-2004 dummy variable is allowed to have an effect on non-almond fees as well. The other recent time effect considered in half of the specifications is a post-2006 dummy variable that we interpret as a CCD indicator; CCD was first widely reported after the 2006 pollinating season, but prior to the 2007 pollinating season. The first three specifications in table 4 do not include a CCD effect; the last three do.

All specifications in table 4 include crop-specific intercepts, and tests of the equality of the intercepts (not shown) are strongly

Table 4. Pollination Fee Panel Regressions - Cropwise Heteroskedastic GLS**Dependent variable = Real (2009 dollars) pollination fee**

Panel of 12 crops over 23 years: 1987–2009, n = 252

Crop-specific intercepts fit in all specifications:

almonds, pears, cherries, apples, red clover, crimson clover, vetch, cucumbers, blueberries, cranberries, radishes, squash

Variable		Specifications with no CCD effect						Specifications with CCD effect					
		(1)		(2)		(3)		(4)		(5)		(6)	
		coefficient	t-stat	coefficient	t-stat	coefficient	t-stat	coefficient	t-stat	coefficient	t-stat	coefficient	t-stat
Honey crop effect: difference between average non-honey crop intercept (excluding almonds) and average honey-crop intercept		16.74	5.83***	17.07	5.86***	17.10	5.87***	16.54	5.65***	17.12	5.76***	16.90	5.69***
Varroa		6.13	5.25***	6.31	5.69***	7.03	5.87***	6.17	5.12***	6.28	5.58***	7.07	5.73***
Log honey price	almonds	6.09	0.52	−21.44	−1.05	7.40	0.38	7.00	0.65	−18.94	−1.15	−1.24	−0.07
	others	8.43	3.74***	5.02	1.76*	2.30	0.69	8.53	3.73***	4.85	1.61	2.43	0.72
Log crop price	almonds	−5.54	−0.35	3.74	0.15	−6.73	−0.32	2.44	0.16	24.64	1.13	10.97	0.51
	others	−1.62	−0.78	−1.35	−0.64	−1.32	−0.62	−1.77	−0.83	−1.30	−0.60	−1.47	−0.68
Log diesel price	almonds	77.90	3.81***			79.51	2.85***	63.10	3.05***			51.10	1.71*
	others	1.17	0.31			−7.74	−1.51	0.15	0.03			−8.82	−1.53
Log almond acres	almonds			88.04	2.05**	−4.05	−0.08			83.32	2.40**	25.70	0.55
	others			8.78	1.92*	15.66	2.45**			9.30	1.86*	15.61	2.41**
Post 2004 = 1	almonds	37.56	3.32***	52.26	3.93***	37.89	3.17***	35.74	3.42***	37.93	3.21***	33.45	3.00***
	others	4.71	2.24**	2.82	1.77**	4.79	2.31**	4.82	2.26**	3.00	1.77*	4.90	2.33**
CCD (post 2006 = 1)	almonds							14.89	1.71*	25.00	2.93***	16.70	1.81*
	others							0.83	0.42	−0.38	−0.22	0.89	0.46
R²		0.889		0.886		0.891		0.890		0.891		0.892	

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively, with two-sided tests.

rejected.²⁴ The first row of table 4 reports a honey crop effect, constructed as the difference between the average intercept for non-honey crops (apples, cherries, cranberries, cucumbers, pears, and squash, excluding almonds) and the average intercept for honey crops (blueberries, crimson clover, radishes, red clover, and vetch). The standard error for the difference in averages is calculated using the variances and covariances of the estimated intercepts. The estimated honey-crop effect is roughly \$17 in all specifications (average non-honey crop fee higher than average honey-crop fee), which is quite close to the difference between the unconditional averages of the honey and non-honey crop fees displayed in figure 5 (\$17.84). The estimate is highly significant statistically, with a 95% confidence interval of the column (1) estimate spanning the interval (\$11.08, \$22.40).

The second row of table 4 reports estimates of a *Varroa* effect, the coefficient on a dummy variable equal to one in 1991 and beyond. The point estimates are similar and strongly significant in all specifications. In column 1, the point estimate of \$6.13 is significant at the 1% level, and centers a 95% confidence interval of between \$3.83 and \$8.44. Industry observers noted after the 1990 pollination season that the long-awaited *Varroa* infestation had arrived in the PNW, causing beekeeper costs to rise. The same observers noted that it was the good fortune of beekeepers that pollination fees rose by just about the right amount to offset the *Varroa*-induced increase in costs.²⁵ We attribute this coincidence not to the good fortune of the industry but rather to the forces of competitive equilibrium.

Beekeepers and farmers agree on pollination fees at the time that colonies are placed in orchards and fields, typically in the spring or early summer months. Fees, then, are determined prior to the time that actual crop prices for the year are known. We model the expectation for crop prices as one-step-ahead forecasts from second-order autoregressive models

in real prices. The parameters are estimated from 1976–2009. The same issues arise for Oregon honey prices, which are determined after pollination fees are agreed upon. In the presence of the honey price support program, however, each year's honey price support level was known at the time that pollination fees were specified. (See Muth et al. 2003) Accordingly, to account for the presence of the honey program during a portion of our sample period, we use the honey price for year *t* when the program was in effect (until 1993), and thereafter use a one-step-ahead forecast from a second-order autoregressive model for the price of honey expected at the time that pollination fees are set (estimated using data during the period that the honey price support was not effective).²⁶

The effect of honey price on pollination fees is theoretically ambiguous. As per our theory, there are two channels of influence from honey price to pollination fees. One is that an increase in honey price makes more valuable the in-kind payment to beekeepers and therefore reduces the required pollination fee. The second is that an increase in expected honey price can decrease the aggregate level of crop pollination activity, which can thereby increase fees. Which of these effects dominates is an empirical question addressed in the table 4 specifications. In the first column of table 4, the estimated log honey price coefficient is reported as 8.43 for non-almond crops and 6.09 for almonds. The non-almond honey coefficient is significant at the 1% level, while the almond honey coefficient is insignificant. This pattern is repeated in specifications (2) and (4).

In the semi-log specification, the non-almond coefficient of 8.43 implies that a 10% increase in the price of honey induces an \$0.843 increase in pollination fee per crop. The average annual absolute percentage change in honey prices between 2000 and 2009 is 15.3%, which according to the table 4, column (1) estimate would induce a \$1.29 change in the typical non-almond pollination fee. Notice that the almond honey price effect is statistically insignificant, but similar in size to the non-almond honey coefficient.

²⁴ Champetier, Sumner, and Wilen (2012) argue that biodynamic factors over the pollinating season should induce seasonality in pollination fees, which would be reflected in the values of the crop-specific intercepts.

²⁵ The following calculation justifies this statement. Annual costs of *Varroa* control (miticide and application costs) are approximately \$18 per colony (Barnett 2002.) A typical colony in our sample was rented out 2.5 times in a year, yielding a per-pollination-placement treatment cost of $\$18/2.5 = \7.20 , which is close to our point estimate of the *Varroa* effect and comfortably within its confidence interval.

²⁶ Note that we use the actual average honey price rather than the support price. Given that there were different support prices for different grades of honey, and given that support prices were binding during the period of our analysis, we assume that the observed average honey price was an appropriately weighted average of the various support prices.

A logical interpretation of the honey price results is as follows. Higher honey prices do not bid beekeepers away from almonds, because almonds bloom in late winter when other nectar sources are scarce; higher honey prices do trigger a substitute supply response away from non-almond crops, which bloom later in the season when honey production is a more viable alternative to pollination work. We also note that the insignificance of the almond coefficient is partly due to the fact that there are only 17 observations on almond fees in the panel and that modest sub-sample size is likely to reveal only a strong effect.

The fourth effect reported in table 4 is the crop price effect. Across all specifications it is robustly statistically insignificant. This supports the joint hypothesis of the equilibrium model of equation (17) and the constancy of stocking densities with respect to crop prices.

Next, turn to the effects of diesel price and almond acres on pollination fees. Due to the previously discussed collinearity between the two variables, we consider specifications with only diesel price (specification 1), only almond acres (specification 2), and both diesel price and almond acres (column 3). The same three models are repeated in specifications 4, 5, and 6, which also include a CCD dummy variable. As with honey and crop prices, the effects of almond acres are estimated separately for almonds and non-almond crops. The diesel fuel price variable is lagged one year to reflect the fact that pollination fees are received in the early part of the year, and the most relevant fuel price is likely to be that involved in trucking bees in preparation for the winter/spring pollination season.

In specification 1, the coefficient on diesel price is large and significant for almond fees. The estimated coefficient of 77.90 implies that a 10% increase in the price of diesel fuel will lead to a \$7.79 increase in almond fees. Interestingly, for non-almond fees the estimated effect of diesel fuel is much smaller and not statistically significant. The contrasting results can plausibly be attributed to the difference between the two types of crops in the importance of pollination transport costs. In recent years, bees have been trucked to the California almond orchards from as far away as North Carolina, and the PNW beekeepers in our data set truck their bees substantial distances south to the examined almond orchards. After pollinating almonds, the PNW beekeepers return their bees to their home bases and, from there,

proceed to pollinate the other 11 crops. Transport represents a lower cost share for the post-almond, home-based crops, which could explain why variations in diesel fuel price have smaller and statistically insignificant coefficients for those crops.

Specification 2 replaces diesel fuel prices with the collinear almond acres. The estimated effect on almond pollination fees from almond acreage is large and statistically significant. The semi-elasticity with respect to almond acres is similar in size to the semielasticity with respect to diesel price estimated in specification 1. Almond acres in specification 2 is also a statistically significant factor in explaining non-almond fees, but the almond acre effect on non-almond fees is much smaller than the almond acre effect on almond fees.²⁷

Specification (3) pits diesel fuel prices and almond acres against one another as possible explanations of pollination fees. In this specification, diesel price remains a statistically significant factor in the presence of almond acres, but the almond acre effect does not survive the inclusion of diesel prices. The opposite is true for non-almond fees: when both diesel prices and almond acres are allowed into the regression (specification 3), almond acres is the significant explanatory variable and diesel price is not.²⁸

Lastly, consider the significance and size of recent changes in pollination fees that are not explained by factors considered so far. All of the specifications in table 4 include post-2004 dummy variables, motivated by the notable recent increases in almond fees, which are visually apparent in figures 5 and 6. The post-2004 dummy variable is statistically significant for both almond and non-almond crops and quite robust across specifications. The post-2004 effect ranges between \$33 and \$52 across specifications for almond fees, and from \$3 to \$5 for non-almond fees. These are statistically significant effects that are puzzling when considered in connection with Colony Collapse Disorder, first reported in late 2006. There were, however, earlier indications of concerns

²⁷ After pollinating almonds, bees are in a more weakened state than they would be if they skipped almond pollination. This could be one reason that almond acres are found to have a positive effect on subsequent non-almond pollination fees.

²⁸ As the t-tests suggest, diesel prices and almond acres have jointly significant effects on almond pollination fees in column 3. A Wald test with two degrees of freedom has a p-value of 0.007. The p-value for the joint significance of the effect of diesel prices and almond acres on non-almond pollination fees is 0.047.

over honey bee health in the spring of 2005. See Mussen (2005) for a discussion of abnormally high overwinter bee mortality among California beekeepers in the winter of 2004/2005, which could imply a leftward shift in the supply of bees, and an increase in equilibrium fees for all crops.²⁹

To represent CCD itself, specifications 4–6 replicate specifications 1–3, but add a post-2006 dummy variable, again interacted with an almond indicator to allow different CCD responses in almond and non-almond fees. The indicator coefficient shows a statistically significant \$15–25 rise in almond pollination fees, depending on specification, beginning in 2007—in addition to the post-2004 effect. This could represent a CCD supply shift, but if so, why does it not also show up in non-almond fees? Non-almond fee increases in the post-CCD period are statistically insignificant in specifications 4–6 and their point estimates are small (less than \$1). One possible explanation is that if some beekeepers get hit particularly hard by CCD over the winter, then they will not be able to recover for almond pollination, and almond fees will increase. There is a lag between almonds and subsequent crops, allowing colonies to recover or new colonies to build, implying little or no impact on pollination fees for these other crops.

The main conclusions of the empirical analysis are as follows. The factors that we find to be significantly related to pollination fees are those that influence beekeeper costs and returns: honey yield, *Varroa* mites, the price of diesel fuel (for California almonds) and the price of honey. The factor that we find not to be significantly related to pollination fees—crop prices—is one that influences farmer costs and returns. This makes sense, as the cost shares of pollination fees are typically small to farmers, and we infer from our estimates that there is little or no year-to-year response to them by farmers, just as we find little or no response in stocking densities. On the other hand, honey price, the costs of *Varroa* control, and the value of honey obtained from pollinating different crops loom large in the beekeepers' balance sheets. As predicted by theory, we see evidence of substantial response to these influences. The

fact that farmers regularly employ bees to pollinate their crops demonstrates the existence of robust derived demands for pollination, but our results suggest the demands are relatively inelastic. At the same time, the supply-side influences from the costs of beekeeping and the value of in-kind returns to beekeepers are measurably important factors in determining pollination fees.

Beyond measuring and confirming effects that flow directly from the theoretical model, the results offer evidence on the effects of recent concerns over honey bee health. Significant and sizeable increases in almond pollination fees are seen to begin after 2004—and they appear not to be explained by the cost factors in our analysis, or by increases in almond acres. A portion of this increase (\$15–25) can plausibly be attributed to CCD. More modest increases are measured for non-almond crops, but they do not coincide with the arrival of CCD.

Summary and Conclusions

Despite the importance of honey bee pollination for many agricultural crops, there has been little economic analysis of pollination markets. In this paper, we develop a model to represent modern pollination markets and empirically test its predictions. Our empirical analysis, based on annual surveys of Oregon and Washington beekeepers, suggests that pollination markets respond to changes in economic factors that are predictable in light of the model.

Our results have important implications for the growing body of literature on the status of wild pollinators and the valuation of related ecosystem services—they suggest that, at least in the United States, there are relatively inexpensive substitutes for wild pollinators that are coordinated by market prices. Economically defensible estimates of the value of related ecosystem services should account for the availability and costs of such substitutes. Beyond the U.S. border lie related research questions—which we leave for future work—involving the evolution and current status of pollination markets elsewhere: where have such markets developed and why? What are the resulting implications for agricultural development, the organization of production in agriculture, and the ability of human-managed pollination to adapt to changing environmental and economic circumstances?

²⁹ Mussen suggested (p. 2) that the high overwinter mortality was “easiest to blame (on) *Varroa*,” but that some of the bee mortality may have been due to “lack of brood rearing during the extremely critical time from August through September, when the bees are rearing their ‘winter bees.’” Lack of brood results in “colony populations that just dwindle in numbers continually from October to death before March.”

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