The Roles of Risk and Honey Bee Colony Strength in Determining Almond Pollination Contract Provisions

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Abstract

Managed honey bee colonies provide pollination services, which are an essential input in production of many crops in the United States. Over the last decade, U.S. honey bee colony populations have become volatile as a result of many colony health inhibitors. This paper investigates the impact that colony supply uncertainty has on the California almond pollination market, the largest user of managed pollinators in the world. I develop a theoretical model and find that almond growers can reduce moral hazard in pollination agreements by paying beekeepers according to delivered colony strength. Additionally, I utilize two unique datasets to empirically explore determinants of almond pollination fees. Using the California State Beekeeper's Association pollination fee survey for years 2008-2015, I find that providing low strength colonies for almond pollination results in lower fees collected by the beekeeper. I pair the beekeeper-reported data analysis with an empirical study of an almond grower pollination contract survey that I conducted at the 2015 Almond Conference. The results of the almond grower data analysis suggest that growers whose almond pollination contracts specify minimum colony strength requirements pay higher pollination fees compared to those who have no colony strength requirements. The empirical results support the theoretical model finding that almond growers use colony strength requirements to elicit optimal beekeeper effort. Since almond pollination represents a fraction of beekeepers' yearly income, this paper highlights the need for additional research on the total economic impact of volatility of U.S. honey bee colony populations to effectively implement policies that promote managed pollinator health.

JEL Classifications: Q12, Q13, Q57

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1 Introduction

Managed honey bee colonies are an economically important component of United States (U.S.) agriculture. U.S. crops valued at over $18 billion dollars depend on managed honey bee colonies for pollination services and California almond production is the largest user of such pollination services. Many U.S. beekeepers now consider almond pollination their main source of income, and in turn, the U.S. almond industry is reliant on the U.S. beekeeping industry to meet almond pollination needs. In 2016, approximately 76% of U.S. honey-producing colonies were demanded for almond pollination.

In recent years, commercial beekeepers in the U.S. have experienced abnormally high winter mortality rates due to many colony health issues, e.g., Colony Collapse Disorder (CCD), varroa mites, and poor nutrition. These health issues have increased the volatility of honey bee colony populations during a given year. U.S. managed honey bee colony health issues, especially CCD, have received media attention, drawing concern from the general public and consequently policy makers. In 2015, the White House Pollinator Task Force released its *National Strategy to Promote the Health of Honey Bees and Other Pollinators* showing the commitment of the U.S. government to reducing the stresses to U.S. honey bee colonies.

The supply of honey bee colonies for almond pollination is extremely sensitive to volatility in the total number of honey bee colonies for two reasons: 1) the number of colonies it requires necessitates shipment from beekeepers across the U.S. and 2) almond bloom occurs in mid-February almost simultaneously with the discovery of overwinter colony mortality rates. Beekeepers expect that a percentage of colonies will perish during the winter months, however volatility in colony health has lead to unpredictable rates of loss.

The objective of this paper is to identify the ways in which the uncertain supply of colonies impacts almond growers and beekeepers and their almond pollination agreements. The primary focus is the influence of colony strength on almond pollination fees. Using a theoretical model and multiple econometric analyses, I find that more stringent colony strength requirements are associated with higher almond pollination fees paid to beekeepers and that high winter mortality rates significantly decrease almond pollination fees paid to beekeepers. Almond pollination fees paid to beekeepers also vary systematically with other pollination agreement components. These findings illustrate that almond growers and beekeepers are in fact influenced by increased colony supply uncertainty as almond growers are willing to pay a risk premium for a more secure pollinator supply.

The paper proceeds as follows: I begin in Section 2 by providing background information on honey bee colony strength and almond pollination agreements. I continue in Section 3 by introducing the past economic literature on pollination services markets and outlining where this paper fits into the existing literature. In Section 4, I develop a theoretical principal-agent model to describe almond pollination contract decisions between the almond grower (principal) and beekeeper (agent). Section 5 lays out two empirical analyses of almond pollination fees using survey data from beekeeper and almond grower perspectives. Finally, Section 6 concludes with a few closing comments.

2 Background

A honey bee hive is the physical container for a honey bee colony. It consists of a wooden box with frame inserts on which worker bees construct the comb that they use to store honey and developing bee brood. Industry members define colony strength by counting the number of standard frames in a hive that are at least 75% covered in bees and brood. This is referred to as an "active" frame. In pollination agreements, almond growers, beekeepers and almond pollination brokers refer to various colony strength requirements in terms of the number of active frames per hive.

Honey bee colonies exhibit increasing returns to scale in pollination; Sheesley et al. (1970) found that one 12-frame hive will pollinate significantly more than three 4-frame hives. This relationship between colony strength and pollination efficiency of a hive influences growers' pollination decisions.

Almond pollination agreements are typically settled months in advance of almond bloom. Thus, many almond growers make pollination decisions regarding the number of hives to stock per acre, colony strength requirements, and per-colony pollination fees prior to almond bloom. These decisions are made under uncertainty in multiple dimensions, since the weather at the time of almond bloom is unknown, in addition to the number and strength of available colonies. If weather during bloom is sub-optimal, a grower would prefer more bees per acre to ensure high yields. The grower can increase bees per acre by increasing either colony strength requirements and/or the number of hives per acre. In recent years, the supply of colonies has been equal to or less than the quantity desired during almond bloom, so growers typically have a difficult time finding additional colonies during almond bloom (Traynor (2016)).

Almond pollination agreements are also made prior to when beekeepers make important input decisions for almond pollination and observe resulting colony strength. In order to meet colony strength requirements for almond pollination, beekeepers must provide food supplements to colonies to jumpstart their transition from a natural dormant state. Even providing food supplements does not guarantee a strong colony because of the many colony health inhibitors that beekeepers face. Additionally, beekeepers make their pollination contract decisions before winter mortality rates are realized. Thus, there is uncertainty at the time of contracting for almond pollination in both the strength and number of colonies that beekeepers will be able to provide.

Honey bee colonies are a dynamic population, so health issues and input decisions during one time of the year can carry over into future time periods (Champetier et al. (2015)). The biggest influence on winter mortality rates are beekeeping decisions made in the fall in preparation for overwintering, e.g., honey extraction and varroa treatments, and these are often made prior to contracting for almond pollination. Many exogenous factors affect the outcomes of fall management decisions. For example, a varroa treatment could be made ineffective if nearby colonies are highly infested with varroa mites. Due to the dynamics of honey bee colonies, winter mortality rates and colony strength during almond pollination are highly correlated; in other words when winter mortality rates are high, average colony strength during almond pollination is low. This relationship is displayed in Figure 1. This complicates the uncertainty of the supply of bees for almond pollination, because when fewer colonies are available, the colonies that are available are likely of lower strength.

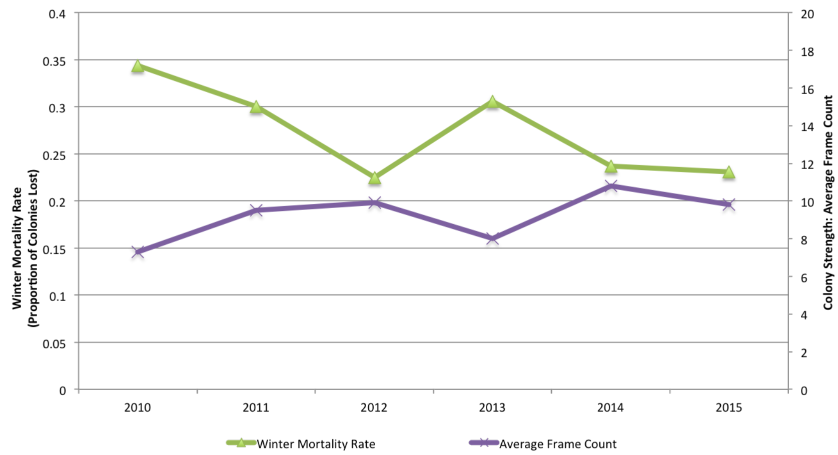
A healthier hive coming out of winter will be much less costly to expand for almond pollination, in terms of supplemental food and pest/disease treatment costs, than a less healthy hive. Thus, there are two components of a beekeeper's delivered colony strength for almond pollination: 1) Effort and inputs that are influenced by almond pollination fees and contract stipulations, and 2) Random error associated with exogenous variables that influenced overwinter mortality rates. So, while colony strength for almond pollination is likely dependent on the price and contract stipulations the beekeeper and grower agree to, it also is influenced by through exogenous colony health shocks taking place during the fall and winter months. The ability of a beekeeper to increase colony strength is correlated with winter mortality rates through these exogenous shocks. So contracting for a high colony strength prior to realization of winter mortality rates is risky for the beekeeper, given that it may end up being very costly for her to meet these colony strength stipulations.[1]

Forward contracting benefits both the beekeeper and almond grower by reducing the risk borne by each party. A grower can forward contract to ensure delivery of the specified number of colonies at the desired strength, while the beekeeper can lock in a price to guarantee coverage of her costs of transporting colonies for almond pollination.

Moral hazard arises in almond pollination agreements primarily because of the gap in time between almond pollination decision-making and the beginning of almond bloom. Almond growers are unable to observe the inputs and effort a beekeeper puts in to providing colonies for his pollination needs. A beekeeper could invest a substantial amount of time and money

[1]To reduce confusion, I use female pronouns to describe the beekeeper and male pronouns to describe the almond grower throughout the rest of the paper.

Figure 1: Almond Pollination Colony Strength and U.S. Winter Mortality Rates, 2010-2015



Source: Goodrich, B. & Goodhue, R.E. "Honey Bee Colony Strength in the California Almond Pollination Market." *ARE Update* 19(4) (2016): 5-8.
Data Sources: The Pollination Connection; Bee Informed Partnership Winter Loss Surveys

into increasing colony strength for almond pollination, but because of recent exogenous shocks due to colony health issues, such as CCD, pesticides or varroa mites, the beekeeper could still experience high winter mortality rates and low colony strength. Similarly, due to such shocks a beekeeper who put in less effort could find herself better off. Thus, risk aversion on the behalf of the beekeeper creates the moral hazard problem. Adding to the moral hazard problem is the fact that almond growers cannot easily distinguish between low and high strength colonies. Since effort and inputs are costly, without colony strength requirements and inspections, beekeepers would prefer to provide lower strength colonies for almond pollination.

To deal with this moral hazard issue, almond pollination agreements (both oral and written) often contain requirements for colony strength. Almond growers are typically not able to easily estimate the colony strength of hives provided to their almond orchards, but they can obtain this information by paying for a colony strength inspection to be performed by a trained inspector. The inspector inspects a sample (typically 10-25%) of hives provided to an almond orchard and counts the number of active frames in each hive. The active frames per hive are averaged across the sample, and this average is reported to the almond grower and beekeeper.

The most common colony strength requirement is the minimum average frame count, in which the average number of active frames reported in a colony strength inspection of an orchard must meet this minimum. Approximately 86 percent of almond growers surveyed at the Almond Board of California (ABC) 2015 Almond conference reported that minimum average frame counts were stipulated in their largest almond pollination contracts, and nearly half of the growers reported a minimum average of eight frames. If the minimum average frame count requirement is not met, growers can impose monetary and non-monetary penalties on beekeepers which can be specified explicitly or implicitly in the agreement.

A minimum frame count requirement can be imposed so that the beekeeper is not paid for any individual hives that do not meet this minimum colony strength. This colony strength stipulation can be required in lieu of or in addition to a minimum average frame count. The minimum frame count used in addition to the minimum average frame count provides beekeepers with the incentive to deliver colonies of uniform strength, rather than delivering very high along with very low strength colonies that would still average to meet the minimum average colony strength.

Some almond growers use incentive pollination contracts, where a beekeeper is paid according to the average frame count she provides in comparison to a specified benchmark colony strength. If a beekeeper exceeds the benchmark colony strength she is paid a per-frame bonus for the number of frames above the benchmark. Similarly, if a beekeeper does not meet the benchmark, a per-frame penalty is imposed for the number of frames below the benchmark. Approximately 20 percent of almond grower survey respondents used incentive contracts of this nature in 2015.

3 Previous Literature

Previous work on pollination markets has concentrated on theoretically and empirically modeling the reciprocal benefits of honey bee pollination. Meade (1952) outlines the reciprocal benefits of pollination to a beekeeper and an apple grower: A beekeeper places bees near an apple orchard to produce honey. In doing so, the apple grower receives pollination, an input to apples, from the beekeeper's bees, and the beekeeper receives nectar, an input to honey, from the grower's apple orchard. Meade models the benefits as reciprocal externalities in which both the apple grower and beekeeper are not being paid for the benefit each is providing to the other party. It wasn't until over 20 years later that Meade's market failure explanation was corrected by Cheung (1973), Gould (1973) and Johnson (1973) who each noted the existence of pollination markets prior to 1952.

Cheung (1973) provides one of the first econometric analyses of pollination markets by using survey data from Washington state beekeepers. Cheung develops a basic model of multiple crops' pollination fees by using marginal products of pollination and honey production to explain reciprocal benefits. In doing so, he implicitly introduced the equilibrium bee wage concept, later discussed explicitly in Rucker et al. (2012), in which the beekeeper receives both a pollination fee and honey from pollinating a crop and, in theory, a grower and beekeeper would take both of these products into account when determining a pollination fee. Thus, in a perfectly competitive pollination market the bee wage should be equal across all crops, despite the fact that crops differ in marginal pollination value and honey products. Cheung tests this relationship with the Washington pollination fee data and finds that it holds.

Rucker et al. (2012) extend the Cheung (1973) analysis by developing a more detailed theoretical model of reciprocal benefits. This model describes the determinants of the equilibrium bee wage and pollination fees through the use of comparative statics. Rucker et al. outline and econometrically test empirical predictions of pollination fee and stocking density determinants, using an extensive collection of U.S. pollination fee data. The data set consists of survey data from beekeepers in Oregon and Washington collected by Michael Burgett of Oregon State University from 1979 to 2009. The authors find that stocking densities are relatively inelastic across crops, and that the crop price and the potential for honey production in that crop, as well as varroa mite indicators and diesel fuel prices, are influential in determining pollination fees.

This paper expands on previous work by accounting for uncertainty and differences in colony strength and focusing on almond pollination agreements to discover specific factors influencing almond pollination fees. An advantage of focusing on almond pollination markets stems from the ability to ignore the influence of reciprocal benefits. Almond honey is unpalatable to humans, so beekeepers cannot sell it as a by-product of almond pollination. I develop a theoretical model to show the influences of uncertainty in colony strength on almond pollination agreements. Additionally, I use two unique datasets that provide information on individual pollination agreements from both the beekeeper and almond perspectives: the California State Beekeeper's Association Pollination Fee Survey and a pollination contract survey I conducted at the Almond Board of California (ABC) 2015 Almond Conference. Neither dataset has been used in previous economic work on pollination services. In doing so, this paper provides an increased understanding of the function of almond pollination markets and the full extent to which recent colony health issues impact almond pollination fees.

4 Theoretical Model

I use a traditional principal-agent model to incorporate the influence of uncertainty and moral hazard on almond pollination agreements. I assume only two actors, where the almond grower is the principal and the beekeeper is the agent. This model follows closely to that described in Anglin and Arnott (1991) who describe a general principal-agent model in the context of residential real estate brokerage. I choose to investigate the specific case of a risk neutral principal and risk averse agent in the context of pollination agreements to solve explicitly for a solution and explore how the agent's risk aversion impacts the optimal solution. The model is described in the following subsections, and concludes with a discussion of the influence that the beekeeper's risk aversion parameter has on the model solutions.

4.1 Beekeeper

The beekeeper is a risk averse agent with a utility function of the exponential form u(x)=1-e^{-Ax} where $A = \frac{-u''(x)}{u'(x)} > 0$ is the beekeeper's coefficient of absolute risk aversion and x represents the beekeeper's income.

There are two possible outcomes that can occur and the beekeeper influences the likelihood of each outcome by exerting costly effort, e. The number of bees provided to an almond orchard (with a fixed acreage normalized to one) is a random variable defined as:

$$b = \begin{cases} b_H & \textit{with probability } p(e), \\ b_L & \textit{with probability } 1 - p(e), \end{cases} \tag{1}$$

where $b_H > b_L$ are the two possible numbers of bees provided. I choose to use the number of bees provided because this can account for both the colony strength of provided hives as well as the overall number of hives provided. The probability that a high number of bees are provided, $p(e)$, is a concave function of effort, thus it is assumed to have the properties: $p'(e) > 0$, $p''(e) \leq 0$, and $p'''(e) = 0$. A beekeeper can increase her probability of providing a high number of bees by exerting additional effort, but the marginal returns to doing so are decreasing in the amount of effort provided. I assume that the beekeeper faces a linear disutility of effort, $c(e)$, i.e., $c'(e) > 0$ and $c''(e) = 0$.

The beekeeper is paid a fixed pollination fee by the grower according to the following schedule:

$$t = \begin{cases} t_H & \textit{when } b = b_H, \\ t_L & \textit{when } b = b_L. \end{cases} \tag{2}$$

Thus, the beekeeper maximizes expected utility by choosing effort as follows:

$$\underset{e}{max}\ p(e)\left(1-e^{-At_H}\right)+(1-p(e))\left(1-e^{-At_L}\right)-c(e). \tag{3}$$

The beekeeper takes the payments t_H and t_L as given, so her first order condition is:

$$p'(e)\left(e^{-At_L}-e^{-At_H}\right)-c'(e)=0. \tag{4}$$

4.2 Almond Grower

The almond grower receives the following yield (in total pounds) dependent on the number of bees the beekeeper provides to the almond orchard:

$$y=\begin{cases} y_H & when\ b=b_H, \\ y_L & when\ b=b_L, \end{cases} \tag{5}$$

where $y_H > y_L$. I assume that the grower cannot access additional colonies from another beekeeper during almond pollination which reflects the almond pollination market in recent years. I also assume that the almond grower can perfectly observe the number of bees provided and the corresponding yield.[2]

I assume the almond grower is a risk neutral principal, thus the grower's expected profits are:

$$E[\pi]=p(e)\left(Py_H-t_H\right)+(1-p(e))\left(Py_L-t_L\right), \tag{6}$$

where P is the price of almonds in dollars per pound. The grower chooses the payments t_H and t_L that he will make to the beekeeper based on the probabilities of the realized value of the number of bees, b. The almond grower offers his optimal payment schedule to the beekeeper prior to the beekeeper's effort decision.

[2] It would be beneficial to investigate uncertainty in these variables in future models so as to more accurately represent reality.

4.3 Observable Effort Solution

If the almond grower could perfectly observe the amount of effort a beekeeper puts in, the almond grower could condition the beekeeper's payment on the beekeeper's effort level directly. This case is the first best scenario and does not involve moral hazard. Under observable effort, the grower chooses the payment schedule to offer the beekeeper as well as his own optimal effort level by maximizing expected profits subject to the beekeeper's participation constraint which ensures that the beekeeper's expected utility is greater than some reservation utility. I normalize the beekeeper's reservation utility to be zero. The almond grower's optimization problem is as follows:

$$\begin{aligned} \underset{e,\, t_H,\, t_L}{max} \;\; E[\pi] = p(e)\left(Py_H - t_H\right) + (1-p(e))\left(Py_L - t_L\right) \quad s.t. \\ p(e)\left(1-e^{-At_H}\right) + (1-p(e))\left(1-e^{-At_L}\right) - c(e) \geq 0. \qquad (\Gamma) \end{aligned} \tag{7}$$

The following first order conditions result from the almond grower's optimization problem under observable effort:

$$p'(e)\left[P\triangle y - (t_H - t_L)\right] - \Gamma\left[p'(e)\left(e^{-At_L} - e^{-At_H}\right) - c'(e)\right] = 0, \tag{8}$$

$$p(e) + \Gamma p(e) A e^{-At_H} = 0, \tag{9}$$

$$(1-p(e)) + \Gamma\left(1-p(e)\right) A e^{-At_L} = 0, \tag{10}$$

where $\triangle y = y_H - y_L$ is the difference in yield benefit to the grower from the difference in provided bees, and $\Gamma = -\frac{e^{-At_H}}{A} = -\frac{e^{-At_L}}{A}$ is the multiplier associated with the participation constraint in (7). From the first order conditions $\Gamma < 0$ implies that the beekeeper's participation constraint is binding and that $t_H = t_L$. Using this information, the first best solution is characterized as follows:

$$t_H = t_L = t_{FB} = -\tfrac{\ln(1-c(e_{FB}))}{A},$$
$$\tfrac{c'(e_{FB})}{p'(e_{FB})(1-c(e_{FB}))} = AP\triangle y. \tag{11}$$

Thus, with observable effort, an almond grower could specify a given amount of effort, e_{FB}, and not make the beekeeper's payment dependent on the observable outcome. The beekeeper will comply and exert e_{FB} because doing so provides an expected utility equal to her reservation utility of zero.

4.4 Unobservable Effort (Moral Hazard) Solution

In the case where effort is unobservable, the only information a grower can obtain about the effort that a beekeeper exerts is indirectly through the observed outcome. Thus, the grower must provide a beekeeper with an incentive schedule to induce the beekeeper to exert the grower's optimal level of effort. The grower maximizes expected profits subject to the beekeeper's participation constraint and the beekeeper's incentive compatibility constraint:

$$\begin{aligned} \underset{e,\ t_H,\ t_L}{max}\ E[\pi] = p(e)\left(Py_H - t_H\right) + (1-p(e))\left(Py_L - t_L\right) \quad s.t. \\ p(e)\left(1-e^{-At_H}\right) + (1-p(e))\left(1-e^{-At_L}\right) - c(e) \geq 0, \qquad (\lambda) \\ p'(e)\left(e^{-At_L} - e^{-At_H}\right) - c'(e) = 0, \qquad (\mu) \end{aligned} \tag{12}$$

where λ and μ are multipliers for the participation and incentive compatibility constraints, respectively.

The first order conditions for the grower's optimization problem under unobservable effort are:

$$p'(e)\left[P\triangle y - (t_H - t_L)\right] - \lambda\left[p'(e)\left(e^{-At_L} - e^{-At_H}\right) - c'(e)\right] - \mu\left[p''(e)\left(e^{-At_L} - e^{-At_H}\right) - c''(e)\right] = 0, \tag{13}$$

$$p(e)+Ae^{-At_H}\left[\lambda p(e)+\mu p'(e)\right]=0, \tag{14}$$

$$1-p(e)+Ae^{-At_L}\left[\lambda p(e)-\mu p'(e)\right]=0. \tag{15}$$

These equations can be simplified to the following, given (4) and $c''(e)=0$:

$$P\triangle y=\frac{\mu}{\lambda}\frac{p'(e)}{Ap(e)(1-p(e))}+\frac{\mu p''(e)\left(e^{-At_L}-e^{-At_H}\right)}{p'(e)}, \tag{13 $\prime$}$$

$$\lambda=-\frac{e^{At_H}}{A}-\mu\frac{p'(e)}{p(e)}, \tag{14 $\prime$}$$

$$\lambda=-\frac{e^{At_L}}{A}+\mu\frac{p'(e)}{(1-p(e))}. \tag{15 $\prime$}$$

Since $\mu\leq 0$, equation (15 $\prime$) implies that $\lambda<0$ and the participation constraint is binding. Equation (13 $\prime$) implies that as long as $P\triangle y>0$, μ is negative and the incentive compatibility constraint is binding. Thus, solving this system of equations, the solution to the optimization problem with unobserved effort is characterized by:

$$\begin{gathered}
P\triangle y=\tfrac{\mu}{\lambda}\tfrac{p'(e_{SB})}{Ap(e_{SB})(1-p(e_{SB}))}+\tfrac{\mu p''(e_{SB})\left(e^{-At_L}-e^{-At_H}\right)}{p'(e_{SB})},\\
t_H^*=-\tfrac{1}{A}\ln\left[(1-c(e_{SB}))-\tfrac{(1-p(e_{SB}))c'(e_{SB})}{p'(e_{SB})}\right],\\
t_L^*=-\tfrac{1}{A}\ln\left[(1-c(e_{SB}))+\tfrac{p(e_{SB})c'(e_{SB})}{p'(e_{SB})}\right],\\
\mu^*=\tfrac{p(e_{SB})(1-p(e_{SB}))}{Ap'(e_{SB})}\left[\left((1-c(e_{SB}))+\tfrac{p(e_{SB})c'(e_{SB})}{p'(e_{SB})}\right)^{-1}-\left((1-c(e_{SB}))-\tfrac{(1-p(e_{SB}))c'(e_{SB})}{p'(e_{SB})}\right)^{-1}\right],\\
\lambda^*=-\tfrac{1}{A}\left[(1-p(e_{SB}))\left((1-c(e_{SB}))+\tfrac{p(e_{SB})c'(e_{SB})}{p'(e_{SB})}\right)^{-1}+p(e_{SB})\left((1-c(e_{SB}))-\tfrac{(1-p(e_{SB}))c'(e_{SB})}{p'(e_{SB})}\right)^{-1}\right].
\end{gathered} \tag{16}$$

Because the following relationship holds:

$$(1-c(e_{SB}))\text{-}\tfrac{(1-p(e_{SB}))c'(e_{SB})}{p'(e_{SB})}=(1-c(e_{SB}))+\tfrac{p(e_{SB})c'(e_{SB})}{p'(e_{SB})}\text{-}\tfrac{c'(e_{SB})}{p'(e_{SB})}<(1-c(e_{SB}))+\tfrac{p(e_{SB})c'(e_{SB})}{p'(e_{SB})},$$

the payment to the beekeeper under the high bee outcome, t_H^*, is greater than the payment in the low bee outcome, t_L^*. Additionally, without further assumptions, it is possible for $t_H^* \leq 0$ and/or $t_L^* \leq 0$. I focus on the solution in which $t_H^*, t_L^* > 0$, i.e., the almond grower pays the beekeeper a positive fee for pollination services in both the low and high cases. This is the only realistic case in the almond pollination market. Because of this, the following is true:

$$0 < \left[(1 - c(e_{SB})) - \frac{(1 - p(e_{SB}))c'(e_{SB})}{p'(e_{SB})}\right] < \left[(1 - c(e_{SB})) + \frac{p(e_{SB})c'(e_{SB})}{p'(e_{SB})}\right] < 1. \qquad (17)$$

4.5 Comparative Statics: Effect of Risk Aversion on Unobservable Effort Optimal Solution

In order to derive the effect that the beekeeper's risk aversion has on the optimal solution when effort is unobserved, I use the Implicit Function Theorem:

$$\begin{bmatrix} \frac{\partial e_{SB}}{\partial A} \\ \frac{\partial t_H^*}{\partial A} \\ \frac{\partial t_L^*}{\partial A} \end{bmatrix} = - \begin{bmatrix} \frac{\partial F1}{\partial e} & \frac{\partial F1}{\partial t_H} & \frac{\partial F1}{\partial t_L} \\ \frac{\partial F2}{\partial e} & \frac{\partial F2}{\partial t_H} & \frac{\partial F2}{\partial t_L} \\ \frac{\partial F3}{\partial e} & \frac{\partial F3}{\partial t_H} & \frac{\partial F3}{\partial t_L} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial F1}{\partial A} \\ \frac{\partial F2}{\partial A} \\ \frac{\partial F3}{\partial A} \end{bmatrix}. \qquad (18)$$

where F1=Equation (13), F2=Equation (14) and F3=Equation (15). Using Cramer's Rule, the following results:

$$\frac{\partial e_{SB}}{\partial A} = -det \begin{bmatrix} \frac{\partial F1}{\partial A} & \frac{\partial F1}{\partial t_H} & \frac{\partial F1}{\partial t_L} \\ \frac{\partial F2}{\partial A} & \frac{\partial F2}{\partial t_H} & \frac{\partial F2}{\partial t_L} \\ \frac{\partial F3}{\partial A} & \frac{\partial F3}{\partial t_H} & \frac{\partial F3}{\partial t_L} \end{bmatrix} /det[H], \qquad (19)$$

where H is the Hessian matrix defined by:

$$H = \begin{bmatrix} \frac{\partial F1}{\partial e} & \frac{\partial F1}{\partial t_H} & \frac{\partial F1}{\partial t_L} \\ \frac{\partial F2}{\partial e} & \frac{\partial F2}{\partial t_H} & \frac{\partial F2}{\partial t_L} \\ \frac{\partial F3}{\partial e} & \frac{\partial F3}{\partial t_H} & \frac{\partial F3}{\partial t_L} \end{bmatrix}.$$

The Hessian matrix must be negative definite for the optimization problem to be concave, i.e., $(-1)^3 det[H] > 0$ is true, thus $det[H] < 0$. To find the sign of $\frac{\partial e_{SB}}{\partial A}$, only the numerator of (19) must be found. Because $\frac{\partial F2}{\partial t_L} = \frac{\partial F3}{\partial t_H} = 0$, the numerator of equation (19) is characterized as follows:

$$Num(19) = \frac{\partial F1}{\partial A}\frac{\partial F2}{\partial t_H}\frac{\partial F3}{\partial t_L} - \frac{\partial F2}{\partial A}\frac{\partial F1}{\partial t_H}\frac{\partial F3}{\partial t_L} - \frac{\partial F3}{\partial A}\frac{\partial F1}{\partial t_L}\frac{\partial F2}{\partial t_H}. \tag{20}$$

Equation (20) simplifies to:

$$Num(19) = -2A^4 e^{-A(t_L+t_H)} \mu p''(e) \left(t_H e^{-At_H} - t_L e^{-At_L}\right) (\lambda p(e) + \mu p'(e)) (\lambda(1-p(e)) - \mu p'(e)), \tag{20 ′}$$

where $(\lambda p(e) + \mu p'(e)){=}\frac{-p(e)}{A}\left[(1-c(e)) - \frac{(1-p(e))c'(e)}{p'(e)}\right]^{-1}{<}0$ and $(\lambda(1-p(e)) - \mu p'(e)){=}\frac{-(1-p(e)}{A}\left[(1-c(e)) + \frac{p(e)c'(e)}{p'(e)}\right]^{-1}{<}0$. Thus, the only unsigned component of equation (20 ′) is $\left(t_H e^{-At_H} - t_L e^{-At_L}\right)$, whose sign depends on whether At_L is greater than or less than one. This is shown below:

$$\left(t_H e^{-At_H} - t_L e^{-At_L}\right) = e^{-A(t_H - t_L)} - \frac{t_L}{t_H} = e^{-At_L \triangle t} - \frac{t_L}{t_H},$$

$$where \;\; \triangle t = \frac{t_H - t_L}{t_L}.$$

Using the exponential property regarding percentage changes, $e^r \approx (1+r)$ where r is a percentage change, this leads to the following:

$$\left(t_H e^{-At_H} - t_L e^{-At_L}\right) = \left(e^{\triangle t}\right)^{-At_L} - \frac{t_L}{t_H} \approx \left(\frac{t_H}{t_L}\right)^{-At_L} - \frac{t_L}{t_H} = \left(\frac{t_L}{t_H}\right)^{At_L} - \frac{t_L}{t_H}.$$

Two cases result because $\frac{t_L}{t_H} < 1$, which are described below.

Case 1: $At_L \geq 1$ implies that $\left(t_H e^{-At_H} - t_L e^{-At_L}\right) \leq 0$.

It follows that equation (20) is positive, so

$$\frac{\partial e_{SB}}{\partial A} = -\frac{1}{det[H]}\left[\frac{\partial F1}{\partial A}\frac{\partial F2}{\partial t_H}\frac{\partial F3}{\partial t_L} - \frac{\partial F2}{\partial A}\frac{\partial F1}{\partial t_H}\frac{\partial F3}{\partial t_L} - \frac{\partial F3}{\partial A}\frac{\partial F1}{\partial t_L}\frac{\partial F2}{\partial t_H}\right] \geq 0. \tag{21}$$

An increase in the beekeeper's risk aversion parameter increases the optimal level of effort the grower wants to elicit. Using this, it is illustrative to use the effect of the risk aversion parameter on effort to determine how the payments to the beekeeper will change:

$$\frac{\partial t_L^*}{\partial A} = \frac{\ln\left[(1-c(e_{SB})) + \frac{p(e_{SB})c'(e_{SB})}{p'(e_{SB})}\right]}{A^2} + \frac{1}{A}\left[(1-c(e_{SB})) + \frac{p(e_{SB})c'(e_{SB})}{p'(e_{SB})}\right]^{-1}\left[\frac{p(e)c'(e)p''(e)}{(p'(e))^2}\right]\frac{\partial e_{SB}}{\partial A} < 0, \tag{22}$$

$$\frac{\partial t_H^*}{\partial A} = \frac{\ln\left[(1-c(e_{SB})) - \frac{(1-p(e_{SB}))c'(e_{SB})}{p'(e_{SB})}\right]}{A^2} \tag{23}$$

$$-\frac{1}{A}\left[(1-c(e_{SB})) - \frac{(1-p(e_{SB}))c'(e_{SB})}{p'(e_{SB})}\right]^{-1}\left[\frac{(1-p(e))c'(e)p''(e)}{(p'(e))^2}\right]\frac{\partial e_{SB}}{\partial A} \lesseqgtr 0.$$

The increase in the risk aversion parameter will decrease the payment to the beekeeper for a low bee outcome, while the effect on the high bee outcome is ambiguous.

Case 2: $At_L < 1$ **implies that** $\left(t_H e^{-At_H} - t_L e^{-At_L}\right) > 0$

It follows that equation (20) is positive, so

$$\frac{\partial e_{SB}}{\partial A} = -\frac{1}{det[H]}\left[\frac{\partial F1}{\partial A}\frac{\partial F2}{\partial t_H}\frac{\partial F3}{\partial t_L} - \frac{\partial F2}{\partial A}\frac{\partial F1}{\partial t_H}\frac{\partial F3}{\partial t_L} - \frac{\partial F3}{\partial A}\frac{\partial F1}{\partial t_L}\frac{\partial F2}{\partial t_H}\right] < 0. \tag{24}$$

In this case, an increase in the beekeeper's risk aversion parameter decreases the optimal level of effort the grower wants to elicit. The effects of the risk aversion parameter on the payments to the beekeeper are:

$$\frac{\partial t_L^*}{\partial A} = \frac{\ln\left[(1-c(e_{SB})) + \frac{p(e_{SB})c'(e_{SB})}{p'(e_{SB})}\right]}{A^2} + \frac{1}{A}\left[(1-c(e_{SB})) + \frac{p(e_{SB})c'(e_{SB})}{p'(e_{SB})}\right]^{-1}\left[\frac{p(e)c'(e)p''(e)}{(p'(e))^2}\right]\frac{\partial e_{SB}}{\partial A} \lesseqgtr 0, \tag{25}$$

$$\frac{\partial t_H^*}{\partial A} = \frac{\ln\left[(1-c(e_{SB})) - \frac{(1-p(e_{SB}))c'(e_{SB})}{p'(e_{SB})}\right]}{A^2} \tag{26}$$

$$-\frac{1}{A}\left[(1-c(e_{SB})) - \frac{(1-p(e_{SB}))c'(e_{SB})}{p'(e_{SB})}\right]^{-1}\left[\frac{(1-p(e))c'(e)p''(e)}{(p'(e))^2}\right]\frac{\partial e_{SB}}{\partial A} < 0.$$

The increase in the risk aversion parameter will decrease the payment to the beekeeper for a high bee outcome, while the effect on the low bee outcome is ambiguous.

The two cases likely result from the curvature of the beekeeper's utility function and the probability function for the high bee outcome. In Case 1, it is likely that the benefits of increasing effort in terms of the higher probability of the high outcome are large. In this case, if the grower decreases the payment of the low bee outcome, the more risk averse beekeeper exerts more effort to increase the probability of the high payment. In Case 2, it could be that the benefits of increasing effort in terms of the high outcome are small, so the grower must increase the high payment to get a smaller (but optimal) amount of effort from the more risk averse beekeeper. These two cases need to be explored further before definitive conclusions can be reached.

5 Empirical Analysis of Almond Pollination Fees

It is likely that almond pollination fees are influenced by both colony supply and demand factors, as well as the overall decision of the contract, which includes other contract provisions influencing the actual colony strength provided by the beekeeper. A general relationship between the per-colony pollination fee and determinants for beekeeper-almond grower pair i in year t is shown here:

$$Fee_{it} = f\left(ColonyStrength_{it},\ ContractStipulations_{it},\ Supply_t,\ Demand_t\right) + \epsilon_{it}. \tag{27}$$

$ColonyStrength_{it}$ represents the colony strength the beekeeper delivers to the grower's almond orchard in year t, and $ContractStipulations_{it}$ represents the contract stipulations agreed upon between the members of each beekeeper-almond grower pair in year t. $Supply_t$ and $Demand_t$ are supply and demand factors associated with colonies available for almond pollination in year t.

The theoretical model outlined in Section 4 showed that colony strength for almond pollination is influenced by the pollination fee and contract stipulations when there is random error component due to colony health inhibitors. This is because the beekeeper makes effort decisions after being offered a price schedule dependent on colony strength for almond pollination. Thus, an endogeneity issue arises in (27) where the pollination fee is determined by the delivered colony strength, but delivered colony strength is also determined by the fee and colony strength options offered. However, as seen in Figure 1, winter mortality rates are highly (negatively) correlated with colony strength during almond pollination, and as discussed in Section 2, are likely not influenced by almond contract stipulations. Because of this, winter mortality rates can be used to instrument for $ColonyStrength_{it}$.

5.1 California State Beekeeper's Association (CSBA) Pollination Survey Analysis

The CSBA surveys its members yearly to collect pollination colony rental information. The survey asks about the fees charged per colony and the number of colonies provided for pollination services in various pollinated crops, as well as the beekeeper's winter mortality rate. I use survey data for individual beekeepers from the years 2008 through 2015 to determine influences on pollination fees.

5.1.1 Hypothesized Fee Determinants

The equation (28), provides a reduced form representation of the relationship between the almond pollination fee received by beekeeper b in year t and exogenous determinants.

$$Fee_{bt} = \beta_0 + \beta_1 Reg_{bt} + \beta_2 WinterMort_{bt} + \beta_3 AlmondAcre_t + \beta_4 USWinterMort_t + \beta_5 NDHoneyProd_{t-1} + \epsilon_{bt} \tag{28}$$

Ideally, beekeeper-almond grower pairs representing specific contracts would be used, however these data do not exist. Instead each beekeeper specific variable is assumed to be an average over all of their pollination contracts with different growers.

In equation (28), Reg_{bt} represents the region in which beekeeper b places colonies for almond pollination in year t. Three almond producing regions in California are defined by CSBA as follows: Madera-Kern (Madera, Fresno, Kings, Tulare and Kern counties), San Joaquin-Merced (San Joaquin, Stanislaus and Merced counties) and Sacramento-North (Tehama, Glenn, Butte, Colusa, Sutter, Yolo and Solano counties). These control for regional colony supply/demand variation.

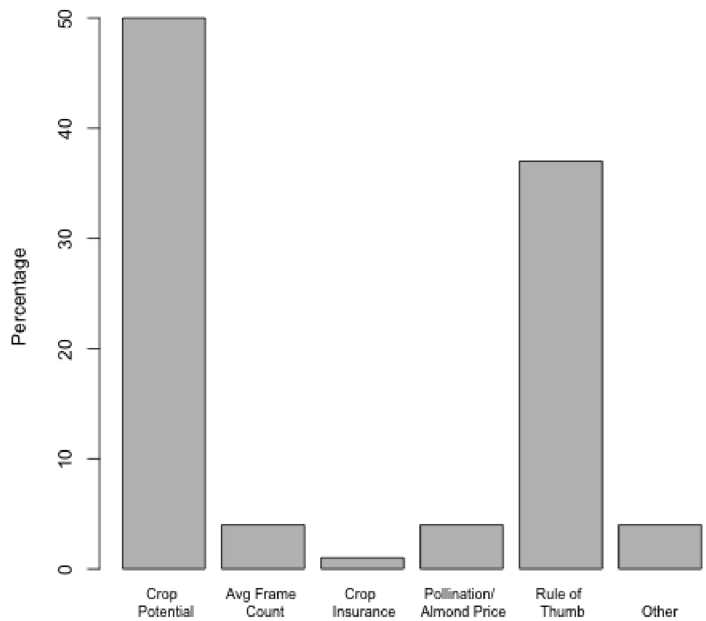
$WinterMort_{bt}$ is the percentage of colonies lost by beekeeper b over the winter between years $t-1$ and t. As discussed previously, winter mortality rates and colony strength at almond pollination are highly correlated, so beekeepers with lower winter mortality rates are likely able to produce stronger colonies. Therefore I expect that as a beekeeper's winter mortality rate decreases, colony strength supplied at almond pollination increases. The increased colony strength causes the pollination fee to increase, as the theoretical model predicted.

The remaining variables are exogenous measures of supply and demand in each year and are not variables collected in the CSBA survey. The demand for colonies for almond pollination is likely exogenous based on findings in the 2015 ABC pollination contract survey and previous literature. Growers at the 2015 Almond Conference were asked about the main factors influencing the number of hives they stock per acre. Half of the growers answered that their density decisions were influenced by factors affecting crop potential, such as the orchard variety and age, while 37 percent of growers stated that the rule of thumb was most influential.[3] Only four percent of growers stated that they consider the average frame count stipulated in their contract when making hive density decisions, and four percent use a relative comparison of almond prices to pollination costs to determine hive density. This is consistent with a finding of Rucker et al. (2012) that hive densities were relatively inelastic to pollination fees and were mostly influenced by specific crop fixed effects. This topic deserves further investigation, as it is still unclear as to why this happens. As Rucker et al. hypothesized, it could be due to the small portion of total almond operating expenses that pollination represents. University of California Cooperative Extension estimates that pollination expenses vary based on age from 9-17% of total operating costs throughout an orchard's useful life. Alternatively, it could be due to the current gap in knowledge of the direct link between colony strength, hive density and almond yields.

Thus, almond pollination demand for hives is relatively inelastic to pollination fees and colony strength, so the total number of almond acres in year t, $AlmondAcre_t$, is an exogenous measure of colony demand in year t. I expect that as the number of almond acres increases, the almond pollination rental fees will increase.

[3] A rule of thumb of two honey bee hives per acre emerged in industry interviews with almond growers, beekeepers and pollination brokers.

Figure 2: Main Factor Influencing Hive Density (N=100)



The quantity supplied of colonies for almond pollination depends on the pollination fee. The colony rental fee determines the distance beekeepers will travel with their colonies to participate in almond pollination. However, the overall health of U.S. colonies has a large impact on the number of colonies that are available for transport for almond pollination, and as discussed earlier U.S. colony health on average is likely not influenced by almond pollination fees. The variables $USWinterMort_t$ and $NDHoneyProd_{t-1}$ are included as measures of nationwide colony health in year t. $USWinterMort_t$ is the total percentage of U.S. colonies lost nationwide during the winter between years $t-1$ and t. These data come from a large sample of U.S. beekeepers collected yearly by the Bee Informed Partnership. I expect that as the U.S. mortality rate increases, on average lower strength colonies will be delivered to almond orchards. Thus almond pollination fees will decrease as it becomes more difficult throughout the nation to provide strong colonies for almond pollination.

$NDHoneyProd_{t-1}$ represents the per-colony honey production in North Dakota in year

$t-1$. North Dakota is the largest honey producing state in the country and most of the U.S. managed honey bee colonies are transported to the upper Midwest for honey production during the summer months. The better the pesticide-free honey flow is during the summer, the stronger colonies are coming out of winter for almond pollination.[4] Thus, honey production per colony can be used as a predictor of colony strength and numbers for almond pollination, and in fact, many growers pay attention to honey flows during the summer to gauge colony strength for the upcoming pollination season. The data for this variable were obtained from USDA NASS. I expect that as the previous year's honey production per colony increases, almond pollination fees will decrease due to the larger supply of colonies and increased competition amongst beekeepers.

This CSBA dataset does not include individual contract provisions for each observation. Thus, it is important to note that there could be omitted variable bias in this regression if any of the exogenous variables are significantly correlated with specific contract requirements that are agreed to by the beekeeper. This does not seem likely to be an issue.

5.1.2 CSBA Results

Regression Model (1) in Table 1 below shows the Ordinary Least Squares (OLS) estimation results of equation (28). This model specification does a fair job explaining the variation of almond pollination fees, as the adjusted R^2 value is 0.33. Two of the variables have impacts significantly different from zero at the 5% significance level: the beekeeper specific winter mortality rate and the total bearing almond acres. The statistically significant coefficients in this regression support the hypothesized relationships between almond pollination fees and their determinants. The regression shows that over all years, there is no statistically significant difference between regional fees. The U.S. winter mortality rate and North Dakota honey production per colony in the previous year do not have significant effects on pollination fees, although they do have the predicted signs.

[4] Personal communication with Dr. Gordon Wardell, Director of Pollination Operations at Wonderful Orchards.

Table 1: Determinants of Almond Pollination Fees: CSBA Data, 2008−2015

	Dependent variable:	
	Per-Colony Fee	
	(1)	(2)
Region: Merced-San Joaquin	−2.40	−2.40
	(1.856)	(1.848)
Region: Sacramento-North	1.82	1.88
	(2.159)	(2.139)
Individual Winter Mortality Rate	−0.13**	−0.12**
	(0.053)	(0.052)
Bearing Almond Acreage (in 1,000's)	0.13***	0.13***
	(0.023)	(0.020)
U.S. Winter Mortality Rate	−0.29	
	(0.277)	
ND Per Colony Honey Production (in lbs)	−0.11	
	(0.096)	
ND Honey*U.S. Winter Mortality		−0.005*
		(0.003)
Constant	68.96**	68.12***
	(27.379)	(20.936)
Observations	274	274
R^2	0.347	0.350
Adjusted R^2	0.332	0.338
F Statistic	23.625*** (df = 6; 267)	28.820*** (df = 5; 268)
Note:		(*s.e.*); *p<0.1; **p<0.05; ***p<0.01

I hypothesize that the exogenous supply variables may have an interaction effect, rather than individual effects on the supply of colonies for almond pollination.The negative relationship between winter mortality rates and colony strength for almond pollination means that if winter mortality rates are low, this dilutes the effect of North Dakota per colony honey production on price because these supply variables move price in conflicting directions. Higher North Dakota per colony honey production likely decreases almond pollination fees through increases in supply, but lower winter mortality rates likely increase prices through higher delivered colony strength.

Model (2) of Table 1 shows a regression with the interaction of U.S. winter mortality rates and North Dakota per colony honey production included. This model seems to do a slightly better job explaining the variation in almond pollination fees as the adjusted R^2 increases marginally, and the F statistic of the model increases over that of the regression Model (1). The coefficients on the individual beekeeper's mortality rate and bearing almond acreage remain significant and with signs according to their hypothesized relationships with almond pollination fees. Additionally, the interaction variable between the North Dakota per colony honey production and the U.S. winter mortality rate is significant at the 10% level.

From Table 1 it can be concluded that an increase in an individual beekeeper's winter mortality rate decreases the almond pollination fee she receives by \$0.12 per colony. This does not seem like a large amount given that the average fee across all regions in 2015 was \$175.52, however over the 2015-2016 winter, the Bee Informed Partnership reported the average winter loss in the U.S. to be approximately 11 percentage points above the acceptable level. Thus, a beekeeper experiencing the U.S. average winter loss rate would lose \$1.32 per surviving colony compared to those with an acceptable winter loss level, in addition to having fewer colonies for pollination.

Table 1 can be used to draw conclusions about the almond pollination supply and demand influences over time. An increase in bearing almond acreage by 1,000 acres increases almond pollination fees by \$0.13 per colony. The interaction variable coefficient shows that at the mean per-colony North Dakota honey production level over all years (79 lbs), an increase in the average U.S. winter mortality rate of one percent decreases per-colony pollination fees by \$0.39. Similarly, at the mean U.S. winter mortality rate over all years (29%), an increase in per-colony honey production would decrease almond pollination fees by \$0.15.

5.2 Almond Board of California (ABC) Pollination Contract Survey Analysis

I conducted an almond pollination contract survey at the ABC 2015 Almond Conference. In this survey, I collected responses from a total of 114 almond growers on various components of their almond pollination contracts as well as characteristics of their almond operations.[5]

5.2.1 Hypothesized Fee Determinants

Equation (29) provides a reduced form representation of the relationship between an almond grower's fee and the contract stipulations used in 2015.

$$Fee = \delta_0 + \delta_1 Form + \delta_2 Provider + \delta_3 AvgFC + \delta_4 Action + \delta_5 Inspection + \delta_6 PFBonus + \delta_7 TotalClauses + \delta_8 HiveDen + \delta_9 Relationship + \delta_{10} Beekeepers + \delta_{11} Experience + \delta_{12} Yield + \epsilon \quad (29)$$

The dependent variable Fee is the per colony fee reported by the almond grower for his largest almond pollination contract in 2015. The variables $Form$, $Provider$, $AvgFC$, $Action$, $Inspection$, and $PFBonus$ are categorical variables representing various contract stipulations. There is one continuous variable representing contract stipulations: $TotalClauses$. The variables $HiveDen$, $Relationship$ and $Beekeepers$ are categorical variables determin-

[5]Many growers did not answer one or more questions. Regressions are performed on complete observations only making the observation numbers significantly less than 114. Because the variables differ across regressions, the sample sizes differ as well.

ing grower characteristics that may impact contract stipulation decisions while $Yield$ and *Experience* are continuous variables to control for grower characteristics.

Form represents the form(s) of almond pollination agreement the grower used in 2015. Thus, it can take on three values: written, oral, or both written and oral. Written contracts are likely more formal than oral agreements, which probably reflects risk preferences of the grower and/or beekeeper, since a written contract could be more easily enforced. It seems likely that written contract fees would be higher than oral agreement fees because beekeepers need to receive a risk premium when there is a higher possibility of contract enforcement of low delivered colony strength.

Almond growers can choose to contract directly with a beekeeper for their pollination needs, or they may contract through a pollination broker who performs the beekeeper coordination. Pollination brokers also absorb some of the risk otherwise borne by almond growers because they guarantee the grower delivery of strong colonies. The *Provider* variable determines the pollination provider(s) used by an almond grower in 2015. It can take on three values: Broker only, beekeeper only, both broker and beekeeper. Since the broker is taking on some of the grower's coordination and risk, I predict that contracting through a broker will lead to higher pollination fees paid.

The *AvgFC* variable specifies if a minimum average frame count was a requirement in the almond grower's largest pollination contract. This variable is binary and equals 1 when a minimum average frame count was specified and 0 when there was no minimum average frame count specified. As predicted by the theoretical model, a grower who specifies a minimum average frame count will likely pay more than one who doesn't.

The variable *Action* represents the actions specified in a grower's pollination contracts that he would have taken if a beekeeper provided colonies of low strength to one of his almond orchards. It is composed of six different actions that would have been taken alone or in combination with one another. Each of the following variables equals 1 if the action would have been taken, or 0 if not:

1. *Per-frame Penalty*: The grower would have penalized the beekeeper in the form of a per-frame deduction for the number of frames the beekeeper was below the stipulated minimum average frame count.

2. *Fixed Penalty*: The grower would have penalized the beekeeper in the form of a fixed or percent of the total amount paid to the beekeeper for pollination.

3. *Replace Hives*: The grower would have removed the beekeeper's hives and found another provider to replace them.

4. *Communicate*: The grower would have communicated with the beekeeper to bring more colonies to compensate for the low strength.

5. *No Future Contract*: The grower would have planned to not contract with that beekeeper in the future.

Per-frame Penalty, *Fixed Penalty*, and *Replace Hives* are penalties likely explicitly written into a pollination contract, or discussed with the beekeeper beforehand. Thus, I predict that growers whose contracts include these actions will pay higher pollination fees since there is an increased risk of enforcement for low delivered colony strength. *Communicate* and *No Future Contract* are likely implicitly understood in all almond pollination agreements, so I predict that there is no relationship between the use of these and pollination fees paid. If a relationship does exist, these would be associated with higher fees paid for the same reasons as the explicit provisions.

The *Inspection* variable describes the almond grower's decision to pay for colony strength inspections. The variable has three options: Inspect, inspect if low, and never inspect. A grower "inspects" if he pays for a colony strength inspection every pollination season. He "inspects if low" by paying for a colony strength inspection only in years when colony strength seems low, and a grower "never inspects" if he never pays for a colony strength inspection. Thus, inspecting every year or in years of seemingly low colony strength will lead to higher pollination fees paid as there is an increased risk of contract enforcement for the beekeeper when delivered colony strength is low.

$PFBonus$ represents a binary variable that equals 1 if the grower offers a contract that provides a per-frame bonus for colonies that exceed a benchmark colony strength, and equals 0 if the grower does not offer a contract of that type. This variable signals whether the grower was using an incentive contract or not. I hypothesize that the use of an incentive contract involve higher pollination fees paid due to the increased incentive for high strength colonies and guaranteed colony strength inspections.

Growers were asked if nine other specific clauses were included in any of their 2015 pollination agreements. The variable $TotalClauses$ represents the number of additional clauses that each grower selected. This variable likely provides insight into the complexity and formality of growers' agreements. Nearly half of the almond growers did not select any of the clauses, signaling there may be a difference between those who have these clauses versus those that do not. I predict that almond pollination fees will be higher as the number of additional clauses increases.

$HiveDen$ is a categorical variable that represents an almond grower's reported average number of hives/acre across all mature almond orchards. As discussed in Subsection 5.1.1, hive densities reported by growers were exogenous to pollination fees, and often reflected a rule of thumb of two hives per acre. Thus, the variable is segmented into three categories about the rule of thumb: Less than 1.6 hives/acre, 1.6-2 hives/acre, and above 2 hives/acre. I hypothesize that growers in the lower category will pay lower pollination fees, because they are less concerned with the number of bees per acre and likely contract using low or no colony strength requirements. Similarly, the growers in the high hive density category will pay higher pollination fees because they are more concerned with the number of bees per acre and likely contract with higher colony strength requirements.

The *Relationship* variable describes growers' longest contractual relationship with a beekeeper or pollination broker used in the 2015 pollination season. *Relationship* is 1 if the longest contractual relationship was less than three years, and 0 if it was more than three. Three was chosen as a cutoff because nearly 80 percent of the respondents had worked with one of their 2015 pollination providers for four or more years. Thus, any relationship three years or less seemed to be relatively new. I predict growers in the longer relationship category will pay more to their beekeepers to keep the relationship strong.

The variable $Beekeepers$ represents the total number of beekeepers that supplied colonies to growers' almond orchards in 2015. This variable is 1 if a grower was supplied by more than three beekeepers, and 0 if it was less than three. The number three was chosen, since most growers worked with one or two beekeepers. Using more than three beekeepers seemed to signal a different type of grower, perhaps a grower with more almond acreage. It seems likely that large growers would pay beekeepers more, as they are more likely to pay for colony strength inspections because they have more acres to oversee. This higher possibility of contract enforcement requires a higher payment for the beekeeper.

$Experience$ is the number of years the almond grower has been growing almonds. I predict that as experience increases, pollination fees paid will decrease as a result of increased knowledge of pollination agreement negotiations. $Yield$ is the average almond yield in pounds per acre over all of the grower's mature orchards. I predict that yield will increase pollination fees paid to beekeepers. Growers with higher yields may realize the importance of securing strong colonies and reliable beekeepers.

Almond pollination supply and demand influences for 2015 will be included in the constant. The only fee determinant from equation (27) omitted in this regression is the instrument for colony strength that each grower received in 2015. Since winter mortality rates are influenced by decisions made prior to almond pollination contracting decisions, this omitted variable is uncorrelated with the regressors and should not cause a problem in the regressions that follow.

The specification of this model is subject to identification issues, since contract stipulations are often determined simultaneously. The almond pollination fee could potentially be determined simultaneously with other contract stipulations, leading to an endogeneity problem. The models in Subsection 5.2.2 were ran excluding contract stipulations, and in doing so the signs of all other grower characteristic variables remained the same and only two (Provider: Beekeeper Only and $<$1.6 Hives/Acre) lost their significance. Thus, it seems likely that the models are robust to this potential endogeneity issue, but it should be explored further. In the discussion of results, I will only discuss correlations of fees with contract stipulations because of the potential identification problem.

5.2.2 Results

Model (1) in Table 2 below reports the results of the multivariate OLS regression of almond pollination fees reported by growers on the contract stipulation and grower characteristic variables. Many of the variables in this regression do not have coefficients statistically different from zero. Thus, Model (2) in Table 2 provides estimation with a subset of the contract stipulations that have a statistically significant relationship with pollination fees. The adjusted R^2 and F statistic are higher for the regression in Model (2), showing that it provides a better explanation of fee variation than that of the regression with all variables. This could be due in part to the increase in observations between the regressions which occurs because the use of fewer variables allows for more respondents that answered all questions.

Model (2) in Table 2 shows that the following contract stipulations have a statistically significant relationship with the almond pollination fee at the 10% level of significance: the pollination provider, the total number of clauses reported, offering a per-frame bonus, specifying a minimum average frame count, and specifying a fixed penalty for low delivered colony strength. A grower's average yield across all mature orchards, years of experience growing almonds, whether three or fewer beekeepers were used, and hive density category are grower characteristics that have an impact on the per-colony almond pollination fees he paid. A grower's form of agreement, frequency of paying for inspection, and the other actions specified as a result of low delivered colony strength did not have significant relationships

Table 2: Relationship Between 2015 Per-Colony Almond Pollination Fees and Almond Pollination Contract Stipulations

	Dependent variable:	
	Per-Colony Fee	
	(1)	(2)
Form: Oral	−0.48 (4.728)	
Form: Written and Oral	−0.29 (5.811)	
Provider: Broker Only	−3.68 (10.292)	−2.06 (8.526)
Provider: Beekeeper Only	8.75* (4.708)	7.78** (3.611)
Total Number Clauses	2.23** (0.932)	2.39*** (0.733)
Action: Communicate	4.02 (4.529)	
Action: Per-frame Penalty	−0.19 (5.468)	
Action: Fixed Penalty	6.62 (4.515)	6.75* (3.441)
Action: Replace Hives	−0.32 (7.302)	
Action: No Future Contract	2.42 (3.975)	
Bonus Offered	−10.53* (5.665)	−7.89* (4.371)
Inspect: If Low	2.20 (7.731)	
Inspect: Never	−2.78 (5.185)	
Experience	−0.58*** (0.150)	−0.56*** (0.113)
Yield	0.006 (0.004)	0.007** (0.003)
Avg Frame Count: Specified	11.99* (6.280)	11.53** (5.212)
<3 Years Contracting	−0.71 (6.378)	
<1.6 Hives/Acre	9.87 (6.534)	9.85** (4.570)
>2 Hives/Acre	14.36*** (4.238)	15.10*** (3.321)
>3 Beekeepers	10.42* (5.324)	10.28** (3.879)
Constant	137.64*** (14.407)	137.12*** (8.061)
Observations	56	61
R^2	0.656	0.616
Adjusted R^2	0.459	0.529
F Statistic	3.334*** (df = 20; 35)	7.138*** (df = 11; 49)

Note: (*s.e.*); *p<0.1; **p<0.05; ***p<0.01

with pollination fees.

Contract Stipulation Results Contracting through a beekeeper directly has a positive relationship with the almond pollination fee paid. This was opposite the sign of the predicted effect. There was no statistically significant relationship between fees and contracting through a pollination broker. This insignificance is likely due to the small portion of growers that responded that they contract through a broker only ($<3\%$).

The number of clauses reported was positively correlated with the grower's pollination fee paid. Thus, more issues discussed prior to almond pollination by the beekeeper/broker and grower were associated with higher pollination fees paid.

A grower offering a per-frame bonus for providing high strength colonies was associated with lower fees paid for pollination. This is opposite of the predicted relationship. This could have been a result of growers reporting the fee for the benchmark colony strength without the bonus included, or that the grower's largest contract involved low strength delivered colonies on average.

Growers whose contracts specified a minimum average frame count paid more per colony than those who did not specify a minimum average frame count. This is consistent with the findings of the theoretical model that fees should reflect higher colony strength stipulations. In the case where a grower does not specify a minimum average frame count, he is providing the beekeeper with a pricing schedule where the beekeeper is paid the same amount regardless of the colony strength outcome. By specifying a minimum average frame count, the grower provides the beekeeper with a schedule that pays the full per colony fee for certain only if the colony strength stipulation is met.

Specifying a fixed penalty for colonies delivered below the stipulated minimum average frame count was associated with higher pollination fees paid. This is consistent with the predicted relationship between this explicit contract provision and almond pollination fees.

From Table 2 it seems that the more stipulations a contract has, the higher the per colony pollination fee. This is displayed through the positive relationship between fees and the total number of clauses, average frame count specification and fixed monetary penalty action. The total number of clauses represents clauses in which only one relates directly to colony strength stipulations. So, even complications due to clauses unrelated to the delivered hive quality are associated with higher pollination fees.

Almond Grower Characteristic Results An increase in a year of experience decreases the pollination fee paid and an increase in average yield increase the pollination fee paid. Both align with predicted relationships. An almond grower who contracted with more than three beekeepers paid $10.28 per colony more than those with three or fewer beekeepers. This also aligns with the predicted relationship.

Almond growers who stocked their orchards with less than 1.6 hives/acre paid $9.85 more per colony than those who stocked 1.6-2 hives per acre. This is contrary to the relationship predicted previously. Growers in the highest hive density category paid $15.10 more per colony than those in the middle category. This is consistent with the predicted relationship. Thus, it can be concluded that growers in the high density category are likely more concerned about the number of bees per acre so they not only stock more hives/acre but pay more per hive as a risk premium.

6 Conclusion

Honey bee colony health issues have lead to volatile honey bee colony populations in recent years. This create riskiness for beekeepers in both honey production and in filling their pollination agreements, as well as growers trying to acquire healthy honey bee colonies for crop pollination. The large use of managed honey bee colonies in the U.S. for almond pollination, as well as the timing of almond bloom makes almond pollination markets extremely sensitive to the fluctuations and uncertainty in honey bee colony populations. Thus, it was important to explore this sector as a first step in determining impacts of colony uncertainty on U.S.

agriculture.

This paper theoretically modeled almond pollination decisions under uncertainty in the number of bees provided to a particular orchard. The moral hazard problem due to unobserved beekeeper effort can be alleviated by the almond grower basing the ending pollination fee on the number of bees provided to the orchard. This gives the beekeeper an incentive to invest effort to meet colony strength requirements.

Two empirical analyses were performed to determine influences on almond pollination fees. The CSBA data analysis of beekeeper reported fees showed that an individual beekeeper's winter mortality rate decreased the almond pollination fee collected by that beekeeper. Winter mortality rates were used as an instrument for colony strength provided for almond pollination, thus the analyses concluded that providing lower strength colonies for almond pollination result in lower fees collected by the beekeeper.

Similarly, the analysis using data from a almond pollination contract survey conducted at the ABC 2015 Almond Conference showed that growers with contracts specifying a minimum average frame count as a minimum threshold for colony strength paid more than those growers whose contracts did not specify one. Additionally, growers who specified that they would impose a monetary penalty for low delivered colony strength of the form of a fixed or percent of the total pollination expense paid higher pollination fees compared with those who did not specify this type of penalty.

The findings of the empirical analyses support the conclusion of the theoretical model. Many almond pollination agreements attempt to correct the moral hazard problem by imposing minimum colony strength standards that elicit optimal beekeeper effort. Almond growers who do not specify colony strength requirements often pay less per colony than growers who do, however they may receive lower strength colonies. Low strength colonies can potentially lead to lower yields, especially in years of sub-optimal weather for almond pollination. Additionally, there is an added risk to being lax in almond pollination contract stipulations in that it will be much harder to solve a dispute over low strength colonies that lead to yield decreases if a colony strength requirement was not outlined in the pollination contract.

The analysis of beekeeper survey data additionally highlighted factors influencing the supply and demand of honey bee colonies for almond pollination. Increases in bearing almond acreage increase the demand for colonies which in turn increases almond pollination fees. North Dakota per-colony honey production and U.S. average winter mortality rates were found to be interacting supply determinants. A higher honey crop in North Dakota likely increases the health of the large portion of U.S. colonies that spend summers there prior to almond pollination. Thus, this likely increases the supply of high strength colonies for almond pollination leading to more competition and decreased almond pollination fees. Since high winter mortality rates are negatively correlated with the average strength of colonies supplied to almond pollination, higher winter mortality rates likely lead to lower almond pollination fees.

This study opens the door for future research on the impact of volatility of U.S. honey bee colony populations on U.S. agriculture and honey production. Almond pollination only makes up a short time period in the commercial migratory beekeeping year, thus the total effect of the risk from colony health inhibitors on beekeeper livelihoods and U.S. agriculture is far reaching and complex. This area of research will only become more important in future years as countries all over the world implement policies to help their dwindling bee populations.

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