AN EMPIRICALLY- AND THEORETICALLY-BASED MODEL OF THE MARKET FOR POLLINATION SERVICES

A Thesis

by

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ABSTRACT

Motivated by increasing threats to pollinator health and the resultant impacts on pollination fees, this thesis models the market for pollination and honey production using the most complete economic model of the joint honey-pollination market developed to date. It incorporates realistic biological population dynamics, multiple crops that bloom both simultaneously and sequentially, and the transportation of bees across several states during the year. The model is used to investigate the market reaction to and economic impact of changes in winter and summer survival rates and number of hives demanded on almonds. The model is first tested using a scaled-down representation of the system, then calibrated using the best available data and personal communications with professional beekeepers.

The model predicts that an increase in the quantity of honey bee hives required on almonds causes a rise in pollination prices for early-blooming crops and a decline in prices for pollination of late-blooming crops and for honey. This corroborates hypotheses that increased demand for bees on almonds is pushing the extensive margin outward, driving pollination prices for that crop upward. When simulating changes in survival rates, the model generally predicts a rise in almond and late-season pollination fees and a fall in pollination fees for early-blooming crops other than almonds. Winter or summer colony survival rates less than 93% of the base scenario resulted in an inability of the model to reach equilibrium on a 30-year simulation, suggesting that low survival rates may cause a structural change in the market that goes beyond the scope of this model.

Finally, the model predicts that if, relative to the year 2012, 35% more bees per acre were needed on almonds to achieve the same level of pollination, this would result in a societal cost of around $100 million, borne almost entirely by crop growers. Additionally, a simulation of either winter or summer survival rates dropping to approximately 93% of 2012 levels predicts some benefit to beekeepers but an overall societal cost between $50 and $75 million.

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Y'all are the bees knees.

NOMENCLATURE

BIP	Bee Informed Partnership
CSBA	California State Beekeepers Association
IPEV	Insect Pollination Economic Value
PNW	Pacific Northwest
TVMP	Total Value of the Marginal Product
USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service

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1. INTRODUCTION

Each year, thousands of truckloads of honey bees are shipped throughout the United States to ensure pollination and subsequent production of a long list of fruits, vegetables, and nuts. Apiarists have existed for millennia, but this migratory practice arose due to a combined increase in demand for pollination and decrease in wild pollinators. This industry depends on beekeeper choices and the changing health of wild and managed pollinator populations, which impact the security of insect-pollinated crops. An economic model of the beekeeping industry has not yet fully explained recent market changes; nor is there full knowledge about how colony loss or increased pollination demand will impact prices or social costs.

1.1 Background on the U.S. Beekeeping Industry

Around three-quarters of the world's flowering plants depend on some form of animal pollination to reproduce (National Research Council 2007), including 35% of plant-based food (Klein, et al. 2007). However, modern agricultural areas are not conducive to wild pollinator abundance because of habitat fragmentation, low floral diversity, and pesticide use (Kearns, et al. 1998). About a century ago, plum growers began renting honey bee hives[1] to place in their fields, finding that it resulted in increased yields. By the 1980s, growers of over 50 crops were paying for honey bee pollination to increase production (Olmstead and Wooten 1987). This practice has

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[1] "Hive" refers to the home of a colony of bees, a wooden box in the case of managed honey bees. "Colony" refers to the population of insects that dwell inside the hive.

dramatically expanded in the last three decades, as the increase of monoculture acreage has been met by a decimated population of wild pollinators and feral[2] honey bees (Kearns, et al. 1998).

Although the honey bee, *Apis mellifera*, is neither native to the Americas nor the most efficient pollinator of all crops, it is used to pollinate many U.S. crops because of other attractive qualities (National Research Council 2007). The honey bee colony's perennial[3] nature allows for pollination of both early and late blooming crops (National Research Council 2007). Honey bees are eusocial insects that live in colonies and are therefore easy to transport. Also, by producing honey, the honey bee allows for an additional income source not provided by any other insect pollinator.

Today, large-scale commercial beekeepers in the U.S. manage anywhere from hundreds to tens of thousands of colonies, which are kept on pallets and moved by forklift onto trucks for nighttime transportation, when the bees are inside the hives. Beekeepers move their bees to different locations as the seasons change, following bloom times of cultivated and wild plants while often producing honey. In doing this there are tradeoffs between honey production and pollination services (Burgett, et al. 2010). Beekeeping requires inputs and labor in order to maintain and grow healthy populations, including feeding pollen and nectar substitutes in times of forage dearth,

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[2] Because *Apis mellifera* is not native to the U.S., any non-managed colonies are referred to as "feral." Here, the term "wild" will refer to non-managed pollinators, including the honey bee. The terms "commercial" and "managed" may be used interchangeably to refer to honey bee populations controlled by beekeepers.

[3] Unlike many bee species which regenerate population each year from eggs or a small population, the honey bee colony maintains a population in the tens of thousands throughout the winter National Research Council. 2007. *Status of Pollinators in North America*. Washington, DC: The National Academies Press..

treating for pests, pathogens and parasites, and dividing larger colonies into multiple smaller colonies to encourage population growth.

1.2 Motivation for Research

Honey bee populations naturally increase and decrease in a yearly cycle, with some colony deaths expected during the bloomless winter months. However, over the past decade beekeepers have reported mortality rates of around 30% compared to the historical rates of 15% (Sumner and Boriss 2006, vanEngelsdorp, et al. 2006-2015). In the past few years, summer mortality rates have increased as well, and have lately had an equal or even greater impact on total loss than winter mortality (Steinhauer, et al. 2016, Steinhauer, et al. 2015). These observations have sparked national concern about the security of insect-pollinated crops, which include almonds, apples, sweet cherries, avocados, canola seed, and many others. One of the expected culprits of increased losses is *Varroa destructor*, a parasitic mite that has become widespread throughout the country, and indeed the world, and can wipe out an entire colony if left untreated. Beekeepers and research also point to pesticide use on or near the sites where hives are placed as a problem for honey bee populations (Frazier, et al. 2015). These threats may be contributors to the general issue of sudden disappearances of bees from hives, termed Colony Collapse Disorder (Rucker, et al. 2012).

Native pollinators are also facing threats, and a number of species have been listed or proposed to be listed as endangered by the USFWS. Between 2008 and 2013, wild bees are thought to have declined 23% in the U.S., largely due to the conversion of natural habitat to row crops, including those that are pollinator-dependent (Koh, et al.

2016). Many pollinator-dependent crops, including almonds, blueberries, apples, cherries, pears, squash, and melons, experienced both an increase in acreage and a decline in the abundance of wild bees between 2008 and 2013 (Koh, et al. 2016). In addition, there is evidence that feral honey bee populations have declined and are at risk for further declines due to varroa mites and other pests and pathogens (National Research Council 2007).

Wild pollinator decline and increasing winter losses in managed honey bee populations have caused concerns over food security, leading to the establishment of a Pollinator Health Task Force through a 2014 Presidential Memorandum. This task force presented a strategy that cites pests and pathogens, habitat loss, and pesticide use as stressors to wild and managed pollinator health and establishes goals of reducing winter losses to 15% in the next 10 years and restoring 7 million acres of land to benefit pollinators in the next 5 years (Vilsack and McCarthy 2015).

Despite these concerns, the evidence of a national crisis in managed honey bee populations is not as strong as sometimes reported by the press. While the USDA Honey Report figures are commonly referenced as evidence that the number of managed colonies in the U.S. is declining (Daberkow, et al. 2009, Ward, et al. 2010), those surveys are not meant to be counts of the total number of honey bees in the nation. As Champetier de Ribes (2010) points out, the surveys count honey-producing colonies only, and each colony is counted in each state in which it produces honey, resulting in colonies potentially being counted two or more times. In addition, a change in methodology to exclude beekeepers with fewer than five hives likely accounts for the large drop between 1985 and 1986. The U.S. Census of Agriculture numbers, which are intended to represent the number of colonies in the nation, show that the number of colonies has increased since the late 1990s[4]. The results of both surveys are shown in Figure 1. The information available suggests that if managed honey bee populations have not declined over the past decades from the multiple factors discussed above, it may be due to beekeeper adaptations to higher colony loss rates. To make up for lost colonies, beekeepers can increase their number of colonies through what are called splits or divides. This involves dividing individual colonies into two or more units and placing new queens in the new colonies. Splitting comes at a cost and is possible only under certain environmental conditions – meaning adaptation may include selecting more hospitable locations for the hives, possibly at the cost of foregoing some pollination events. While a great deal of literature and policy is focused on possible population declines or even disappearance of honey bees in the U.S. (Gallai, et al. 2009, National Research Council 2007, Winfree, et al. 2011), there is less emphasis on the economic factors that may be driving population size.

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[4] See Champetier de Ribes, A. 2010. *The Bioeconomics of Pollination in Agriculture*: University of California, Davis. for a more complete description of the difference between the Honey Report and Census of Agriculture figures.

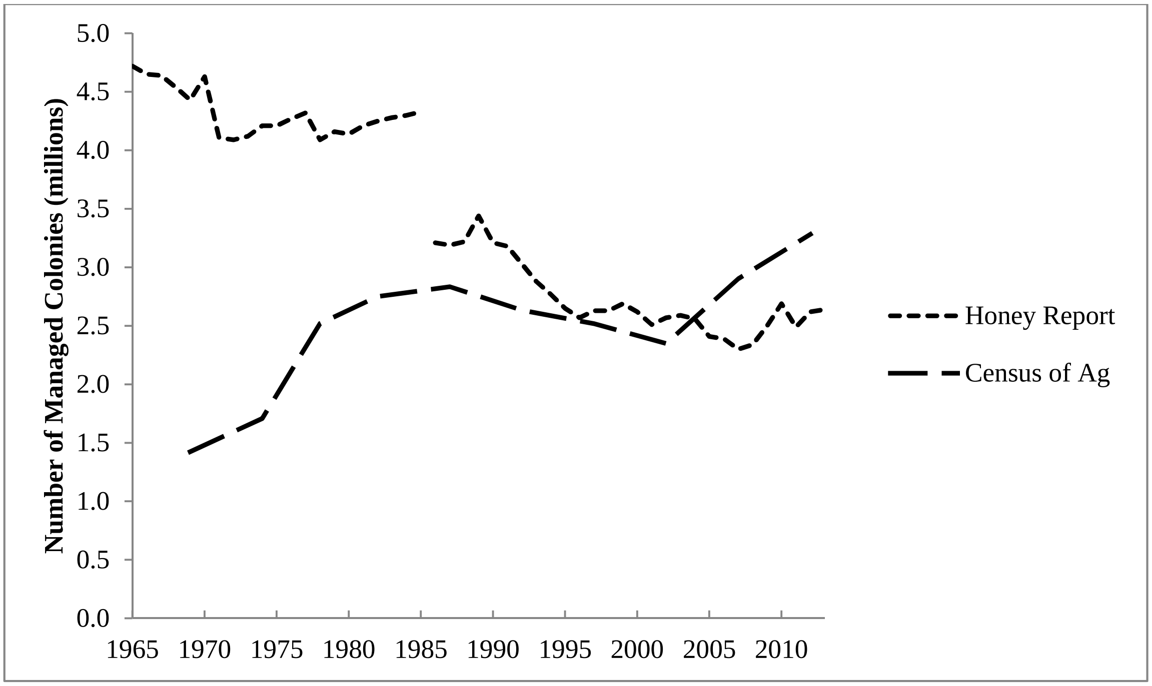

Figure 1: Number of managed honeybee colonies in the U.S. based on two different surveys

After 1985, only beekeepers with more than 5 hives are accounted for in Honey Reports
Data Sources: USDA NASS Honey Reports (U.S. Department of Agriculture 2016), NASS Census of Agriculture(U.S. Department of Agriculture 1969-1997).

A prominent feature of the pollination market in recent years is the skyrocketing of almond pollination fees since the early 2000s, while pollination fees for other major pollinator-dependent crops have shown slower, more gradual growth (Figure 2). One possible cause is the increase in almond-bearing acreage; 93% of the variation in almond prices can be explained through a regression on almond acreage and previous year almond pollination fees (Ward, et al. 2010). However, according to USDA crop data, blueberries have expanded in acreage more rapidly than almonds while maintaining relatively low pollination fees (U.S. Department of Agriculture 2016).

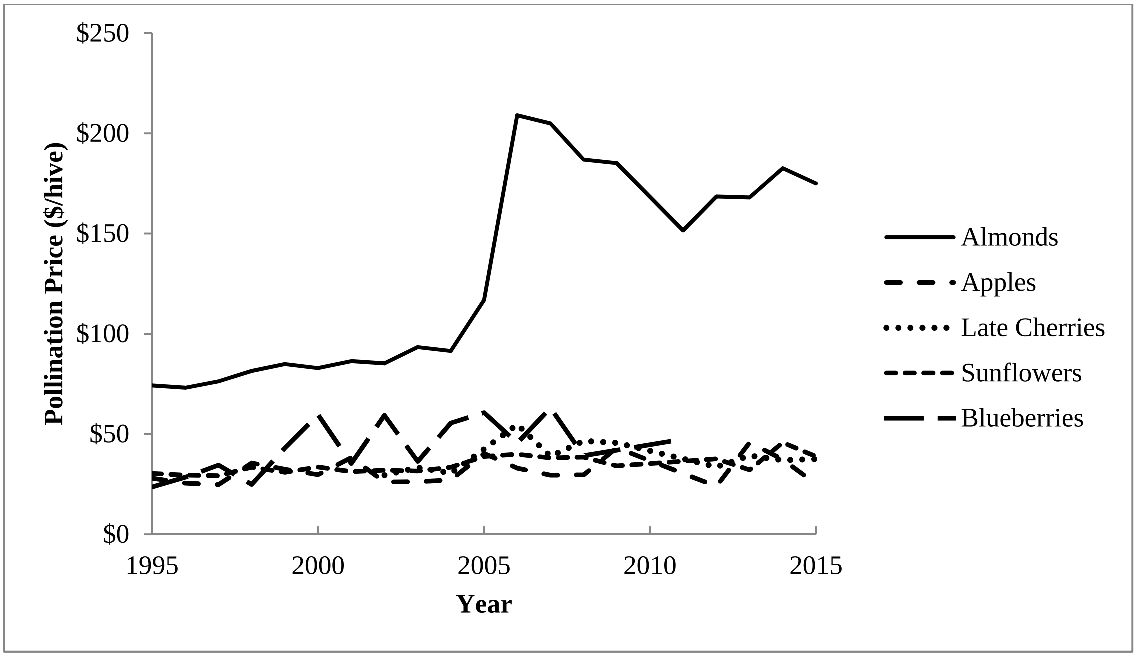

Figure 2: Real pollination fees per hive for a selection of crops (2015 dollars)
Data Sources: California State Beekeepers Association Pollination Survey (California State Beekeepers Association 2007-2015), Pacific Northwest Pollination Survey (Burgett 1992-2010, Dewey M. Caron 2011-2014). Prices are deflated using the Agricultural Services Price Index (found at www.nass.usda.gov).

Two other major pollinator-demanding crops, cherries and plums, bloom at the same time as almonds (Bond, et al. 2014). As shown in Figure 3, while the price increase has not been as dramatic as seen in almond pollination fees alone, average pollination prices for all early-blooming crops have diverged from the pollination fees required for crops throughout the rest of the season.

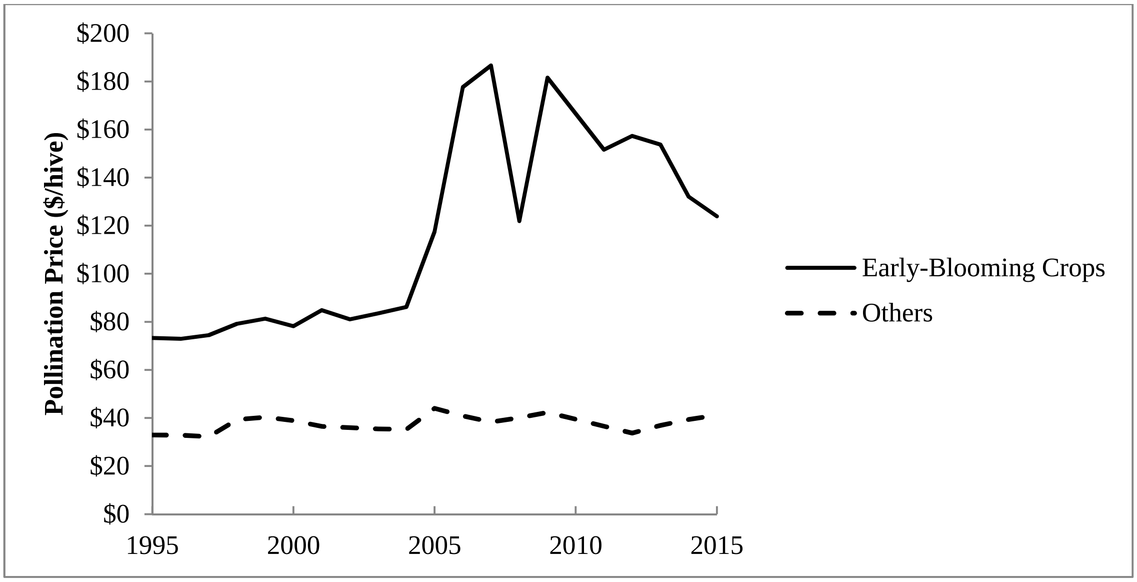

Figure 3: Real pollination fees per colony for early blooming crops (almonds, early cherries, and plums) relative to other crops (2015 dollars)
Data Sources: California State Beekeepers Association Pollination Survey (California State Beekeepers Association 2007-2015), Pacific Northwest Pollination Survey (Burgett 1992-2010, Dewey M. Caron 2011-2014). Prices are deflated using the Agricultural Services Price Index (found at www.nass.usda.gov)

This research is motivated by the existing incomplete understanding of the economics of commercial pollination and resultant pollination prices, as well as by the importance of these to production of a number of staple commercial crops. The research presented in this thesis examines theoretically and empirically how increased almond-bearing acreage would cause a divergence in the pollination prices between early and late-blooming crops. It also examines whether an increase in mortality rates would cause a pollination price divergence between almonds and other crops. A multiyear model with multiple seasonal periods and multiple locations is developed which represents competition between crops based on bloom time, particularly in the case of early blooming crops competing with almonds for pollination.

Almond acreage has been growing rapidly (Figure 4), and may continue to do so in the coming years. On the other hand, continued drought in California may result in a fall in almond acreage. Meanwhile, we may see yet greater winter and/or summer colony losses, or, possibly an increase in survival. Any of these changes may have an important impact on the market for pollination services and will be examined herein.

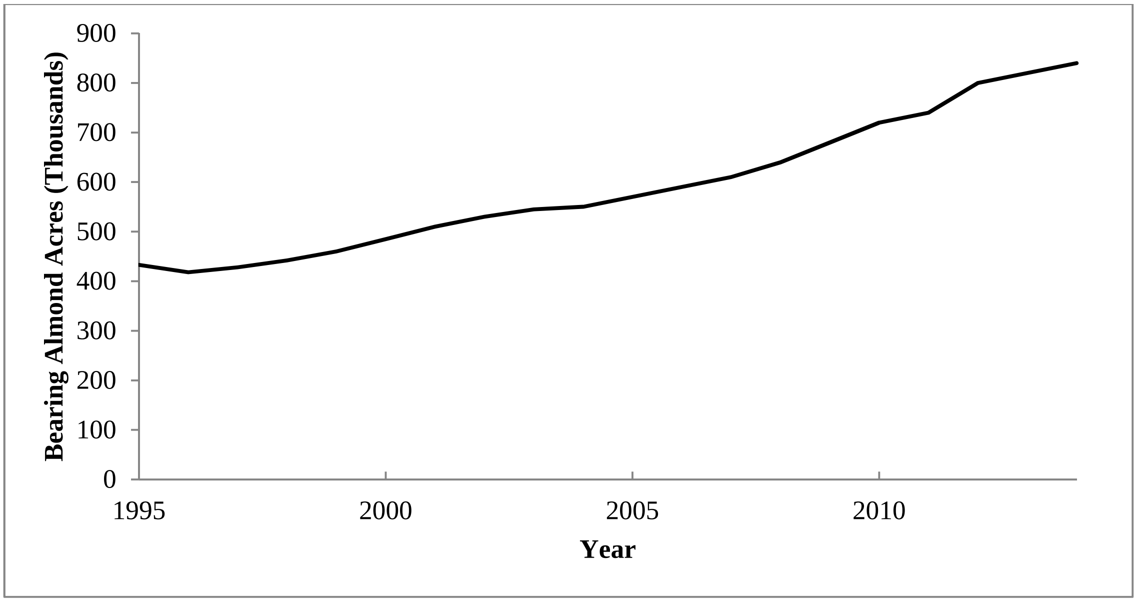

Figure 4: Increase in bearing almond acreage over the past two decades
Data Source: USDA NASS QuickStats Portal (U.S. Department of Agriculture 2016)

This thesis examines the economic impact of, and market reaction to, changes in factors that impact wild and managed pollinator health and populations and is organized as follows. First, the existing literature on valuation of pollination services and previous models of the pollination market are described. This is followed by an explanation of current gaps and how this thesis seeks to fill those gaps. Next, the conceptual model and the data used to calibrate the model are explained. This is followed by the results from the conceptual model, the results and sensitivity analysis of the calibrated model, and an analysis of several possible scenarios using the calibrated model. Finally, assumptions, limitations, and the implications of the work for the future of pollination are discussed.

2. REVIEW OF THE LITERATURE

The main issues addressed in the economic literature on pollination and pollinators are valuation, structure of the market, pollination prices (with a focus on almonds), and health threats to honey bees.

2.1 Studies Valuing Pollination Services

Meade (1952) characterized beekeeping and apple-growing as activities that each produce positive externalities for the other, perhaps sparking the concept of valuation of honey bees through his proposal of a government subsidy. Various methods have been employed for estimating the value of the ecosystem service provided by insect pollinators to agriculture, or the value of agriculture attributed to insect pollinators. One approach, called Insect Pollination Economic Value (IPEV) (O'Grady 1987) involves multiplying a dependence ratio, defined as the fraction of production of a specific crop attributed to the presence of insect pollinators, by the production value of the crop, defined as price times quantity of that crop. Slight variations of this method have been used to estimate the value of native bees in the U.S. to be \$3.07 billion (in 2003 dollars) (Losey and Vaughan 2006) and the value of U.S. honey bees to be \$15.1 billion (in 2009 dollars) (Calderone 2012).

The IPEV model has received criticism from economists. Melathopoulos (2015) challenges the assumption that pollination dependencies are static, and points out that dependence ratios are not reliable numbers. More troubling, any reaction to pollinator decline by consumers and farmers, and resulting price and quantity changes, are unaccounted for in the IPEV model (Allsopp, et al. 2008, Melathopoulos, et al. 2015, Winfree, et al. 2011).

An accounting of producers' and consumers' surplus change improves upon the IPEV method. Southwick and Southwick (1992) account for the loss in consumers' surplus due to production declines in pollinator-dependent crops. They calculate change in consumers' surplus resulting from a shifted supply function based on independently-estimated demand functions for over 50 insect-pollinated crops, finding a range of $1.6 to $5.7 billion to be the total annual gains from honey bees in the U.S. Others present theoretical models incorporating changes in both producers' and consumers' surplus (Hein 2009, Kevan and Phillips 2001). Gallai et al. (2009) estimate worldwide consumers' surplus loss at varying levels of elasticity of demand for food products, and present €153 billion as the total economic value of pollination worldwide. Winfree et al. (2011) incorporate the ability of farmers to adjust variable costs in response to a change in expected yield by subtracting a fall in variable costs from the value of pollination services and evaluate this empirically for watermelon growers.

2.2 Studies of the Beekeeping Industry

Despite the fact that beekeepers take measures to increase their honey bee populations (Burgett, et al. 2010), none of the aforementioned valuation studies closely consider the beekeeping industry and its economic drivers. Beekeeper actions may combat pollinator decline (at a cost), even as winter losses intensify and native populations shrink.

Meade (1952) was the first economist to rigorously consider beekeeping as an economic enterprise, discussing growers and beekeepers as joint producers of fruit and honey with mutual externalities. Later works argue that an efficient market between growers and beekeepers results in an internalization of those benefits (Champetier, et al. 2014, Cheung 1973, Johnson 1973, Muth, et al. 2003, Rucker, et al. 2012). Today pollination fees are an important aspect of the market forces interacting with honey bee populations.

Rucker, et al. (2012) characterize bee-generated revenue as pollination fees and honey revenue, where the total value of the marginal product (TVMP) of bees is comprised of their marginal contributions to honey production (retained by the beekeeper) and fruit production (retained by the farmer). This enables the differentiation between crops such as cherries that allow for production of honey, or crops, like the almond, that do not allow for extraction of salable honey[5]. The value of the marginal product (VMP) for honey is the difference between the TVMP and the VMP for fruit. Hence, when salable honey cannot be produced on a crop, the VMP for fruit is equal to the price that farmers would be willing to pay for pollination services. This implies a higher pollination price if honey cannot be produced, which Rucker, et al. (2012) empirically confirm.

In addition to the impact on pollination fees of a crop's ability to enable honey production, prices of honey are thought to influence the pollination market in various

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[5] On some crops, including almonds, the honey produced is bitter and does not have commercial value.

ways. Rucker et al. (2012) demonstrate that theoretically, the price of honey has an ambiguous effect on pollination fees. An upturn in honey prices increases the value of honey production to beekeepers, thereby reducing the required pollination fee. However, this effect may be overpowered by the attraction away from crop pollination and towards honey production alone, which is in line with their empirical finding that honey price is positively correlated with pollination prices (Rucker, et al. 2012).

Two other recent and important contributions to this literature are Champetier de Ribes (2010) and Champetier, Sumner, and Wilen (2014), which incorporate within-year and between-year population dynamics by creating a dynamic model that reflects honey bee population changes throughout a theoretical honey-producing, or active, period and a winter period. This allows for the honey-producing period and the winter period to be treated differently in terms of beekeeper decision-making. In considering bee population changes, Champetier et al. (2014) recognize that the available forage[6] on a chosen site is an important input to the stock of bees and to the production of honey. Champetier (2010) predicts that the increase in demand for commercial pollination on almonds can explain an increase in fees for other crops that bloom during a similar time period. They also hypothesize that an increase in honey price would put downward pressure on commercial bee populations, due to the negative effect of honey extraction on colony size.

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

Several studies have addressed the recent sharp rise in almond pollination fees apart from other pollination fees. Ward et al. (2010) suggest that because almond pollination is early in the year, beekeepers have not had time to recoup winter losses, resulting in a leftward-shifted supply function for that time of year compared to other months. Because the over 800,000 acres of almonds in the U.S. (NASS 2015) require so many colonies for pollination services, colonies may remain “unemployed” for the remainder of the year (Sumner and Boriss 2006), causing prices for honey and pollination of other crops to fall with respect to prices for almond pollination.

Other studies have analyzed how pollination markets have been affected by threats to honey bee populations that may reduce numbers of colonies, increase beekeeping costs, or both. Champetier (2010) finds that colony losses due to varroa mites and other pests impact pollination fees for early-blooming crops, also contributing to the explanation of high pollination fees in almonds. Rucker, et al. (2012) empirically find that a post-2004 Colony Collapse Disorder dummy variable has a significant impact on almond pollination fees. However, Rucker, Thurman, and Burgett (2015) find a post-2006 dummy variable does not significantly impact population, honey production, or almond fees.

2.3 Gaps in the Literature

The literature on pollinator valuation has not deeply considered the pollination market structure and its functioning. The literature on the economics of beekeeping has not yet incorporated the case of “multiple crops blooming simultaneously and sequentially,” as put by Champetier de Ribes (2010), or transportation costs. In addition, there has not been an empirical calibration of a dynamic model of the beekeeping industry. This thesis contributes to the study of pollination markets by addressing these gaps through a conceptual and calibrated model.

First, the literature has not explored the case of multiple sequentially and simultaneously blooming crops. The competition between simultaneous blooms is important because it logically contributes to the observed spike in pollination fees for crops that bloom at the same time as almonds. The model presented here incorporates a number of crops, each blooming at a specific place and time, that may be overlapping or sequential.

Secondly, the literature has not incorporated the cost of moving bees around the country. Transportation costs are an important inclusion because the fraction of U.S. colonies required for California almond pollination has increased from 15% in the late 1970s to 60% in 2012 (Rucker, et al. 2012). This means beekeepers far from California consider the tradeoffs between transportation costs and pollination fees. This model incorporates transportation costs by including a fixed cost per mile on the average driving distance between each pollination site.

Finally, this work presents the first empirical calibration of a model that accounts for the annual movements and population changes of colonies during each yearly cycle. This calibration incorporates the main pollination events occurring in the western portion of the U.S., including pollination events in California, Oregon, and Washington as well as honey sites in Montana and the Dakotas. The data used for the calibration of a year 2012 pollination market comes from the USDA, NASA, the economics literature, several non-profit and extension organizations, and personal communication with beekeepers and industry experts. This calibration allows for prediction of how prices will respond to the future changes in demand or colony loss discussed above, and gives an indication of how the surplus would be impacted by those changes.

3. METHODOLOGY

The model used in this analysis builds on previously developed models of pollination markets. The model includes jointness in production generating pollination fees and building honey stocks (Rucker, et al. 2012). It also depicts successive seasonal blooms (Champetier, et al. 2014). In turn it represents profit-maximizing behavior of beekeepers who transport bee hives to various crop and forage sites throughout the year. Following Champetier's (2010) assertion that "the most crucial decision of the beekeeper is the schedule of migration of hives and their allocation among different crops," this model focuses on seasonal hive location and abundance and the incentives for and effects of alternative choices.

Key features of the model are the incorporation of bloom times to represent competition between crops that bloom simultaneously, population dynamics between and throughout time periods, and transportation costs. In the model, hives are transported and acted upon as shown in Figure 5 during K bloom periods, k=1,…, K, which cycle through for Y years, y=1,…Y. The division of the year allows representation of competition for bees between crops that bloom at the same time, and the possibility of synergistic relationships between crops that bloom at different times. In the model, crops and pollination demands are distinguished by their location, since features of a crop in California, for example, may be different from features of that same crop in Washington, in terms of bloom time and suitability to population growth or honey production. The division of the year into many bloom periods also allows for transportation of hives to any included location for rest outside of pollination times, subject to particular population change and honey-production parameters.

The model maximizes welfare subject to a number of constraints. In addition to the constraints described in detail below, all movement, management activities, and sales are subject to non-negativity constraints. Table 1 contains descriptions of all parameters and variables used in the model.

Table 1: Model Indices, Variables, and Parameters

	Indexes
i	Location index, representing starting location in a time period prior to shipment
j	Location index, representing end location where the hive remains for a time period
k	Time period during year
K	Terminal time period within a single year
y	Year
Y	Terminal year
	Objective Function
W	Welfare (objective to be maximized)
	Variables
α_i	Number of hives starting in location *i* at $k = 1$, $y = 1$
$A_{i,k,y}$	Number of hives in location *i* at the beginning of period *k*, prior to that period's shipment, when $k > 1$ or $y > 1$
$B_{j,k,y}$	Number of hives in location *j* during period *k*
$T_{i,j,k,y}$	Number of hives shipped from location *i* to location *j* during period *k*
$N_{j,k,y}$	Number of hives added through splits
S_y	Quantity of honey sold in year *y*
$C^M_{k,y}$	Total feeding and splitting cost in period *k*, year *y*
	Parameters
γ_k	Cost of feeding and maintaining a colony for one period k
$\beta_{j,k}$	Number of colonies demanded for pollination at a given place *j* and time *k*
$H_{k,j}$	Excess honey production per colony in location *j* during period *k*
$D_{i,j}$	Cost of shipping from location *i* to location *j*
$L_{i,j}$	Fraction of the colony population lost in transit from location *i* to location *j*.
$V_{k,j}$	Percentage change in colony population expected in location *j* at time period *k*
ε	Price flexibility of demand for honey $\%\Delta Price \div \%\Delta Quantity$
η	Honey demand function multiplicative parameter
λ	Cost of extracting and processing a pound of honey for sale
ρ	Cost of initiating a hive
σ	Cost of splitting one hive
r	Discount rate

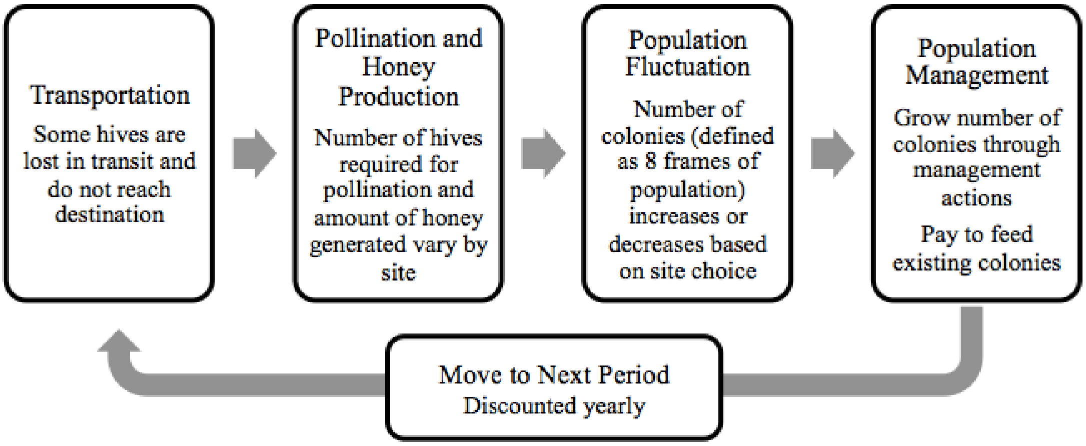

Figure 5: Model treatment of colonies in each time period

3.1 Model Constraints

Transportation

The model incorporates transportation and its associated costs. Shipping between locations i and j, occurs at the beginning of each time period k, and the resultant number of hives in end location j is denoted $B_{j,k,y}$. The first constraint in the model,

$$\sum_j T_{i,j,k,y} = A_{i,k,y} \forall i,k,y, \tag{1}$$

ensures that during each time period, the sum of all hives that are shipped from i to all other points is equal to the number of hives that start out in location i, where $A_{y,k,i}$ represents the starting set of hives (denoted α_i where $k = 1$ and $y = 1$ and chosen by the model in that first period) and $T_{i,j,k,y}$ represents the number of hives shipped from i to j.

This implies that every hive must be shipped in every period; one option is to ship to the current location for zero cost.

Hauling costs are incorporated as a linear function of the distance between *i* and *j*. Cost of hauling bees, both in practice and as reflected in the model, affects pollination fees because beekeepers incur extra costs when driving across the country to meet pollination demand (Champetier de Ribes 2010). For example, in a study over pollination prices between 1987 and 2009, a 10% increase in the price of diesel fuel was predicted to lead to a nearly $8 increase in almond fees (Rucker, et al. 2012). Transport costs are expressed as $\sum_i \sum_j D_{i,j} T_{i,j}$, where $D_{i,j}$ is the cost of transporting from location *i* to location *j*, computed based on distance, and $T_{i,j}$ represents the number of hives transported from *i* to *j*.

Transportation impacts bee populations as well. A fraction of the hives, $L_{i,j}$, is lost due to the stresses of transit before generating revenue for that period. The assumption that hives are lost during shipment is consistent with conversations with commercial beekeepers, who reported that approximately 5-10% of hives are typically lost, depending on the distance travelled. Thus, the second constraint set,

$$\sum_i \left(1 - L_{i,j}\right) T_{i,j,k,y} = B_{j,k,y} \forall j,k,y, \tag{2}$$

ensures that for each time period *k*, the number of hives that arrive in location *j* are equal to the sum of the hives that are destined for *j,* after losses are incorporated.

Pollination Supply and Honey Production

During each time period, revenues are earned from pollination and honey production, depending on the time of year and location of the hive. We assume that pollination demand is perfectly inelastic. Hence, the number of hives allocated by the model to each location is at least equal to the quantity demanded for pollination,

$$B_{j,k,y} \geq \beta_{j,k}. \tag{3}$$

This will be described in more detail in a later section on the demand functions used in the model.

The model assumes that a fixed amount of extractable honey is produced at each site in each time period, rather than incorporating a tradeoff between honey extraction and bee population. Honey is extracted at a fixed cost, λ. A set of constraints for honey sales,

$$S_y = \sum_k \sum_j H_{j,k} B_{j,k,y} \forall y, \tag{4}$$

restricts the amount of honey, S_y, sold in year y to be equal to the amount of excess honey produced in that year. The amount of revenue generated from honey is subject to a demand function that will be described in more detail in a later section.

Population Dynamics and Colony Management

In this model, honey bee populations grow and shrink in a simplified version of the continuous growth concept presented in Champetier, Sumner and Wilen (2014). In consideration of colony population changes, a colony is defined as eight frames in a hive that are occupied by bee brood and adults, the standard unit used for almond pollination contracts. Bee population fluctuates as a percent change during each time period depending on what type of crop or forage the hives are placed on; this change can be manipulated to an extent by management activities.

Population changes take effect at the end of the time period, implying new hives do not generate honey or pollination revenue until the following period. The assumption that population drops immediately at the end of the time period is appropriate for pollination fee revenue, because beekeepers are paid based on the colonies that arrive at the beginning of the pollination period. It is not quite as appropriate for honey production, because population changes during the time period will impact the amount of honey produced. This becomes less important as the year is divided up into a greater number of discrete time periods (K increases). Increases in population due to division of hives take effect after natural population variation, implying new hives are not subject to natural growth or loss until the following period. Again, this is an approximation that becomes less important as K increases.

Bee populations increase or decrease during each period depending on environmental factors specific to that time of year and location. The population afterwards is expressed as a proportion, $V_{k,j}$, of the beginning-of-period population. If conditions are favorable, then $V_{k,j}>1$ reflects a growing population. If conditions are unfavorable, then $V_{k,j}<1$, meaning the population shrinks.

When the timing and location allow for growing population, beekeepers are able to increase their number of hives by dividing the hives (hereafter called a split). The number of splits made is $N_{j,k,y}$, and these are made at fixed cost of σ per split. The number of splits is limited by natural population growth:

$$N_{y,k,j} \leq B_{y,k,j}\left(V_{k,j} - 1\right) \text{ where } V_{k,j} > 1. \tag{5}$$

Splits are only allowed when $V_{k,j}$ exceeds 1. . The only mitigations for population loss are splitting in later periods or choosing to move hives to locations with more favorable conditions for bee populations.

The number of hives that are present in a location prior to movement, $A_{y,k,i}$, is determined through the population dynamics constraint,

$$A_{y,k,i} = \begin{cases} \alpha_i \forall i, k=1, y=1 \\ V_{k-1,j} B_{y,k-1,j}, k>1, V_{k-1,j} \leq 1 \\ B_{y,k-1,j} + N_{y,k-1,j}, k>1, V_{k-1,j} > 1 \\ V_{K,j} B_{y-1,K,j}, k=1, y>1, V_{K,j} \leq 1 \\ B_{y-1,K,j} + N_{y-1,K,j}, k=1, y>1, V_{K,j} > 1 \end{cases}, \tag{6}$$

which describes the translation of hives from one period to the next, and where the parameters depend on time period and location. The number of hives in a location at the end of period $k - 1$ is adjusted for population changes to reflect the number of hives in that location at the beginning of time period k. To describe the translation of hives from one year to the next, the number of hives in the final time period, K, of year $y - 1$, is adjusted for population changes and equated to the number of hives in the first time period ($k=1$) of year y. Sales of hives amongst beekeepers are assumed to take place within the model as a closed system and are not explicitly reflected in the model. As will be discussed below, the number of hives starting out in each location, α_i, are determined through optimization.

Regardless of natural population change, beekeepers must maintain their hives and this has a cost. Total management costs in a given time period, $C^M_{k,y}$, incorporate both splitting costs and other costs including feeding and medicating the colonies, labor costs, and other maintenance costs:

$$C^M_{k,y} = \sum_j \sigma N_{j,k,y} + \sum_j \gamma_k B_{j,k,y}, \tag{7}$$

where the variable cost of beekeeping is denoted γ_k,. The necessary beekeeping activities differ by time period, and these management costs reflect that variation.

3.2 Surplus Maximization

Equilibrium prices and quantities can be simulated by maximizing consumers' plus producers' surplus less transportation costs (McCarl and Spreen 1980). A "quasi-welfare function" for each region and time period can be defined as the area between the inverse supply and inverse demand curves, developed and discussed in equations 12-22 of McCarl and Spreen's discussion of exogenously determined prices in a competitive market (McCarl and Spreen 1980). This approach is followed, but incorporates specific adaptations to reflect the nature of the beekeeping industry.

Following Rucker et al. (2012), demand for pollination is assumed to be perfectly inelastic in the relevant price range. Rucker et al. (2012) argue this inelastic relation fits best based on through two features of the industry. First, the share of total cost of production represented by pollination fees is small for most crops; it is less than 5% in all California crops except almonds, alfalfa seeds, and sunflowers, and for those three it is around 10% (Champetier de Ribes 2010). Secondly, growers do not have perfect knowledge about the marginal product of bees in contributing to fruit production; instead they act according to recommended stocking densities (Rucker, et al. 2012). Thus, in the model each acre of each crop type is assumed to demand a fixed quantity of hives for pollination services. Crop acreage is exogenously determined. Because the sum of the surplus plus revenue in the pollination market is constant in the case of this perfectly inelastic demand function, minimization of costs maximizes total welfare for pollination, and the area under the pollination demand function is ignored.

The demand for honey is assumed to be downward sloping. There is one demand for honey throughout the year, and honey collected in all time periods and locations throughout that year is treated as perfectly substitutable as done in Champetier et al. (2014). This model assumes that the demand function for honey is of constant elasticity form:

$$P_y^H = \eta S_y^\varepsilon, \tag{8}$$

where P_y^H is the equilibrium price of honey for year y.

The resultant annual surplus as expressed in the model is composed of several parts: the consumer surplus in the honey market, $\frac{\eta}{\varepsilon+1} S_y^{(\varepsilon+1)}$ (the integral of equation (8)), less the cost of extracting honey, λS_y, managing hives, $\sum_k \sum_j \left(\sigma N_{j,k,y} + \gamma_k B_{j,k,y} \right)$, and transportation costs, $\sum_i \sum_j D_{i,j} T_{i,j}$. Summing across all years, and discounting by *r* results in the welfare function:

$$W = \sum_y \left(\frac{\eta}{\varepsilon+1} S_y^{(\varepsilon+1)} - \lambda S_y - \sum_j \sum_k \left(+\sigma N_{j,k,y} + \gamma_k B_{j,k,y} \right) - \sum_i \sum_j \sum_k D_{i,j} T_{i,j,k,y} \right) \left(\frac{1}{1+r} \right)^{y-1} . \quad (9)$$

The first and final years of the numerical simulation model are distinct to allow the model to find a long-run equilibrium. During the first year, an initial cost of ρ per hive created (α) is deducted from the objective function. This represents the cost of buying or starting a hive. So that the model does not behave as if all beekeeping ends in the final period, the net benefit for the final year is multiplied by $\frac{1}{r}$ so that it is treated as an infinite annuity, i.e. repeating indefinitely. Because the model is in equilibrium, any year's results within the equilibrium may be presented. When undiscounted, any year within the equilibrium period produces the same results. Finally, all movement, management activities, and sales are subject to non-negativity constraints.

3.3 Optimization

The General Algebraic Modeling System (Gams Development Corporation 2016), or GAMS, is used to solve the model[7]. The shadow prices returned by GAMS for the quantity demanded constraints (3) constitute equilibrium prices paid for pollination services, and the shadow prices from the honey sales constraints (4) are the equilibrium

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[7] A copy of the GAMS code used may be obtained by request from Kendra Williamson (Kendra.m.williamson@gmail.com) or Richard Woodward (R-woodward@tamu.edu).

prices paid for honey. They are transformed to current values by dividing by the discount factor.

The shadow prices returned reflect the marginal cost to the objective function of a tightening of the constraints. In the case of pollination, a tightening of constraint (3) represents an increase in the number of hives required for pollination of a crop in location j, and therefore the shadow price represents the marginal cost of sending an additional hive to location j for pollination. Since beekeepers must be compensated for that cost, the shadow price is the lowest price that would be sufficient to induce that change in supply. Likewise, a change in the honey production constraint (4) might cause more or less honey to be put into the market, and the shadow price represents the marginal change in the objective function due to that change. In the case of honey production, this can be validated by substituting the equilibrium quantity of honey back into the inverse honey demand function (8) to demonstrate that this is equal to the shadow price returned by the model. A variety of data sources were used to calibrate the model, focusing on beekeepers who travel throughout the western half of the country.

4. DESCRIPTION OF DATA

The data used to calibrate the model for the year 2012 was collected from a variety of sources, including the economic literature, the USDA National Agricultural Statistics Service (NASS), USDA publications, HoneyBeeNet (a NASA site), the Bee Informed Partnership, and personal communication with beekeepers, growers, and industry experts. Prices from the California State Beekeepers Association (CSBA) and Pacific Northwest (PNW) Pollination Survey were used to verify model calibration. Pollination sites only in the western region of the country are included due to the availability of pollination price data in those locations.

In order to balance precision and model simplicity, major honey bee pollination crops were selected based on a number of criteria: 1) The fraction of total pollination revenue attributed to that crop (Bond, et al. 2014), 2) the level of the crop's dependency on honey bee pollination, according to the Beekeeper's Handbook (Sammataro and Avitabile 2011), 3) the number of reported colony rentals according to the California State Beekeepers Association Pollination Survey, Pacific Northwest Pollination Survey, and Morse and Calderone (2000), and 4) the availability of pollination price data from the CSBA and PNW surveys. The 15 selected distinct crop locations are listed in Table 2, and the timing for the bloom of these crops is shown in Figure 6.

4.1 Site-Specific Parameters

Quantity of Colonies Demanded

The number of honey bee colonies demanded during bloom for a given crop was estimated as the crop acreage multiplied by the required density of colonies on that crop, shown in Table 2. Each crop is assumed to be uniform and centralized around a single point. The exception to this method is in the separation of sweet cherries into three groups: Washington cherries, California early cherries, and California late cherries. The first cherries on the market each year elicit a higher sales price, so some cherries are treated with a chemical called Dormex to incite early bloom. In the CSBA survey, cherries treated with Dormex are classified as "early cherries" and tend to have higher pollination fees because their pollination period coincides with almond pollination (T. Bunch, personal communication, February 26, 2016). The remaining cherries are classified as "late cherries." Due to possibility of frost further north, it is likely that only California cherry growers participate in this practice (E. Topitzhofer, personal communication, March 2, 2016). Because the USDA does not separate "early cherries" and "late cherries," a fraction of the cherry acreage located in California was assigned to each category based on the CSBA sampling. In 2012, the CSBA survey responses included 2,250 late cherry rentals and 340 early cherry rentals, so it was assumed that this ratio of 13.1% of cherries being "early cherries" was representative of cherry acreage statewide. Therefore, 13.1% of 32,786 acres of cherries in California were classified as "early" with pollinator demand in March, and the remainder were classified as "late" with pollinator demand in April. Washington cherries were treated as a separate crop with the same bloom time as California “late” cherries. The separation of cherries into “California early”, “California late”, and “Washington late” and resulted in a total of 17 distinct crops in the model.

Table 2: Acres and Colonies Required for Selected Crops

	Acreage in U.S.	**Acreage in CA, ID, OR, and WA**	**Percent of U.S. Acreage Located in States Modeled**	**Colonies Required Per Acre**	**Colonies Demanded for Pollination**
Almonds	817,934	817,920	100%	2.08	1,701,274
Apples	336,940	179,542	53%	1.34	240,586
Avocados	64,408	52,026	81%	1.58	82,201
Blueberries	81,942	20,457	25%	2.07	42,346
Cherries (Early)	91,875 (all U.S. cherries)	~4,303	5%	1.54	6,627
Cherries (Late, CA)		~28,491	31%	1.54	43,876
Cherries (Late, WA)		48,731	53%	1.54	75,045
Cranberries	40,117	4,493	11%	1.54	6,919
Cucumbers	111,898	9,748	9%	0.98	9,553
Kiwifruit	3,746	3,739	100%	2.5	9,348
Cantaloupe and Honeydew Melons	82,653	46,681	56%	1.8	84,026
Watermelon	127,472	14,788	12%	1.8	26,618
Pears	51,454	46,024	89%	1.4	64,434
Plums	19,181	19,177	100%	1.3	24,930
Prunes	54,186	54,186	100%	1.3	70,442
Squash	56,993	11,894	21%	0.86	10,229
Vegetable seeds	58,708	55,969	95%	1.6	89,550
Total	**1,999,507**	**1,418,161**	**71%**		**2,592,068**

Data Sources: Rucker, et al. (2012), Burgett, et al. (2010),Phillips (2014), USDA NASS

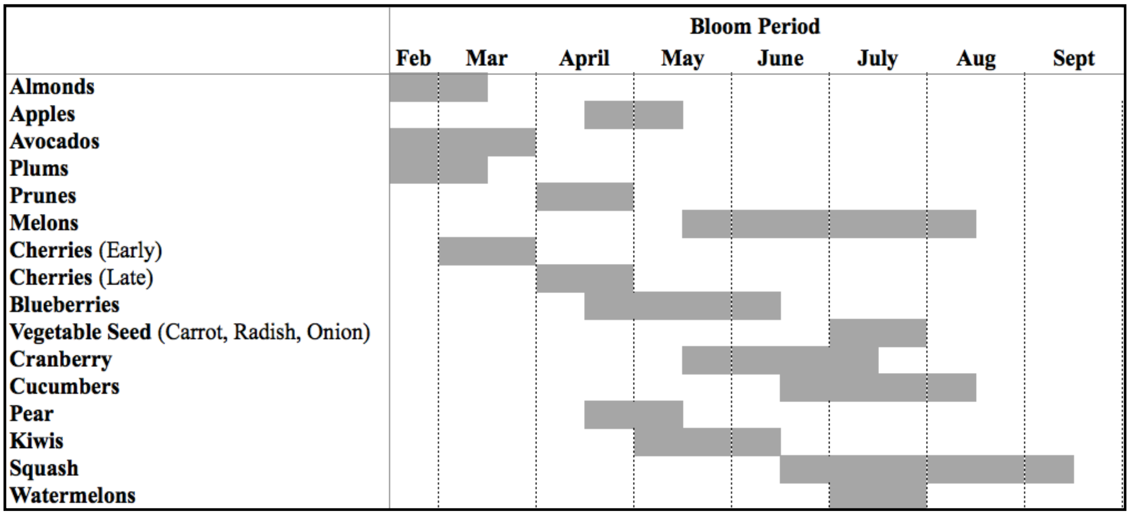

Figure 6: Bloom timing starting at beginning of pollination season
Data Sources: Sumner and Boriss (2006), Morse and Calderone (2000), Nickeson and Esaias (2015), M.Mahoney (personal communication), C. Moore (personal communication), T. Martin (personal communication)

Locations

Locations of each crop were needed to calculate colony transportation costs and population losses during shipping, both of which are dependent on driving distances between locations. The locations for each crop shown in Figure 7 were derived using USDA county-level acreage for each crop. The coordinates of the county seat were used as the reference point for each county, and an "average acre" of each crop was calculated as a weighted average of the county seat coordinates and the acreage grown. Acreage in California, Idaho, Oregon, and Washington was used to determine the locations, because 1) a high percentage of acreage of major pollinator-dependent crops lies within those states, and 2) the CSBA and PNW surveys collect price data from those states. Because the weighted average coordinate may not be accessible by road (and therefore driving distance cannot be calculated), the county seat closest to the central coordinate was used as the central point for each crop.

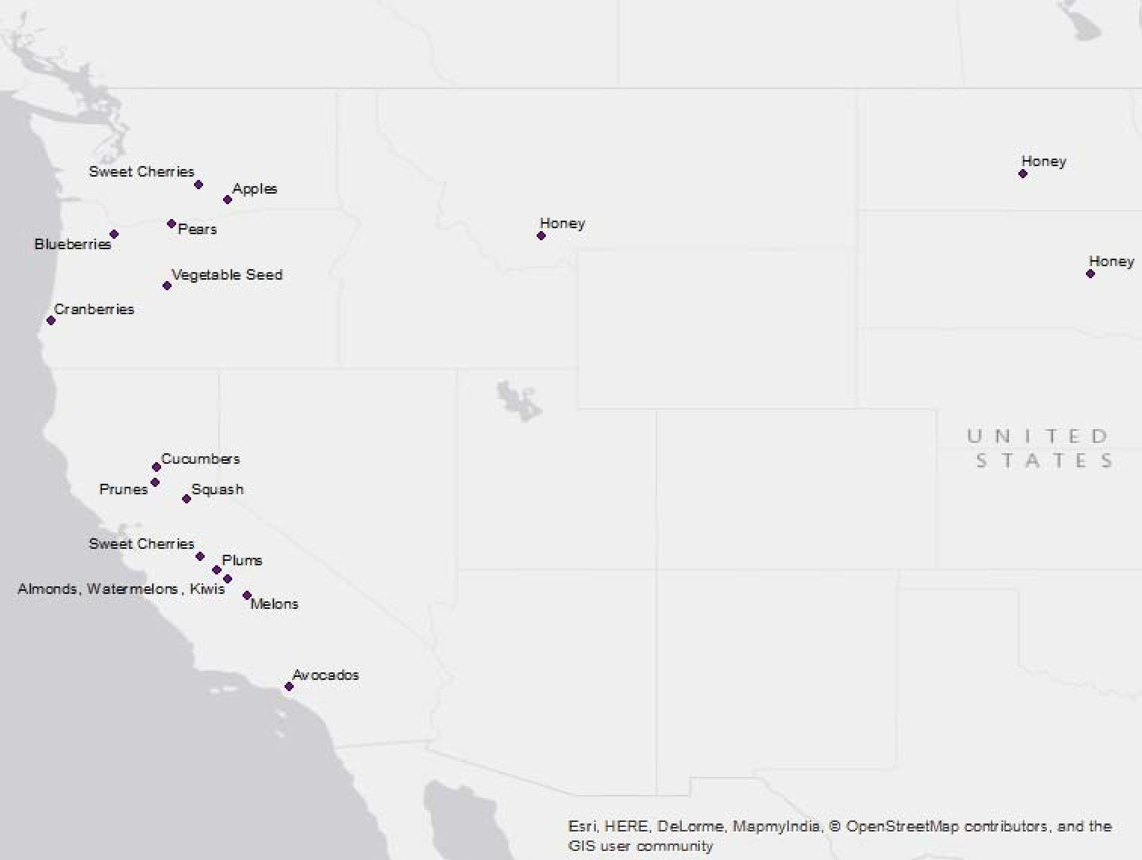

Figure 7: Average crop and honey-production locations
Data Source: USDA NASS QuickStats (U.S. Department of Agriculture 2016)

Because pollination events do not represent the only sites beekeepers visit, important honey-production sites were included as well. North Dakota, South Dakota, and Montana are some of the most productive honey states (Bond, et al. 2014, U.S. Department of Agriculture 2016), so one centralized honey site was included for each of these states. The coordinates of the honey sites were determined similarly to the coordinates for each crop: as a weighted average of the total honey produced in a county, based on data from the USDA Honey Reports, and the coordinates of that county. The weighted average coordinates represent a central honey point for each of these three states and are located at the nearest county seat so that driving distance could be calculated.

Transport Costs and Losses

The transport cost and shipping population loss parameters are directly dependent on driving distances, $D_{i,j}$, between each crop location, which were calculated using a Google Maps API. Personal communication with commercial beekeepers revealed that a semi-trailer truck holds about 450 colonies and costs about \$3.50 per mile to hire. Based on this information, shipping costs are assumed to be \$8.10 per thousand colonies per mile.

Travel is strenuous for colonies, and the number of queens or colonies lost during a trip is dependent on the length of the trip. Based on personal communication with several commercial beekeepers, most inter-state trips result in a loss in the range of 5% to 10%. The population loss, $L_{i,j}$, as a function of distance travelled (in thousands of miles) was calculated as:

$$L_{i,j} = 0.05 D_{i,j}, \tag{10}$$

under the assumption that a 1000 mile trip will result in 5% loss and a 2000 mile trip will result in 10% loss.

4.2 Region- and Season- Specific Parameters

Honey production, feeding cost, and population change parameters are needed for each crop-period combination. Hence, each of these parameter sets consists of a K by J matrix, where each element of the matrix refers to specific regional and seasonal characteristics. Two main data sources were used in characterizing these matrices: NASA's Honey Bee Forage Map (Nickeson and Esaias 2015), which provides a list of honey-bee relevant crops and bloom times by region, and a USDA list of crops and their attractiveness to honey bees in terms of nectar and pollen content (U.S. Department of Agriculture 2015). These sources were combined to create a set of indices of nectar and pollen availability throughout the year in each modeled location. Nectar availability can be used as an indicator of honey production, and pollen as an indicator of population growth potential, according to conversations with commercial beekeepers.

Pollination sites were divided into six regional groups based on the Honey Bee Forage Map (Nickeson and Esaias 2015): South and Central California, Oregon Coast and Mountains, Interior Northwest Washington, Montana, and North Dakota, and South Dakota. These groups basically align with the states in which locations lie, with the exception of pears. The average acre of pears is located in north Oregon, very close to the Washington border, and based on the forage map is more similar to the "Interior Northwest" region of Washington. Pollen and nectar indices were calculated based on the quality and quantity of crops blooming at each time period in each region. These indices were used as a guideline for parameterizing regional and seasonal parameters, as described below.

Population Change

Population change parameters, $V_{k,j}$, reflect changes in the number of colonies or variation in the number of individual honey bees in a colony. $V_{k,j}$ greater than one represent the maximum population growth that beekeepers may create through splits, while values less than one represent decline. These parameters were constrained by data from the Bee Informed Partnership (BIP), which published results from a national survey of 2012-2013 colony losses and management practices (Steinhauer, et al. 2014). The published data is separated into only two seasons, summer and winter; thus the data is more aggregated than what is needed in the model and some assumptions must be made in order to extract more granular parameters. The BIP presents total winter and summer losses by state, and total national winter and summer splits. It was assumed, based on expert opinion, that losses occur between the middle of July and the middle of February and growth occurs during the other half of the year[8]. This assumption in combination with the BIP division of the year into summer (April 1 - October 1) and winter (October 1 – April 1) results in four distinct seasons for the purpose of model calibration: winter loss, winter growth, summer growth, and summer loss (Figure 8) referred to as *WL, WG, SG,* and *SL,* respectively. During *WL* and *SL*, colonies are expected to be lost (or become so weak that they are taken down and used to supplement population in other colonies), and $V_{k,j}$ is less than one. During *WG* and *SG,* colony splits are possible, $V_{k,j}$ is greater

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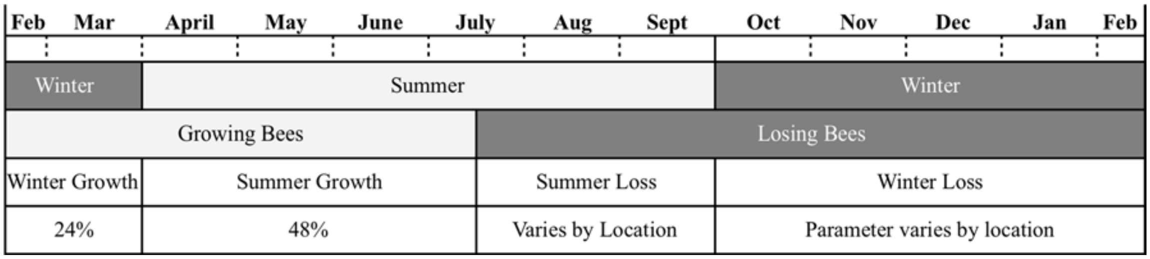
[8] These are not exact dates and may vary depending on location and yearly variation. It is possible, for example, for a beekeeper to continue to lose bees through February and March. Because the BIP reported splits during both summer and winter, it was assumed for the purposes of calibration that some growth occurs during the October 1st – April 1st "winter" period.

than one, and $V_{k,j} - 1$ represents the maximum percent increase in colony numbers a beekeeper may make while maintaining colony health.



Feb Mar	April May June	July Aug Sept	Oct Nov Dec Jan Feb
Winter	Summer		Winter
Growing Bees		Losing Bees	
Winter Growth	Summer Growth	Summer Loss	Winter Loss
24%	48%	Varies by Location	Parameter varies by location

Figure 8: Distinct time periods for honey bee population change starting at beginning of pollination season
Data Source: Bee Informed Partnership (Steinhauer, et al. 2014)
Growth values shown are 2012 reference values

For the two growth periods, BIP reports national estimates of the beginning number of hives, number of splits, and number of reductions (hives sold or given away) for two seasons, winter and summer. Taking these factors into account, in 2012 hives increased by G_S=48% nationally during the summer growth period and G_W=24% during the winter.[9] These aggregate values are used to calibrate the model as follows. First, they imply a bound on the corresponding $V_{j,k}$ parameters in each season:

$$\prod_{j \in SG} V_{j,k} \geq 1 + G_S \text{ and } \prod_{j \in WG} V_{j,k} \geq 1 + G_W . \tag{11}$$

To account for the fact that $V_{j,k}$ represents possible splits while the BIP values measure actual splits, and to account for population gains that occur naturally within the hive during growth periods, the products are set at 1.2 times the BIP values, i.e.

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[9] It is assumed that all reductions occur at the beginning of the corresponding season.

$$\prod_{j\in S} V_{j,k} = 1.2\left(1+G_S\right) \text{ and } \prod_{j\in W} V_{j,k} = 1.2\left(1+G_W\right), \tag{12}$$

which implicitly assumes that the inverse of 1.2, or 83%, of possible splits were carried out in the year of this survey. This assumption is based on personal communication with beekeepers that most of, but not all, possible splits are made each year.

In the case of population loss periods, *SL* and *WL*, BIP provides state-level data (Table 3). Because losses occur without a choice made by the beekeeper, these loss numbers provide an equality rather than a constraint.

$$\prod_{j\in WL} V_{j,k} = 1 - F_{W,k} \text{ and } \prod_{j\in SL} V_{j,k} = 1 - F_{S,k}, \tag{13}$$

where $F_{S,k}$ is the fraction of colonies lost as reported by BIP (Steinhauer, et al. 2014). To approximate half-month population changes from the seasonal losses and gains, population changes were allocated in each of the four periods, *SL, SG, WL,* and *WG,* based on an index of relative pollen attractiveness during each of the *K* periods (see Appendix, Table A-1). To account for crowding and reduced diversity in pollen sources, it was assumed that during pollination events only 92% of bees survive relative to the expected growth or loss outside of cultivated crop pollination ($V_{j,k}$ are multiplied by .92 when k and j represent a pollination event).

Table 3: Summer and Winter Population Losses and Potential Gains

	California	**Oregon**	**Washington**	**Montana**	**North Dakota**	**South Dakota**
Losses 4/1-10/1	27%	19%	29%	14%	24%	40%
Losses 10/1-4/1	29%	27%	23%	20%	27%	39%
Increases 4/1-10/1	48%					
Increases 10/1-4/1	24%					

Data Source: Steinhauer et al. (2014)

Honey Production

Honey production parameters were obtained using USDA NASS (U.S. Department of Agriculture 2016) data on the average annual honey produced per colony, in pounds, by state. As shown in Table 4, to improve the model's fit the honey production levels used were adjusted downward relative to the USDA values. One possible justification for using lower production rates is that a typical hive contains a larger bee population during the summer, when most honey is produced. In the model, additional population is treated as additional hives, meaning that the number of hives in the model would be greater than the number of physical hives during summer months to account for increased population. Therefore, the total honey production in the model is spread amongst a greater number of hives in the model, thus requiring lower per-hive production.

Table 4: Average Annual Honey Production Per Colony

State	California	Oregon	Washington	Montana	North Dakota	South Dakota
Honey per Colony (lbs.)	35	32	41	52	63	69
Adjusted Honey per Colony (lbs)	31	21	24	24	45	49

Adjusted numbers are used in calibration
Data Source: USDA Quickstats Portal

The total honey production levels were allocated across time periods based on nectar indices (see Appendix, Table A-2) and the yearly variation is shown in Figure 9. To account for crowding and reduced diversity in nectar sources, it was assumed that only 25% of the normal amount of honey is produced when the bees are pollinating cultivated crops.

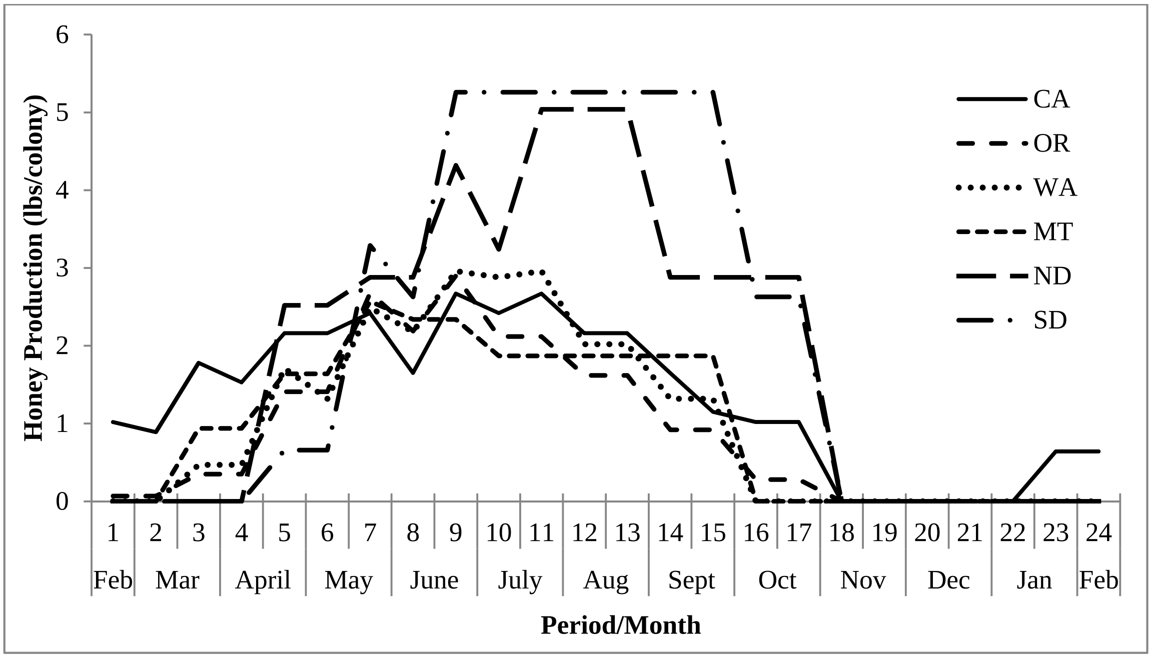

Figure 9: Honey production per colony in half-month intervals
Based on honey production from USDA Quick Stats (U.S. Department of Agriculture 2016) and nectar information from USDA report (U.S. Department of Agriculture 2015)

Variable Beekeeping Costs

A report on beekeeping costs (Hofshi, et al. n.d.) estimated $92 of yearly beekeeping maintenance costs per hive[10], which includes feeding, preventative medication, labor costs, and miscellaneous expenses such as storage and repairs. For all

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[10] The undated report appeared to have been created around 1999-2000 based on the dates of references, so published numbers were inflated to 2015 prices based on the year 2000 consumer price index U.S. Department of Agriculture (2016) "Quick Stats." In*.*, National Agricultural Statistics Service..

costs but feeding, this estimate was used. These costs are assumed to be independent of season and location, so Hofshi's estimate less feeding is allocated equally across the time periods, which comes out to an non-feeding maintenance cost of $3.82 per hive per half-month period.

Hofshi's estimate of feeding costs at $3.60 per hive per year appears to be an underestimate; perhaps due to a changing landscape since these estimations were made and perhaps due to the more demanding nature of migratory beekeeping. Based on personal communication with several beekeepers, feeding costs range from $19.22 to $67.16 per colony per year, allocated unevenly throughout the year, as shown in Figure 10. Variable feeding costs were weighted by location, based on the pollen and nectar indices (locations with high nectar and pollen indices are closer to the minimum costs, and locations with low nectar and pollen indices are closer to the maximum costs).

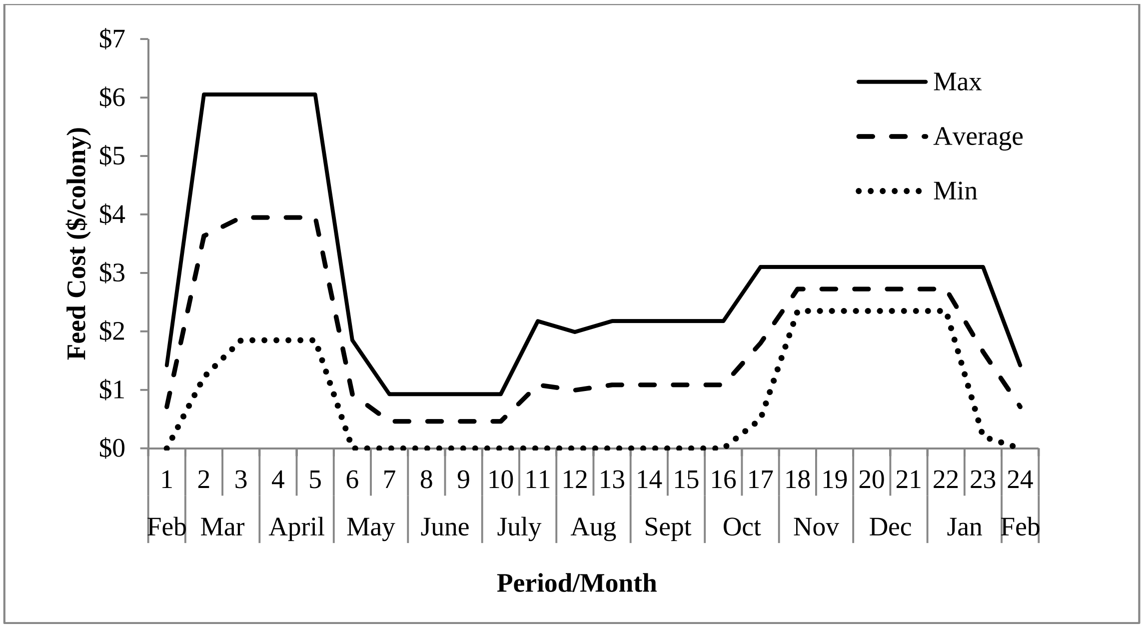

Figure 10: Colony feed cost variation throughout year

The data described in this section were used to calibrate the model to represent year 2012, which is described in more detail in Section 5.2.

5. RESULTS AND DISCUSSION

5.1 Conceptual Model

In order to demonstrate the functionality of the model in the simplest situation possible, and with features of each crop site assumed identical except in the particular areas needed to verify the hypotheses, this section presents the results of various scenarios using a simple conceptual version of the model. The simple conceptual model contains the same objective function and constraints as the full model explained in Section 3.1 and developed in full below, but with a small set of periods and locations and with parameters that are held fixed across all time periods and locations, except when varied for the purpose of investigating the hypotheses. These parameters are not based on real data, so the results are only qualitatively valid. In each scenario, the present value of surplus is maximized over ten years, with an infinite horizon discount factor attached to year ten, to capture the impact of future benefits on current decision-making. The shadow prices on the set of constraints that demand a fixed quantity of colonies for pollination reflect the equilibrium price of pollination, which is one of the indicators examined in this analysis.

This simple model consists of four distinct time periods ($K = 4$) and three locations ($J = 3$), each of which corresponds to a hypothetical major cropping region . There are two competing early blooms followed by one later bloom which allows for examination of the assertion that the high acreage and early bloom timing of almonds impact extensive margins for beekeeping and result in higher pollination prices for early blooms as pollination demand and colony losses increase. Two scenarios are used to examine this hypothesis: 1) a change in pollination demand, and 2) a change in winter losses.

The set of parameters in Table 5 is used in this examination. The base quantity of honey and the base prices for pollination and honey are shown in the figures below, and are not included in a table. The parameters to be altered in examining the first scenario are held fixed in the second scenario, and vice versa.

In the base scenario, early blooms in locations 1 and 2 require 100 and 50 colonies, respectively. The later bloom at location 3 requires 50 colonies. Each location experiences the same change in population throughout the year – a normal cycle with growth during one season and population decline in another. Values for the rest of the fixed parameters are selected to avoid complicating the results with differences amongst locations and time periods. Honey production is equal for all sites, but is staggered so that honey production at any given site does not coincide with the pollination demand at that site. In this simplified model, producers face the same honey demand function as in the calibrated model. Shipping distances, colony losses due to transport, and variable beekeeping costs are the same across all three sites.

Results for year 3 are shown for each analysis. After adjusting for discounting, each scenario reaches equilibrium by year 3 and remains stable until year 9 of the 10-year simulation. Thus, graphics would look identical for each of these years.

Table 5: Base Parameters for Conceptual Model

Parameter	**Value (s)**	**Description**
γ_k	$1 \ \forall \ k$	Variable beekeeping cost
$\beta_{k,j}$	$\begin{matrix} 0 & 0 & 0 \\ (100) & 50 & 0 \\ 0 & 0 & 50 \\ 0 & 0 & 0 \end{matrix}$	Colonies demanded for pollination by time period and location
$H_{k,j}$	$\begin{matrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 0 & 0 \end{matrix}$	Honey production by time period and location
$D_{i,j}$	$\begin{matrix} 0 & .5 & .5 \\ .5 & 0 & .5 \\ .5 & .5 & 0 \end{matrix}$	Shipping cost between locations i and j
$L_{i,j}$	$\begin{matrix} 0 & .05 & .05 \\ .05 & 0 & .05 \\ .05 & .05 & 0 \end{matrix}$	Transport loss between locations i and j
$V_{k,j}$	$\begin{matrix} (.75 & .75 & .75) \\ 1 & 1 & 1 \\ 2 & 2 & 2 \\ 1 & 1 & 1 \end{matrix}$	Colony population change by time period and location
ε	-.9	Price flexibility for the honey demand
η	86.7	Honey demand function multiplicative parameter
λ	0	Cost of extracting one pound of honey
ρ	5	Cost of initiating one hive
σ	5	Cost of splitting one hive
r	.05	Discount rate

Parameters in parentheses are varied in the scenario analysis. Rows refer to periods, k=1,…4, columns refer to crops, j=1,..,3.

Changes in Number of Hives Demanded for Pollination

The number of hives demanded in a location is equal to the crop acreage times the stocking density. So, an increase in the number of colonies demanded could result from an increase in planted acreage (e.g., as in California almonds), or an increase in stocking density (due to, for example, a decline in native pollinators). In the first analysis, the number of colonies required on location 1 is varied over a range from 20 to 200 to allow for an examination of the impact of an increase in demand for early pollination on prices and bee stocks.

Figure 11 illustrates the impact of demand on pollination fees for year 3 in each scenario. As demand for pollination on crop 1 increases in the model, the shadow prices on that constraint increase, indicating a rise in equilibrium pollination fees. Pollination fees for crop 2, which blooms at the same time as crop 1, increase alongside pollination fees for crop 1. Crop 3 blooms after crops 1 and 2, and pollination fees for this bloom decline, as only a fraction of the high number of bees left over after the first pollination event are needed to pollinate crop 3.

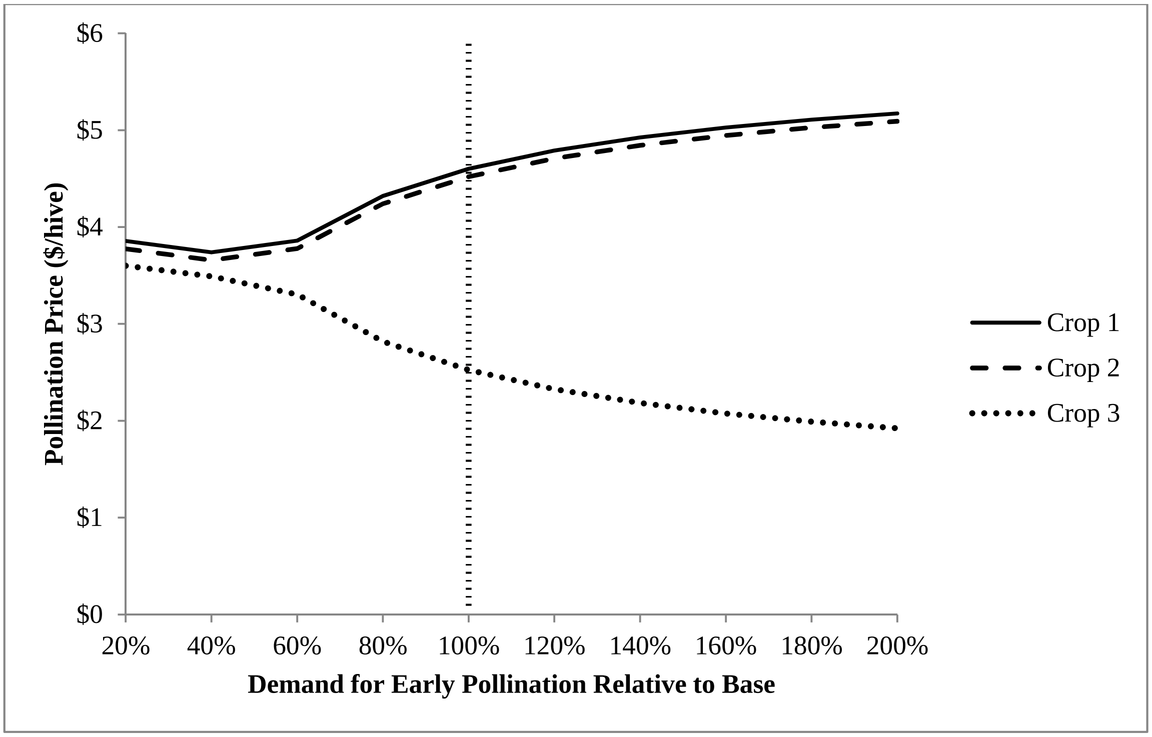

Figure 11: Simulated equilibrium pollination fees for early season crops (1 and 2) and late season crop (3) as a function of quantity hives demanded on crop 1
Dotted vertical line at base level of loss
Conceptual results should only be interpreted on a relative, rather than absolute, scale

These findings are consistent with the hypothesis that the increase in the bearing acres of almonds in the U.S. has put downward pressure on prices for subsequent pollination events by causing more colonies to be present than the number required for the remainder of the year (Sumner and Boriss 2006). The trends shown in this analysis agree with the historical divergence in prices between early and later-blooming crops during the same period of time that almonds saw a doubling in acreage (see Figures 3 and 4). In addition, these findings are consistent with the intuition suggesting that crops blooming at the same time as the expanding crop will face similarly rising pollination fees, due to competition.

Changes in Winter Losses

Increased winter losses seen over the past few decades have been attributed to Colony Collapse Disorder, increased prevalence of the varroa mite, and the increased use of systemic pesticides and fungicides in U.S. agriculture (Frazier, et al. 2015, Rucker, et al. 2012). Although beekeepers may be able to recoup losses caused by these and other factors by making splits throughout the spring and early summer, they work harder to maintain population from year to year, and these increased costs are reflected in higher pollination fees. To evaluate the impact of winter losses on pollination fees and management costs, in the second conceptual scenario the percent of colonies lost during the time period preceding the early bloom is varied from no loss to 45% loss. Based on conversations with beekeepers, a single colony may be split up to 2-3 times in one year, meaning recovery from 50% losses is not out of the question.

As winter loss increases, the pollination prices returned by the model through shadow prices increase simultaneously for the two early-blooming crops. Meanwhile, as shown in Figure 12, the price for the later-blooming crop remains relatively constant, increasing only as losses increase over 35%. The impact of increased losses can also be seen in the per-hive cost of keeping bees. Variable beekeeping cost is calculated as the total yearly management cost returned from the optimization divided by the hive stock during the first pollination event. As more splits need to be made and extra hives need to be managed to compensate for the losses, the variable beekeeping cost increases (Figure 13).

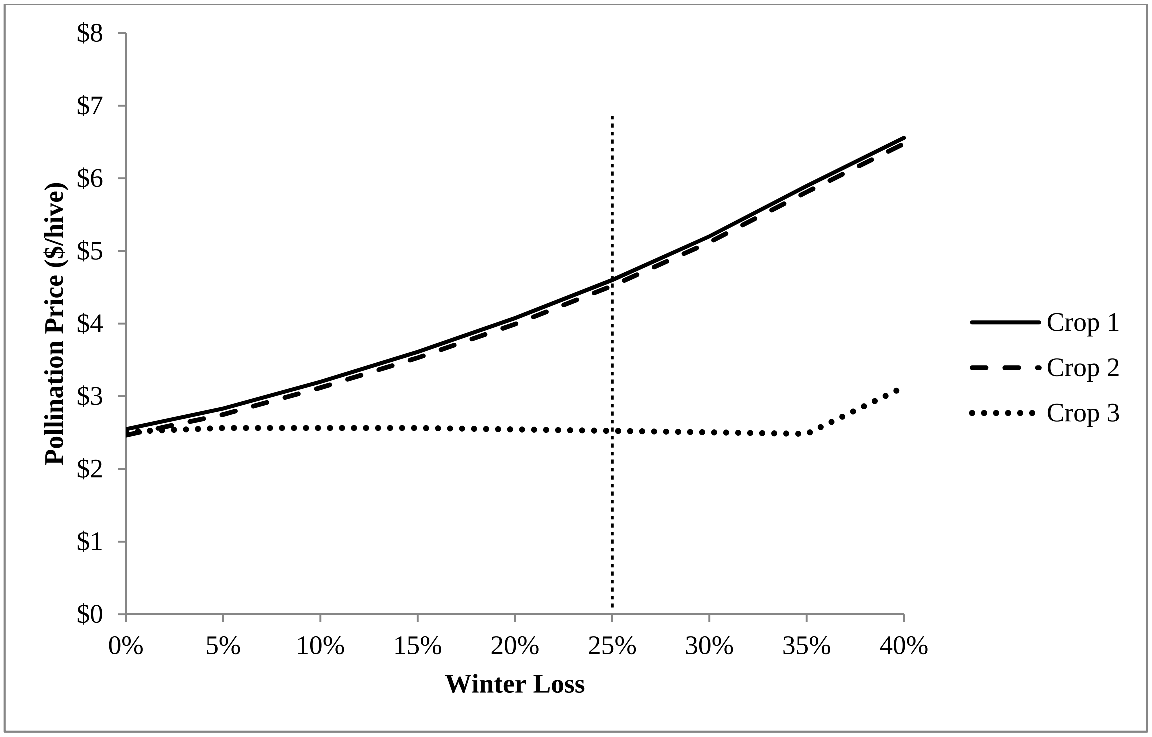

Figure 12: Simulated pollination fees for early season crops (1 and 2) and late season crops (3) as a function of winter loss

Dotted vertical line at base level of loss

Conceptual results should only be interpreted on a relative, rather than absolute, scale

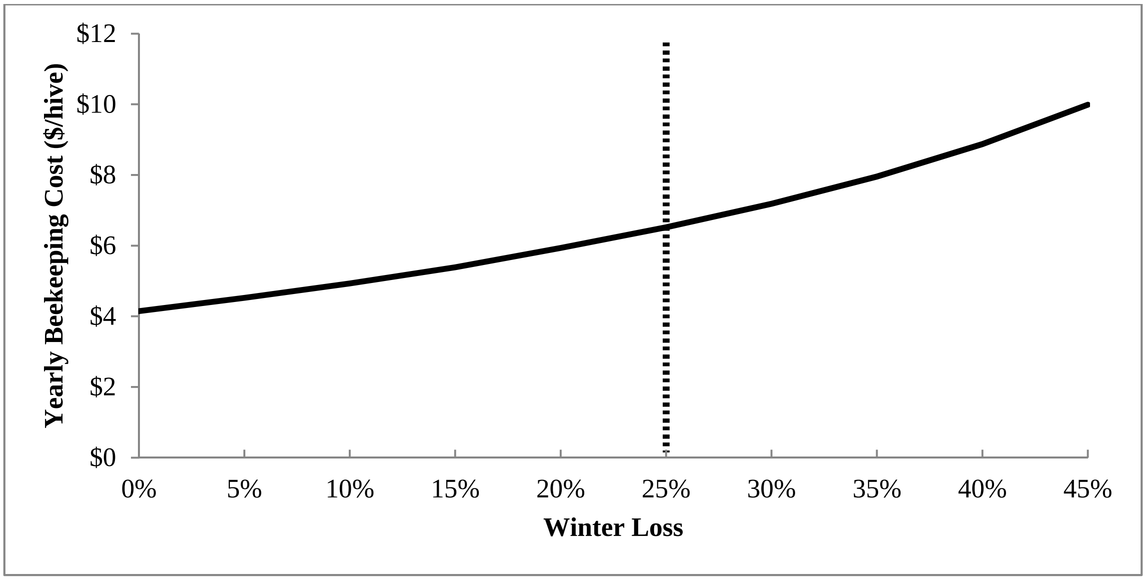

Figure 13: Simulated per-hive beekeeping cost as a function of winter loss

Conceptual results should only be interpreted on a relative, rather than absolute, scale

Ward et al. (2010) suggest that because almond pollination occurs early in the year, beekeepers have not had time to recoup winter losses, resulting in a leftward-shifted supply function for that time of year compared to other months. The findings are consistent with the suggestion that increased winter colony losses more heavily impact crops that bloom at the beginning of the spring.

Summary of Results from the Conceptual Model

Several trends in the market for pollination services have been observed in recent years. This section has evaluated whether the model structure developed is able to respond in a way that is consistent with these trends. Pollination fees for almonds and other early-blooming crops have risen dramatically, and more notably, have strongly diverged from prices paid for pollinating crops that bloom later in the year. Meanwhile, two other significant changes have occurred that appear to be at least partially responsible for the trends in pollination prices: almond acreage has increased and annual winter losses reported by beekeepers have risen.

This model conceptually evaluates the relationship between what are more likely to be key external factors (almond acreage and winter losses) and the prices determined in the market. The results suggest that an increase in almond acreage and an increase in winter losses contribute jointly to almond pollination prices that are not only higher than they were previously, but also higher than pollination prices for other crops.

5.2 Sensitivity Analysis of Calibrated Model

The data described in Section 4 was used to calibrate the model for the year 2012 with 24 half-month time periods and 17 distinct pollination and honey sites. Similarly explained in Section 5.1, the model reaches equilibrium after a few years of simulation. Any of these equilibrium years produces identical results, which are shown in the figures below. The pollination prices returned by the model relative to observed prices for six of the most prominent sites are shown in Figure 14. The honey production returned by the model is shown in Figure 15, separated between states that are modeled with opportunities for pollination revenues (California, Oregon, and Washington) and states that are included only for honey production opportunities (Montana, South Dakota, and North Dakota). The model underestimated honey production by about 10% and consequently overestimated the price of honey per pound at $2.18 relative to the observed price of $1.85 (U.S. Department of Agriculture 2016).

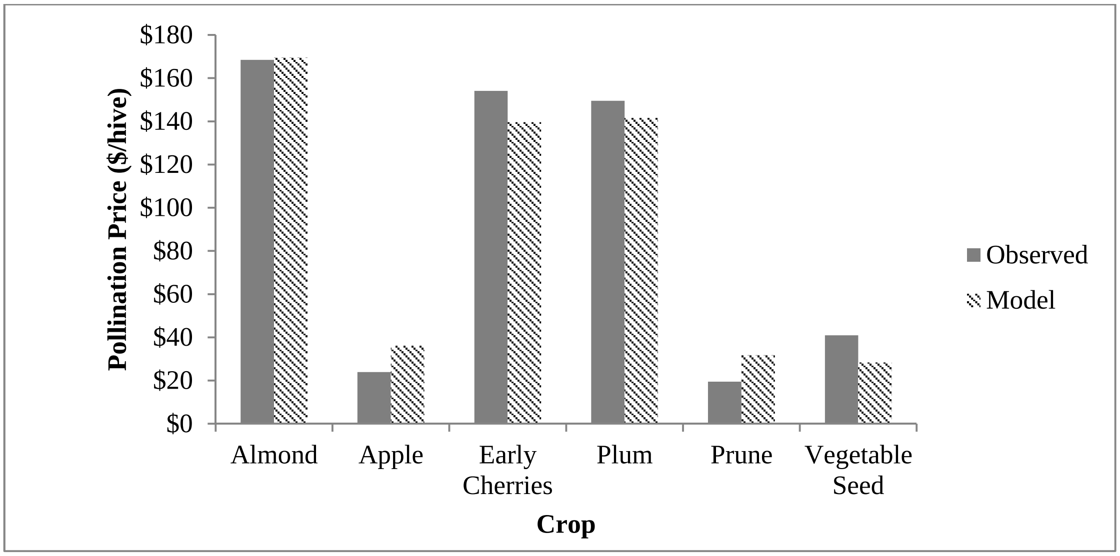

Figure 14: Observed 2012 prices compared to prices returned by model

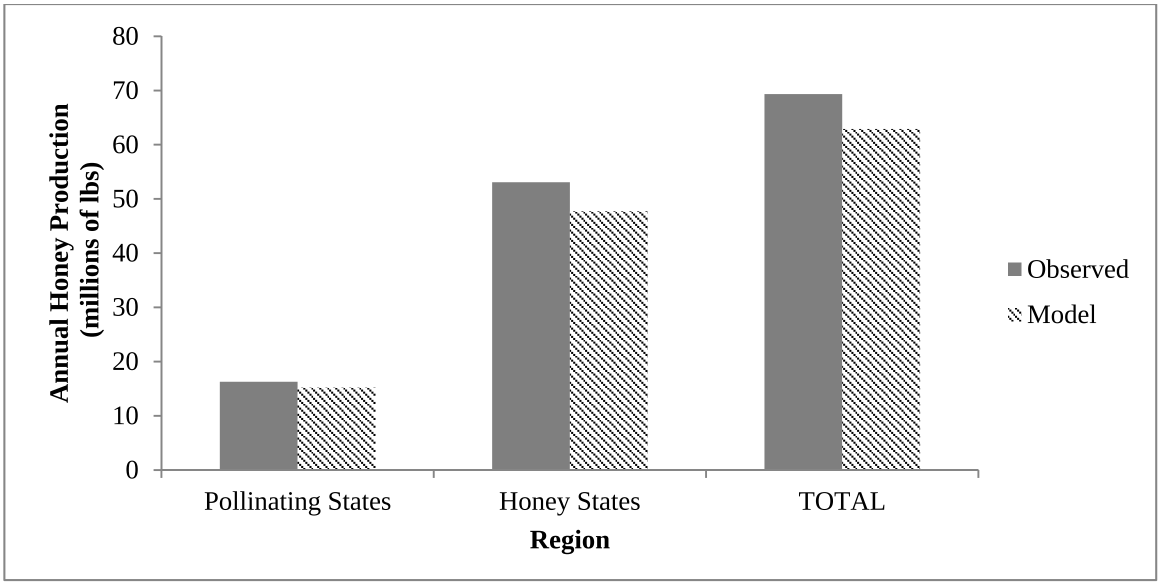

Figure 15: Observed 2012 honey production compared to production returned by model

"Pollinating States" refers to CA, OR, and WA, because these states present opportunities to earn pollination fees in the model. "Honey States" refers to MT, ND, and SD, because honey sales are the only form of revenue modeled in these states

For the most part, parameters used in the analysis are based on published data or clear consensus from beekeepers who were contacted. However, for three of the sets of parameters required in the model, the empirical foundations were weak. To better understand their impact on the market prices, this section presents sensitivity analysis over these parameters: population change, honey production, and hive maintenance cost.

Population Variation

As discussed earlier, the data used for the population change parameters were not sufficiently granular to be compatible with a 24 period-per-year model, and seasonal values for population change were broken up into half-month periods using indices of pollen attractiveness for honey bees. To some extent, the availability of attractive pollen sources should impact population gain or loss. However, how important this is and the extent to which it affects population change rates over the 24-periods in a year can not be exactly predicted with the available data. Hence, sensitivity analysis is carried out over this parameter. On one extreme, availability of attractive pollen sources is assumed to have the greatest impact possible on population change rates during each season without causing population loss during periods of typical gain or vice versa, and half-month population change rates are calculated accordingly; this set of scenarios will be referred to as having “Max Population Variation.” On the other extreme, availability of attractive pollen sources impacts population minimally. When population change rates were set to be equal during each period within a season with no influence from pollen sources, the model did not reach equilibrium. This suggests that such minimal variation is not realistic for the calibrated model. Therefore, a minimal, but non-zero impact of pollen sources on population is used in the sensitivity analysis and referred to as “Min Population Variation.” Figures 16 and 17 show how the pollination prices for almonds and apples were impacted by the movement of this parameter set from max to min. Four series are presented, representing the various levels at which the other two parameters were set. As seen in the figures, this parameter set hardly impacted almond pollination prices but significantly impacted apple pollination prices: minimum population variation resulted in much higher apple pollination prices than maximum variation, regardless of the level at which honey variation or feed cost was set. A possible explanation for the large impact on apple pollination prices relative to almonds is that there was more variation in pollen sources for the season in which apple pollination lies (summer growth) than in the season during which almond pollination lies (winter growth), so a change in the importance of pollen sources had a bigger impact on the population change on apples. The impact of this parameter on the four crops with overlapping blooms to apples may have also had an effect on apple pollination prices.

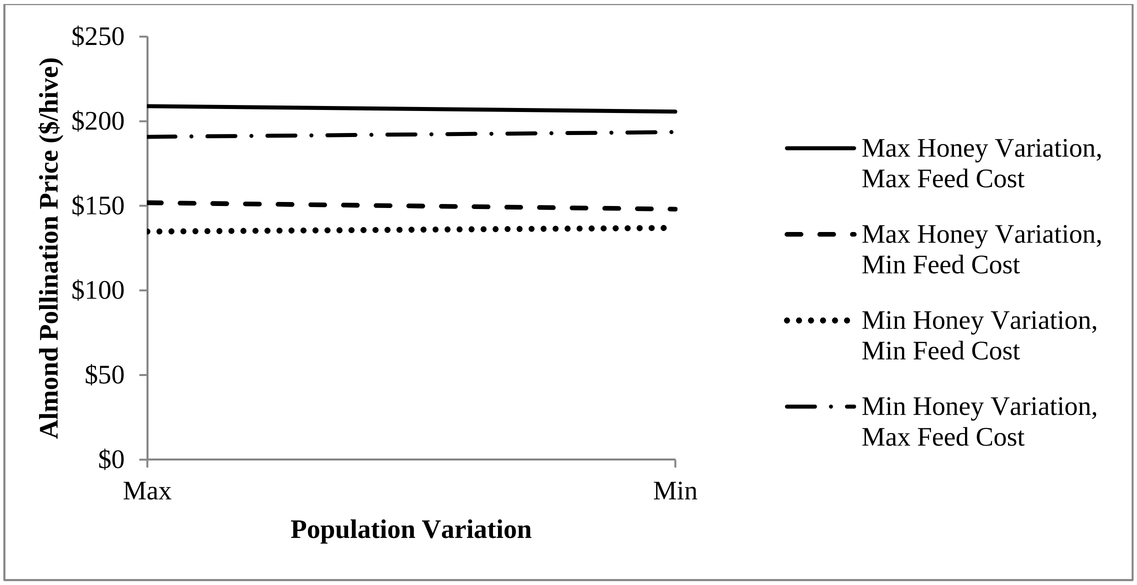

Figure 16: Sensitivity of almond pollination prices to population variation parameter set

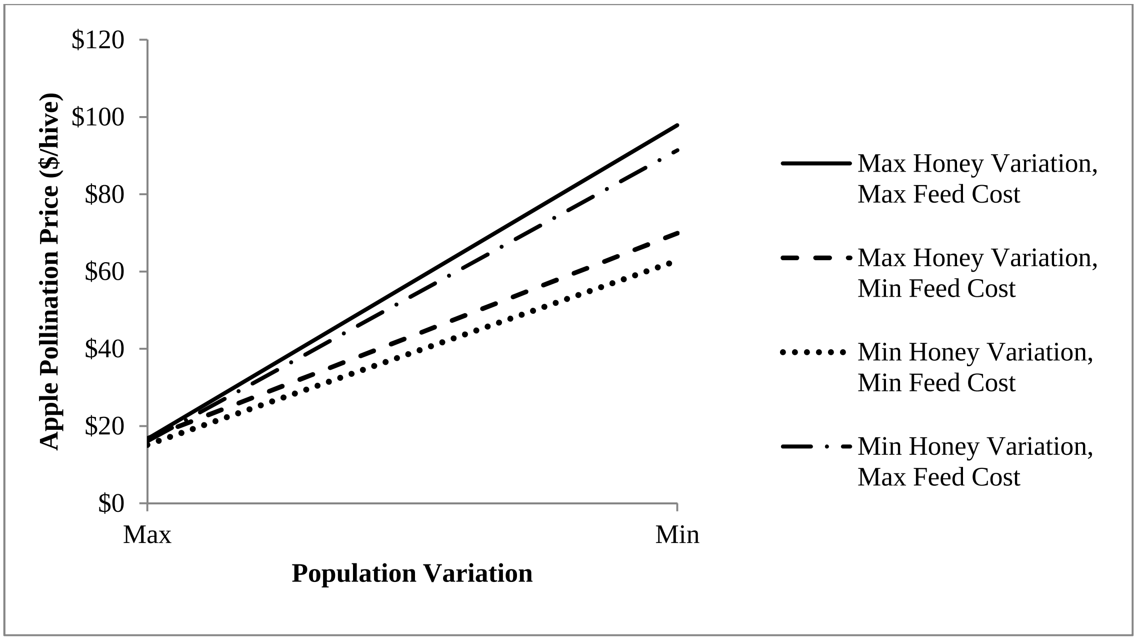

Figure 17: Sensitivity of apple pollination prices to population variation parameter set

Honey Production

The data used for the honey production parameters, similarly to the data used for population change parameters, were not sufficiently granular to be compatible with a 24 period-per-year model, and yearly values were broken up into half-month periods using indices of nectar attractiveness for honey bees. To some extent, the availability of attractive nectar sources should impact honey production, but because the extent of that impact is not quantifiable with the available data, sensitivity analysis is carried out over this parameter. On one extreme, referred to as “Max Honey Variation,” it is assumed that availability of attractive nectar sources significantly impacts honey production and thus the majority of honey production occurs when there is an abundance of attractive nectar-producing plants in bloom. On the other extreme, referred to as “Min Honey Variation,” it is assumed that honey production is evenly distributed throughout the year. Figures 18 and 19 show that neither almond nor apple pollination fees move much when this parameter set is varied between its minimum and maximum, regardless of the level at which population variation or feed cost was set. Honey prices, however, are moderately affected, as shown in Figure 20. “Max Honey Variation” favors the pollen-rich summer “honey” locations that already draw bees. This allows bees to produce more honey there, and therefore lowers honey prices.

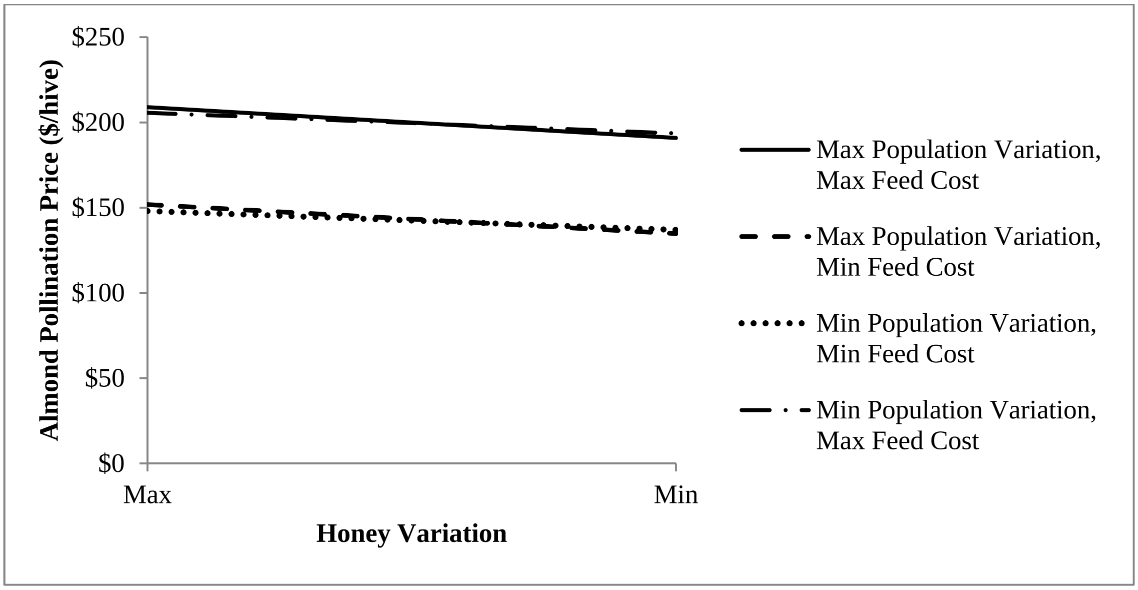

Figure 18: Sensitivity of almond pollination prices to honey production parameter set

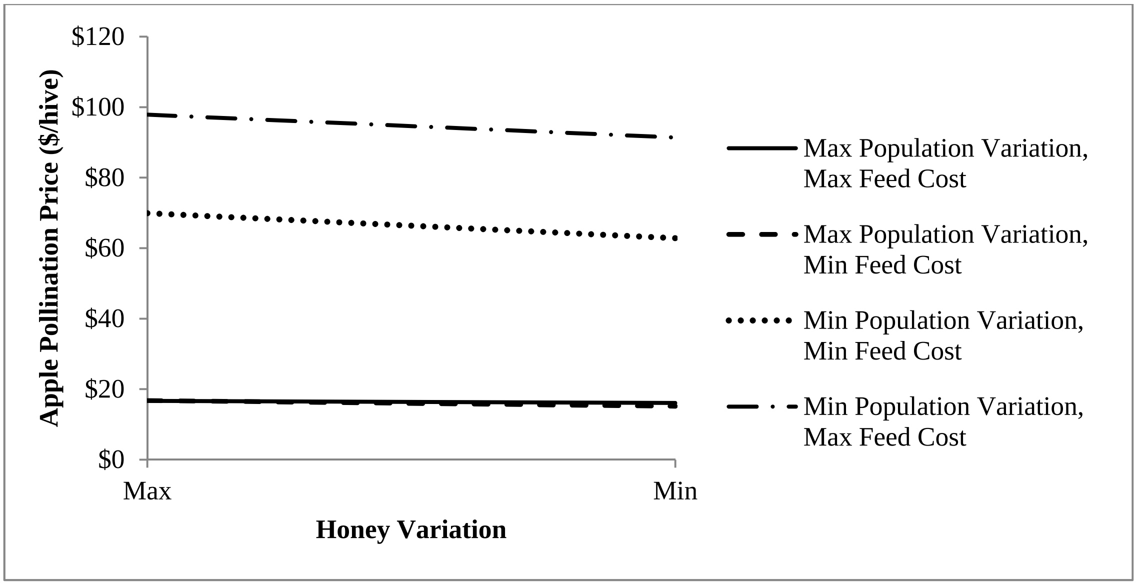

Figure 19: Sensitivity of apple pollination prices to honey production parameter set

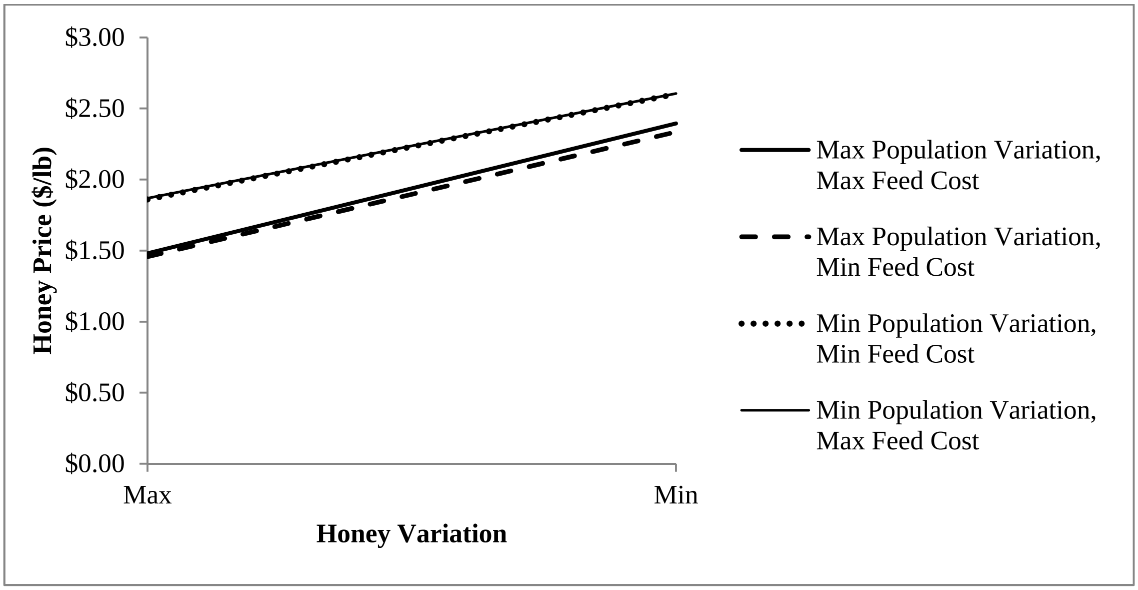

Figure 20: Sensitivity of honey prices to honey production parameter set

Feed Cost

Different beekeepers quoted different costs of feeding a colony throughout the year, as introduced earlier in Figure 10, and Figures 21 and 22 show that both almond and apple pollination fees are moderately sensitive to changes in feed cost parameters.

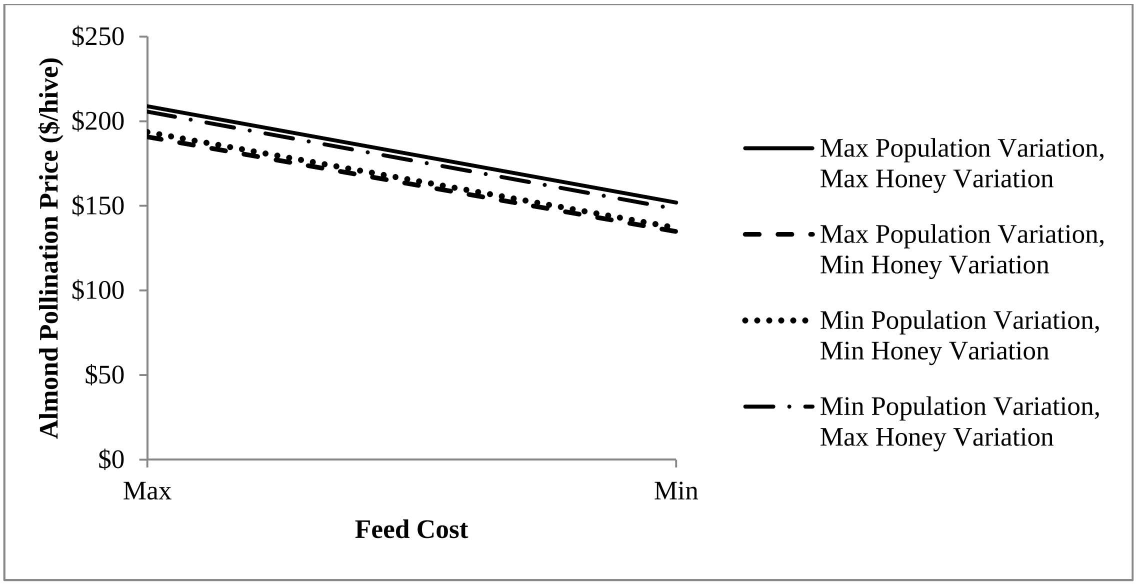

Figure 21: Sensitivity of almond pollination prices to feed cost parameter set

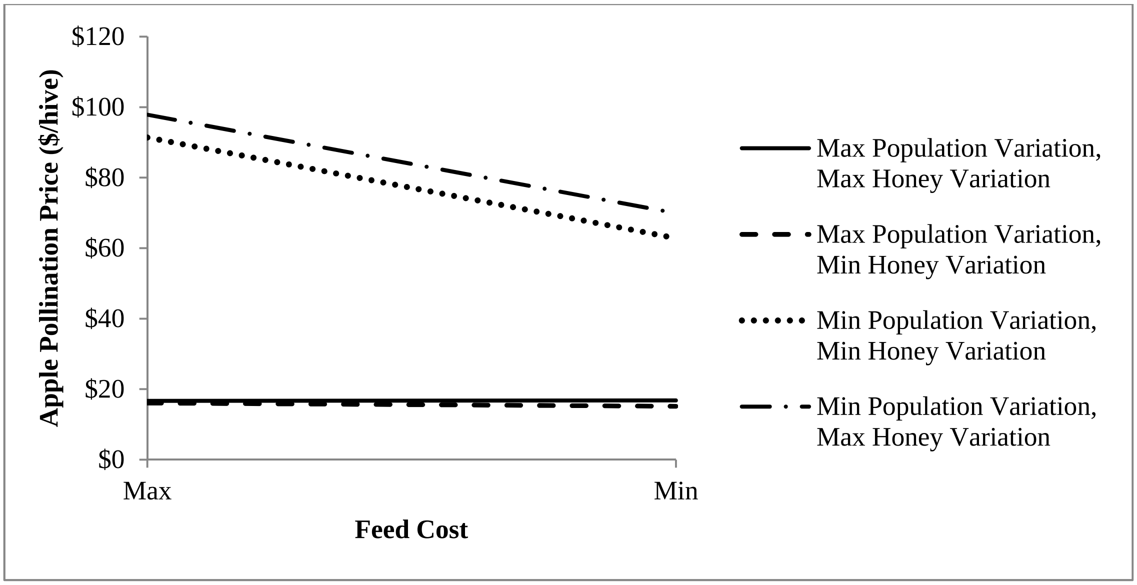

Figure 22: Sensitivity of apple pollination prices to feed cost parameter set

Summary of Sensitivity Analysis

The eight scenarios ranging over the parameter sets described above are summarized in Table 6, and the exact feed costs used are given in Table 7. Exact population change parameters and honey production parameters can be found in Appendix, Tables A-3 and A-4). The pollination prices returned by the base parameters and all eight sensitivity analysis scenarios are shown in Figure 23 and compared to actual prices.

Table 6: Parameter Sets Used in Sensitivity Analysis

Scenario	**Level of variation in population change throughout time periods**	**Level of variation in honey production throughout time periods**	**Feed costs**
Base Case	Somewhat variable	Somewhat variable	Average
1	Highly variable	Highly variable	Max
2	Highly variable	Highly variable	Min
3	Highly variable	Equally distributed	Min
4	Highly variable	Equally distributed	Max
5	Minimally variable	Equally distributed	Max
6	Minimally variable	Equally distributed	Min
7	Minimally variable	Highly variable	Min
8	Minimally variable	Highly variable	Max

Table 7: Maximum and Minimum Feed Costs Used in Sensitivity Analysis

Month	**Period**	**Min**	**Max**
End of Feb.	1	$3.82	$5.25
March	2	$5.05	$9.87
	3	$5.67	$9.87
April	4	$5.67	$9.87
	5	$5.67	$9.87
May	6	$3.82	$5.67
	7	$3.82	$4.75
June	8	$3.82	$4.75
	9	$3.82	$4.75
July	10	$3.82	$4.75
	11	$3.82	$6.00
Aug.	12	$3.82	$5.81
	13	$3.82	$6.00
Sept.	14	$3.82	$6.00
	15	$3.82	$6.00
Oct.	16	$3.82	$6.00
	17	$4.32	$6.92
Nov.	18	$6.17	$6.92
	19	$6.17	$6.92
Dec.	20	$6.17	$6.92
	21	$6.17	$6.92
Jan.	22	$6.17	$6.92
	23	$4.02	$6.92
Beginning of Feb.	24	$3.82	$5.25

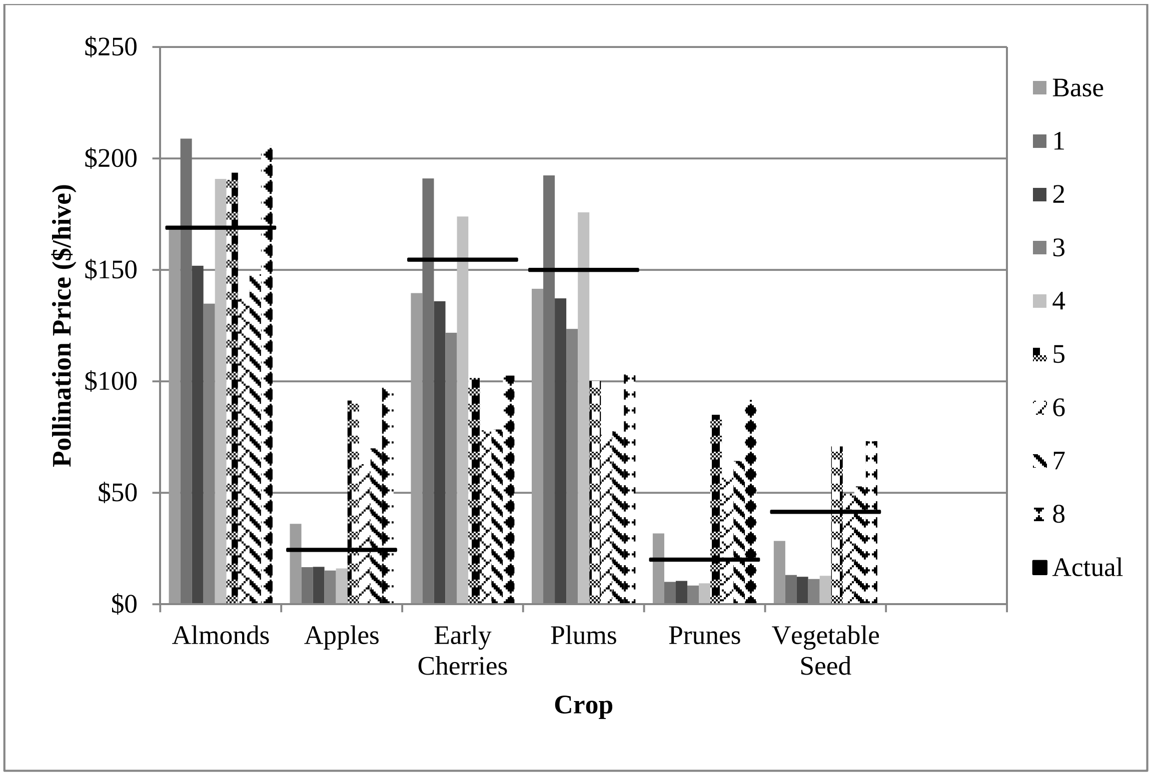

Figure 23: Pollination price sensitivity to 8 varied scenarios of honey production, population change, and maintenance cost parameters
Actual 2012 prices shown

In summary, among the parameter sets over which there is substantial uncertainty, the model is most sensitive to the impact of pollen availability on population changes. Pollination prices are relatively insensitive to the impact of nectar availability on honey production, and moderately sensitive to feed cost parameters. Honey prices are moderately sensitive to the impact of nectar availability on honey production. The sensitivity of pollination prices to population changes and feed costs, and the moderate sensitivity of honey prices to honey production allocation suggest the value in obtaining higher-resolution data for these parameters in future work. Nonetheless, this sensitivity analysis does find that the relative magnitude of pollination prices is consistent. While some scenarios tighten the gap between early and late pollination prices, under all scenarios the prices for early pollination prices are higher than late pollination prices. Hence, the sensitivity analysis suggests that the model's qualitative predictions are reasonably stable.

5.3 Scenario Analysis

Several possible future scenarios were examined in an effort to shed light on how pollination prices and honey price may be impacted by factors such as a change in almond acreage, change in the demand for honey bee pollination, or a change in colony loss rates. The scenarios investigated are 1) a change in the number of hives demanded on almonds, 2) a change in winter colony loss rates, and 3) a change in summer colony loss rates. Up to a 30 year simulation was run for each scenario in an effort to achieve equilibrium. If stable values did not arise, this scenario was interpreted as inconsistent with the structure of the model. Because the values presented are in equilibrium, the choice of year presented does not affect the results shown.

Change in Number of Hives Demanded for Almond Pollination

Given the historical trend in almond acreage, we may see a continued increase in planted almond acreage in the future. Assuming the standard stocking density remains at an average of 2.08 hives per acre, this would lead to an increased demand for hives in almond orchards at the beginning of pollination season. However, the stocking density may not remain fixed. If native pollinators continue to decline, it is possible that a higher density of honey bees may be required to pollinate almonds; this would exacerbate an increase in the number of hive demanded. On the other hand, several years of severe drought in California may lead to a reduction in the planted acreage of thirsty almonds. To investigate the market reaction to any combination of these factors impacting bees required on almonds, a range of values for the number of hives demanded for almond pollination was evaluated, from 70% to 140% of the base value.[11,12]

Figure 24 shows the impact of a change in demand for honey bee pollination on pollination prices for a selected set of crops. Up to around 80% of the base demand (about 1360 hives), pollination prices for the selection of crops are projected to be close together, though almonds require a premium over even other early-blooming crops, likely due to the inability of the beekeeper to produce salable honey on almonds. As the number of hives required on almonds increases, the model projects a divergence in pollination prices between early-blooming crops (almonds, early cherries, and plums shown in Figure 24), and late-blooming crops (apples, vegetable seed, and prunes shown in Figure 24), which actually see a decline in pollination prices. This finding agrees with the prediction that as early demand for bees pushes out the extrinsic margin, demanders of early pollination take on the increased fixed cost (Sumner and Boriss 2006). During the remainder of the year, bees may remain “unemployed,” (Sumner and Boriss 2006), putting downward pressure on pollination prices for late-blooming crops. This is

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[11] Each of the attempted scenarios resulted in model equilibrium within 15 years.

[12] Sensitivity analysis similar to that described in Section 5.2 produced qualitatively similar results to those depicted and described here.

consistent with the observed divergence between early and late pollination fees (Figure 3).

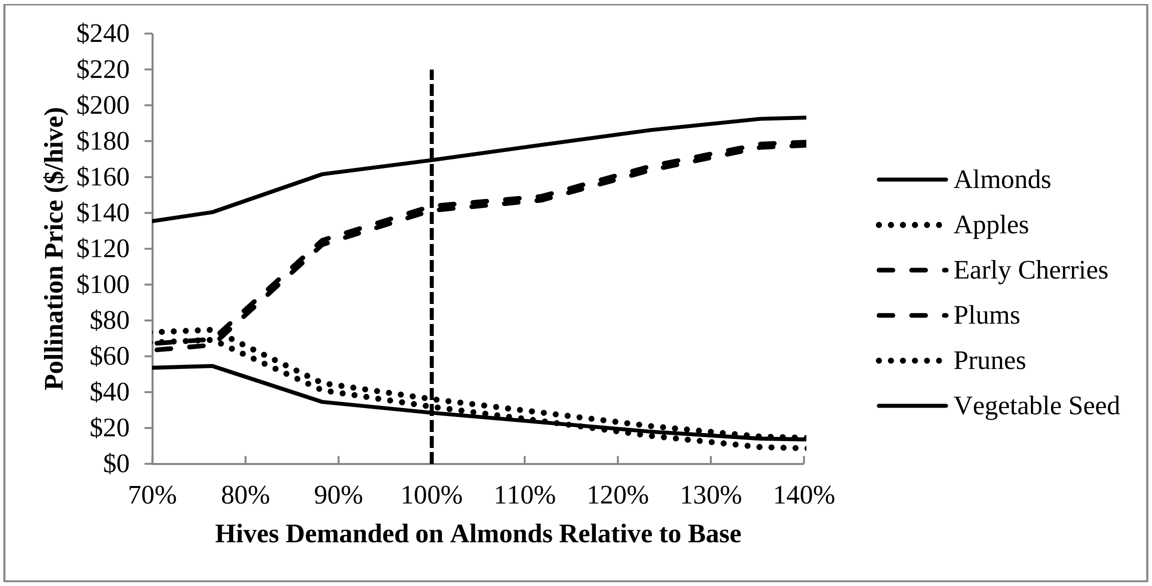

Figure 24: Impact of change in quantity hives demanded on almonds on projected pollination fees

Changes in the number of hives required for almond pollination are also predicted to have an effect on honey prices. The number of bees required for almond pollination affects the honey market in two offsetting ways. First, an increase in the number of hives on almonds has a negative effect on honey production because honey is not produced on almonds, so all bees on almonds are unable to produce honey at the beginning of the season. On the other hand, an increase in bees on almonds pushes out the extrinsic margin and leads to a higher number of bees available in the market to produce honey after almond pollination. As seen in Figure 25, the model finds that the second effect dominates; increased number of bees on almonds leads to an increase in honey production and therefore a fall in honey prices.

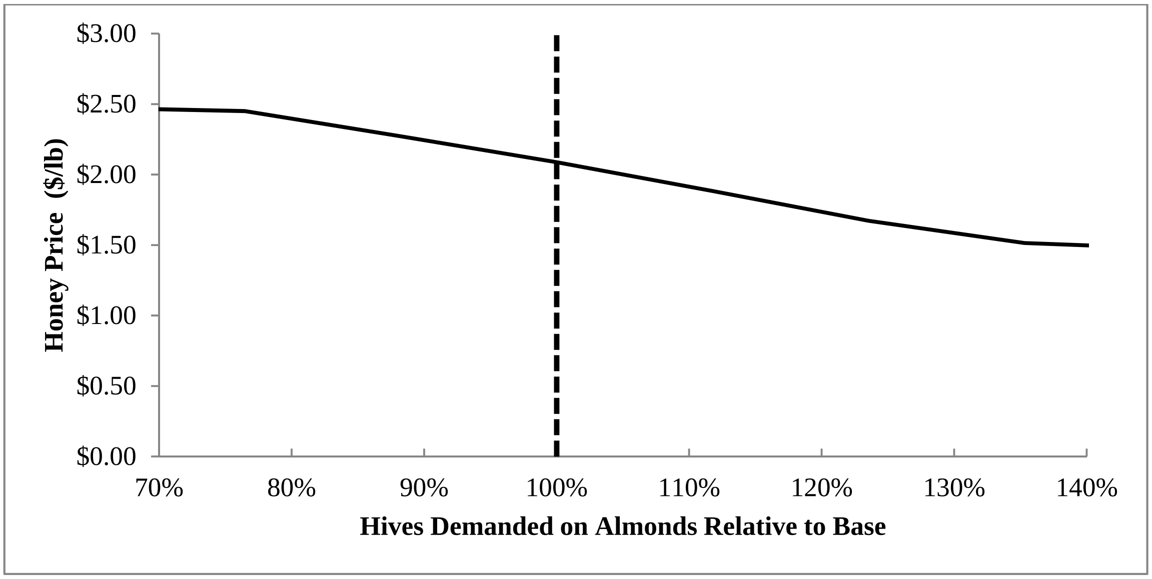

Figure 25: Impact of change in quantity hives demanded on almonds on honey price

In the case that pollination stocking densities change due to a change in wild pollinator abundance, it is relevant to evaluate the resultant change in economic surplus. Because managed colonies are a substitute for wild pollinators in terms of crop pollination (Champetier de Ribes 2010, Rucker, et al. 2012), this surplus change can be thought of as the replacement value of pollination services provided for free by wild pollinators. Although this results in a shift in the demand for commercial pollination, this change is evaluated as a leftward shift in the supply function for all pollination; crop growers are still requiring the same level of pollination but less is being supplied for free from native pollinators. Because the demand for pollination is assumed to be perfectly inelastic at relevant values, the total benefit of pollination is held constant even as there is a change in the number of commercial hives required to achieve that level of benefit. Therefore, the total benefit derived from crop pollination is not subject to change and is not evaluated here. As is explained in more detail in Section 3, equations (8) and (9), the surplus subject to change, notated w_y, can be evaluated as the area under the honey demand curve minus the cost of extracting honey and minus the cost of managing bee populations (feeding, splitting, and transport costs):

$$w_y = \left(\frac{\eta}{\varepsilon + 1} S_y^{(\varepsilon+1)} \right) - \lambda S_y + \sum_j \sum_k \left(\sigma N_{j,k,y} + \gamma_k B_{j,k,y} \right) - \sum_i \sum_j \sum_k D_{i,j} T_{i,j,k,y} \ , \tag{14}$$

which is simply equation (9) modified to calculate a yearly value. This can be broken down into surplus to crop growers (pollination consumers), honey consumers, and beekeepers (producers). Annual grower surplus subject to change, notated w^G_y, can be evaluated as the total amount paid for pollination services,

$$w_y^G = \sum_j \sum_k \left(P_{j,k,y}^P B_{j,k,y} \right), \tag{15}$$

which excludes the assumed fixed benefit derived to growers for pollination services. Annual honey consumer surplus, notated w^C_y, can be evaluated as the area under the honey demand curve minus the total amount paid for honey:

$$w_y^C = \left(\frac{\eta}{\varepsilon + 1} S_y^{(\varepsilon+1)} \right) - P_y^H S_y \ , \tag{16}$$

and changes to this value represent change in welfare to consumers of honey. Annual producer (beekeeper) surplus, notated w^P_y, can be evaluated as the total revenue from pollination and honey production minus the cost of extracting honey and minus the cost of managing bee populations:

$$w_y^P = P_y^H S_y + \sum_j \sum_k \left(P_{j,k,y}^P B_{j,k,y} \right) - \lambda S_y - \sum_j \sum_k \left(\sigma N_{j,k,y} + \gamma_k B_{j,k,y} \right) - \sum_i \sum_j \sum_k D_{i,j} T_{i,j,k,y} \,. \quad (17)$$

Figure 26 shows the change in each surplus relative to the base if the number of bees required on almonds changes but the benefit of pollination to almond growers remains the same. As the demand for substitutes for native pollinators increases, a previously free ecosystem service requires costly human intervention. This decreases the economic surplus as represented by equation (14) in an essentially linear fashion; surplus falls by about $30 million annually for each 10% increase in required stocking density on almonds. Crop growers lose closer to $40 million annually per 10% change. The surplus loss for crop growers might in reality be passed on to the consumers of those goods, but that is beyond the scope of this model. Moreover, here we assume that crop acreage is held constant and the increase in pollination demand comes from increased need of bees per acre. If instead, crop acreage increased, this would yield offsetting benefits for the almond growers. The model finds that, from a societal standpoint, the loss to crop growers is partially offset by an increase in the surplus of honey consumers, who benefit from the greater amount of cheaper honey. Beekeeper surplus remains relatively unchanged as the number of hives required on almonds is varied.

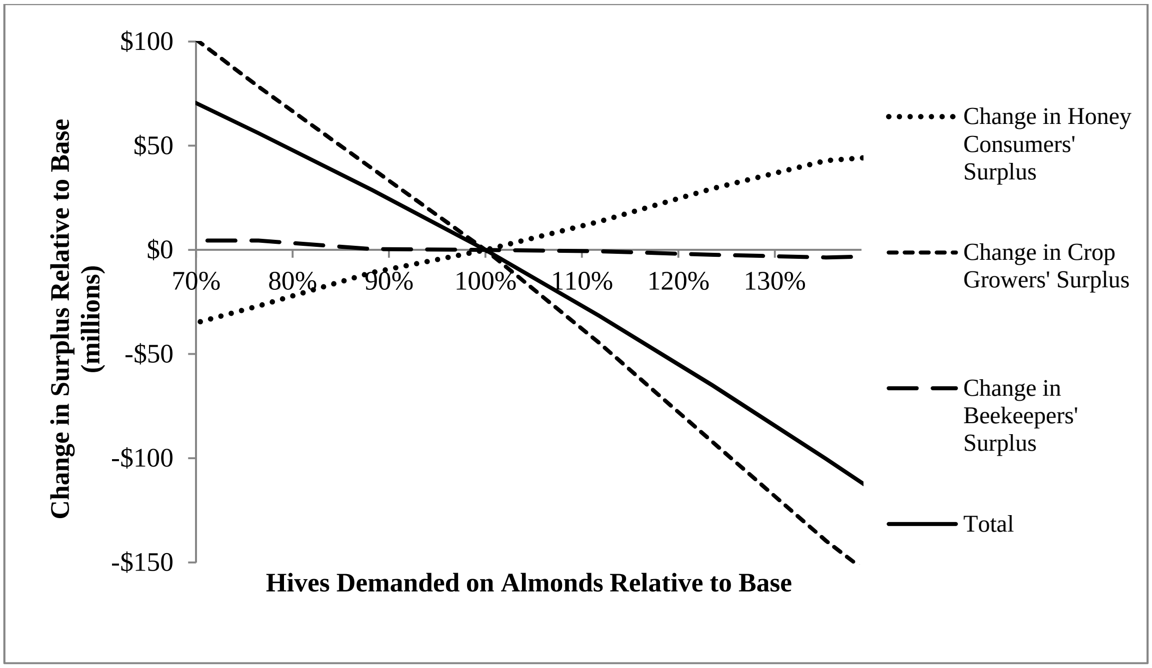

Figure 26: Surplus change relative to base as a result of increased need for hives on almonds for reasons other than increased almond acreage

Change in Winter Colony Loss Rates

As discussed earlier, over the past decade winter colony loss has reached levels far exceeding historical rates. Given the possible impact of public policy (such as pesticide spray policies) on colony losses, winter loss may change in either direction in the coming years. To explore the impact of the phenomenon, winter survival rates were varied from 125% of the base rates (lower loss) to 93% of base rates (higher loss) [13]. Survival rates less than 93% of the base scenario resulted in an inability of the model to reach equilibrium in a 30 year simulation; suggesting a structural change in the market

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[13] A sensitivity analysis for these scenarios produced qualitatively similar results to those presented here.

that goes beyond the scope of this model. At a total reported loss rate of 45% (Steinhauer, et al. 2016), 2012 (the base year) represented a particularly bad year for overall mortality, and no other year has seen higher levels of winter loss paired with similar or higher levels of summer loss. However, winter loss rates have varied from as low as 23% to as high as 36% over the past decade, so a change of the magnitude being discussed here does not seem out of the question. Though the market is unlikely to suffer abrupt changes, structural change below 93% of current survival may reveal itself in a variety of changes in this market. One change that may occur is a breakdown in the assumption of perfectly inelastic demand: if the price reaches certain levels, farmers may decide to forego pollination or go with a different stocking density, change their planted acreage, or find new technical solutions. Another possibility is the movement or sale of hives from other parts of the country, which does occur but is not captured here due to data limitations. Another possible scenario is that, because pollination contracts are made prior to the knowledge of loss rates, the market may see years where pollination demands are not met. Finally, if loss rates were to become too high for beekeepers to recover their stock, the market could reach a state where honey bee populations are continually declining.

Figure 27 shows the resultant pollination fees for various winter survival levels for scenarios in which an equilibrium was found. This finding partially agrees with the hypothesis that colony losses lead to higher pollination fees for early-blooming crops. As winter loss increases, the model predicts rising pollination fees for all crops except early cherries and plums, the two early blooming crops included in Figure 27. One possible explanation for this result lies in the fact that population growth is less on almonds than on cherries and plums. So, when winter losses rise, beekeepers have a strong incentive to place their bees on crops that allow for higher growth, meaning that a higher price will be demanded for almond pollination.

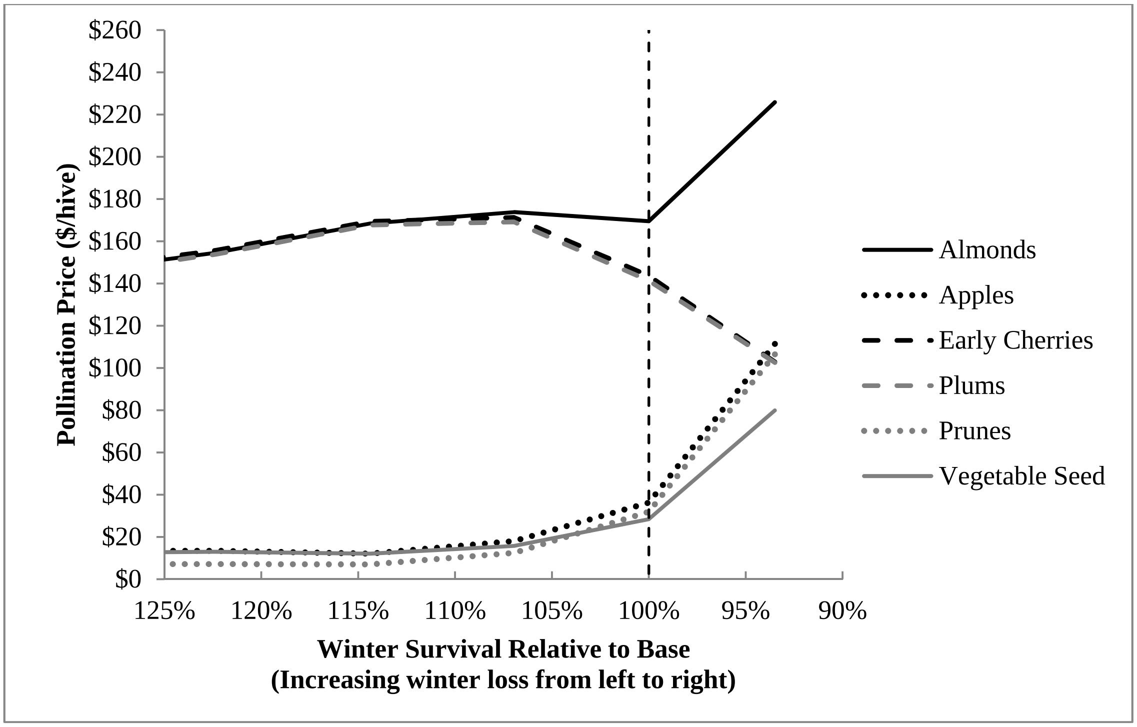

Figure 27: Impact of winter survival rate on pollination fees

Honey prices, depicted in Figure 28, show some movement upward as the winter loss rate increases, but ultimately fall at high loss levels. A look into bee populations and their predicted fluctuations throughout the year helps to explain this shift. As shown in Figure 29, at base levels of winter survival and higher, the population reaches a minimum of around 1.8 million hives and only diverges for parts of the year – under higher loss rate scenarios, more hives are created during the growth seasons to make up for the higher number being lost during the loss seasons. Therefore, high loss rates result in a higher number of hives at peak period. Since, as loss increases, there are barely enough hives available to meet pollination demand, good growth locations must be chosen over good honey locations and honey prices rise. As winter survival continues to fall below base levels, the optimal population shifts to a new, higher equilibrium, and higher populations produce more honey, causing the price of honey to fall. Because this is an equilibrium result, it is not capturing critical changes that would occur during the transition period to this higher equilibrium population.

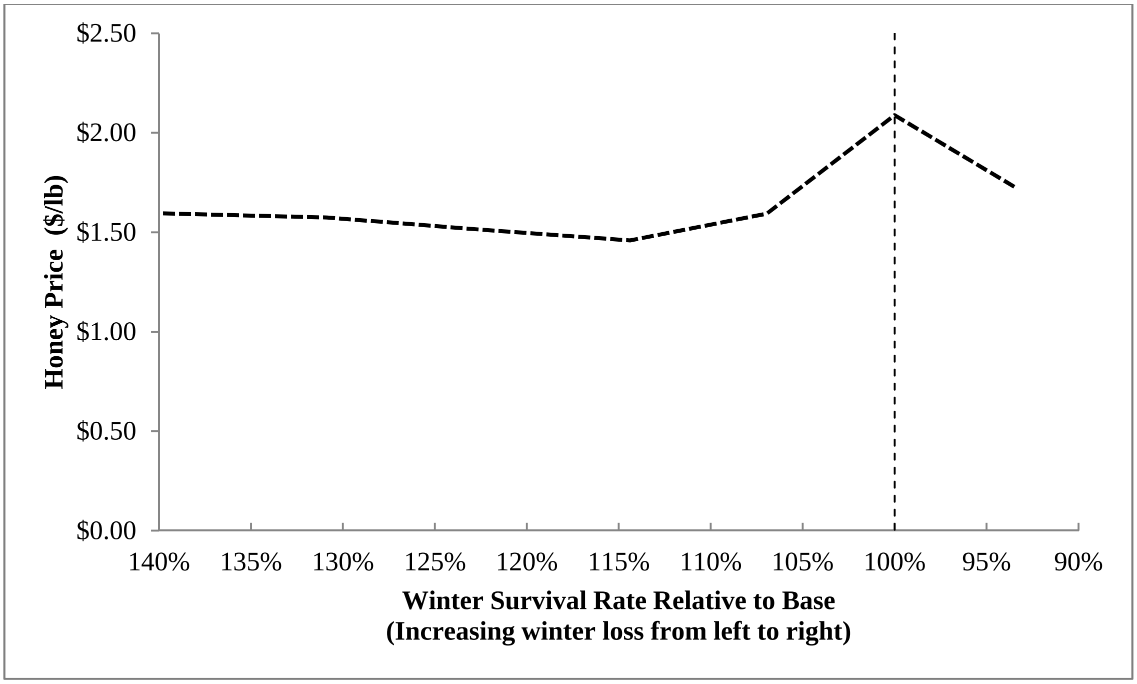

Figure 28: Impact of winter survival rate on honey price

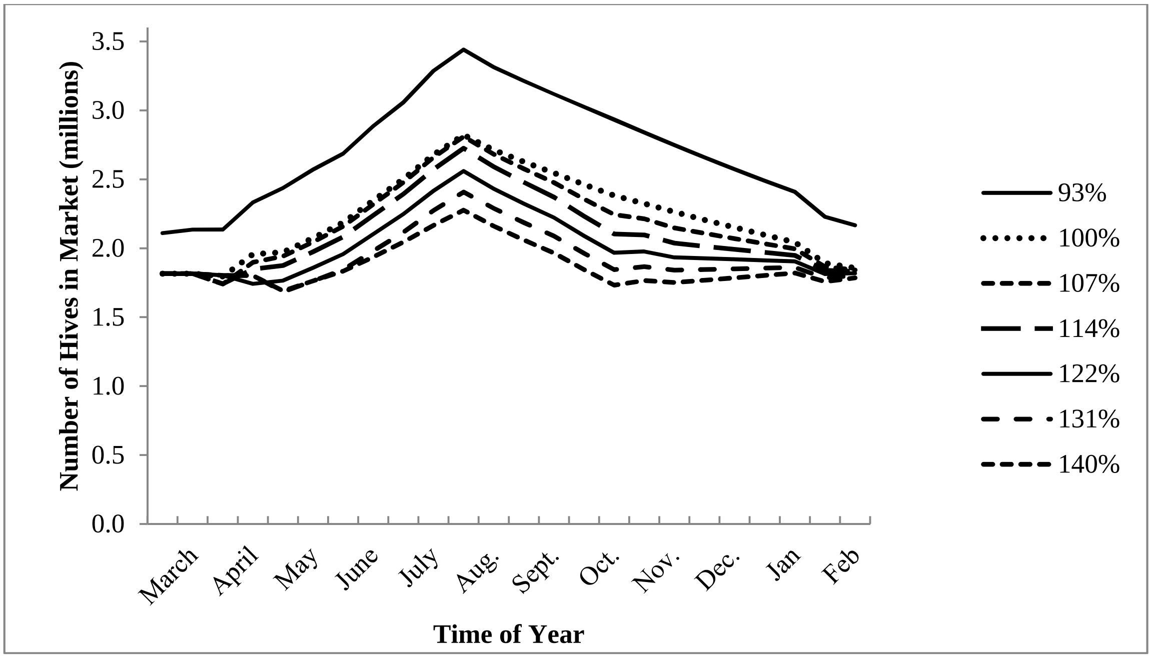

Figure 29: Fluctuation of hives throughout year given different winter survival scenarios relative to base

Surplus change as a result of colony loss is evaluated as a shift in the supply function, similarly to in the evaluation of surplus change due to an increase in the number of bees required on almonds. As seen in Figure 30, the model predicts substantial and increasing declines in total economic surplus as survival rates fall. This means that small changes in loss rates could have large impacts on economic surplus. However, this surplus loss is borne by the crop growers, and beekeepers actually see a rise in producer surplus as winter colony losses rise thanks to higher prices. It is important to note that this is a competitive market result; therefore no individual beekeeper would have an incentive to increase their losses, instead an overall increased loss rate resulting in higher pollination prices would benefit beekeepers as a whole.

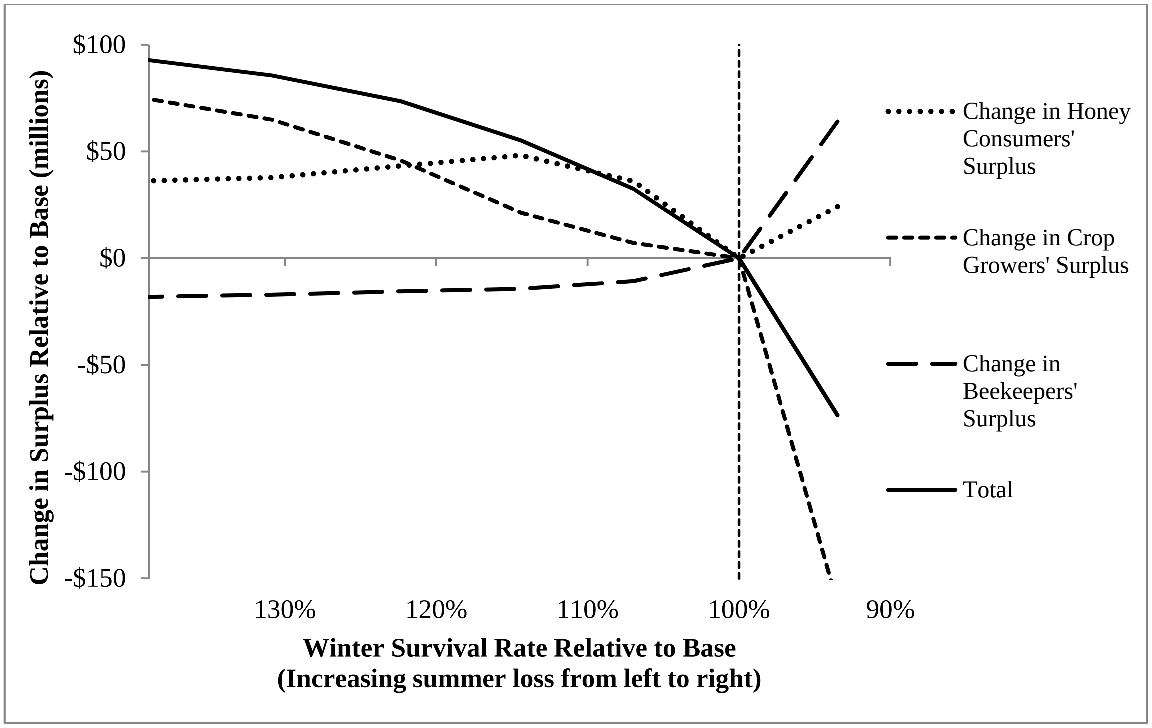

Figure 30: Surplus change relative to base winter survival rate

Change in Summer Colony Loss Rates

As discussed in Section 1.2, summer mortality has become a significant problem for beekeepers in recent years, and during some years has even surpassed winter mortality (Steinhauer, et al. 2016, Steinhauer, et al. 2015). Summer colony loss rates impact prices in a qualitatively similar fashion to winter colony loss rates in many ways, and similarly, at survival rates below 94% of base levels the model does not reach equilibrium during a 30-year simulation. A key difference between the impact of winter and summer losses is that declines in summer survival cause fees for early-blooming crops to fall more, pushing them closer to and even below the prices for late-blooming pollination[14]. Figure 31 shows a decline in almond pollination prices as loss rates go from slightly less than base levels to base levels, followed by a spike in almond pollination prices at higher loss rates. Honey price reactions to increased summer losses are qualitatively similar to the reactions to winter losses, as shown in Figure 32. Again, there exists a threshold such that at loss rates above base levels, a higher number of hives are maintained throughout the year (Figure 33). A change in summer survival rates also impacts surplus similarly to a change in winter survival rates, as depicted in Figure 34.

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[14] Note that there are far more late-blooming crops than early-blooming (early-blooming defined as mid-February to mid-March), both in the model and in reality; only a selection are presented in these figures to reduce clutter. Thus, there are more crops and more time periods later in the season to dilute the cost changes, and price increases on any one crop are dulled.

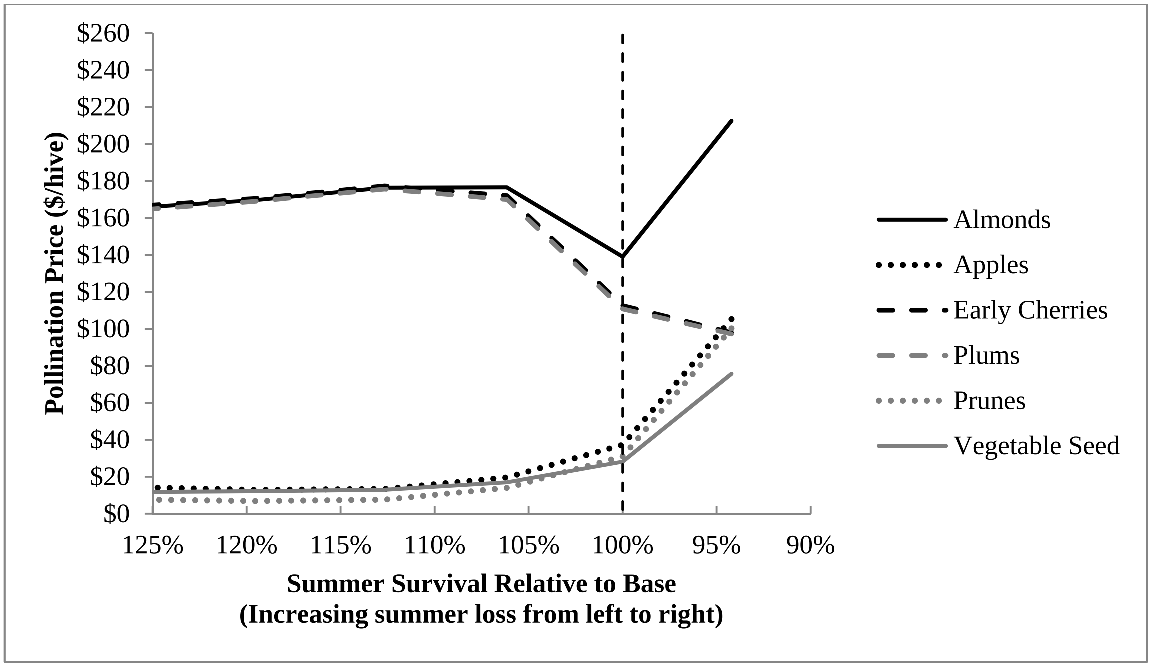

Figure 31: Impact of change in summer survival rates on projected pollination fees

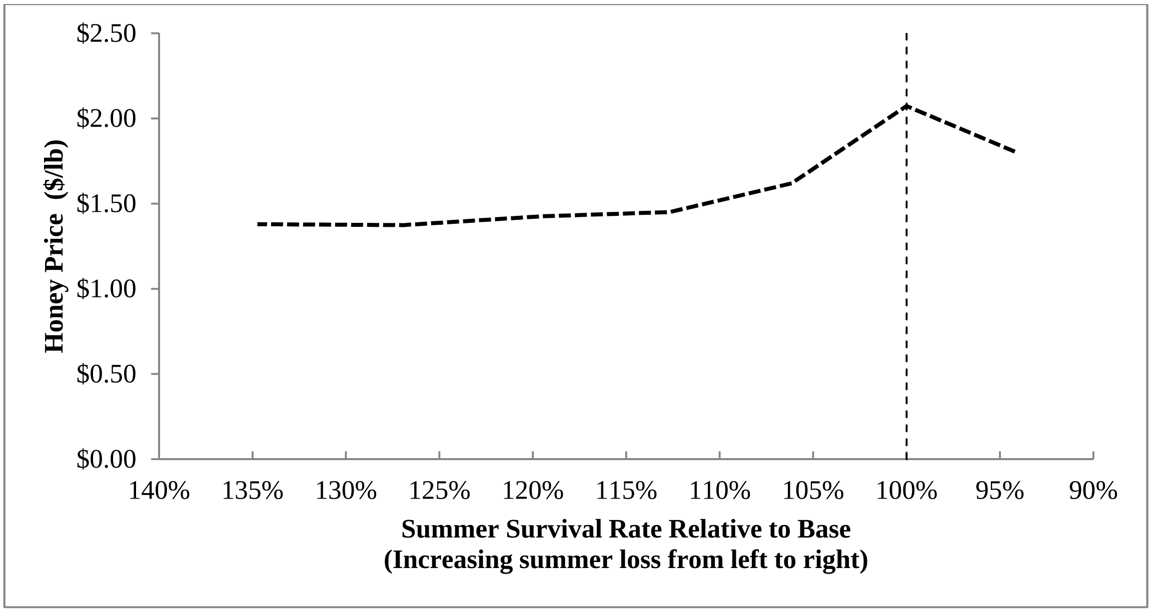

Figure 32: Impact of change in summer survival rates on projected honey price

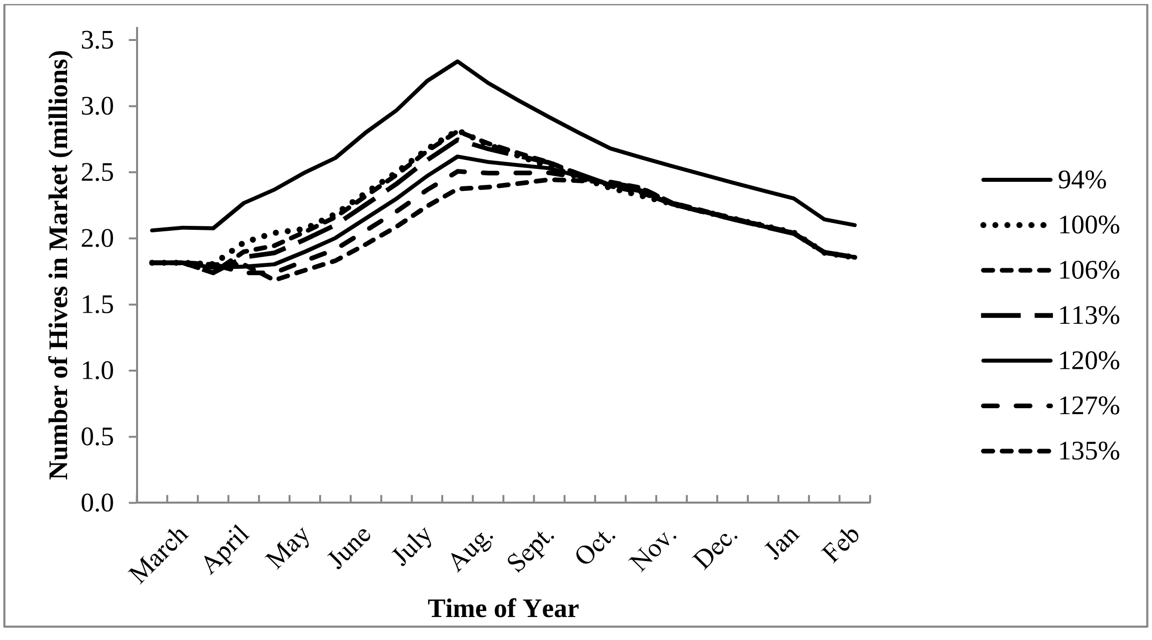

Figure 33: Fluctuation of hives throughout year given different summer survival scenarios relative to base

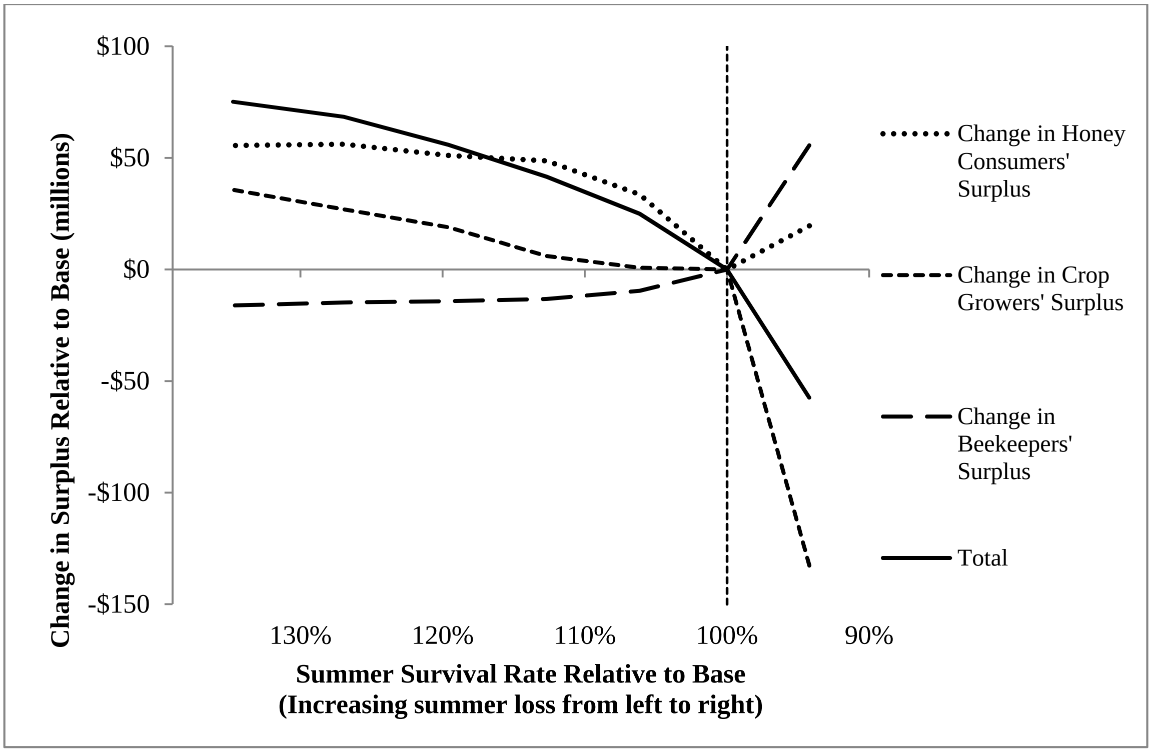

Figure 34: Surplus change relative to base summer survival rate

Summary of Scenario Analysis

The results of this section suggest that a fall in survival rates, either in summer or winter, or a decline in native bee populations around almonds would all result in a societal cost. These results also contribute to the explanation of the observed pollination price changes seen over the past decade. While an increase in the number of honey bee hives needed on almonds demonstrates a divergence between pollination prices for early-blooming and late-blooming crops, increases in summer or winter losses contribute to either a rise in both early- and late-blooming or a closing of the price gap, depending on the level of loss. This disagrees with the results of the conceptual model (Section 5.1), which found that colony losses would contribute to the spike in early pollination fees relative to others. In the conceptual model, there are no differences between the features of the early-blooming crops, but in the calibrated model each has its own set of honey production and population variation parameters. Based on the data discussed in Section 4, almonds have less attractive population change and honey production parameters than do the other early-blooming crops, leading to a different result.

The model finds that pollination prices can be affected by several forces that have been playing out in recent years. An increase in almond acreage is predicted to put upward pressure on early pollination prices and downward pressure on late pollination prices. An increase in either summer or winter honey bee mortality puts upward pressure on almond pollination prices, downward pressure on other early pollination prices, and upward pressure on late pollination prices. These predictions are consistent with the observed price changes in recent years. As shown in Figures 2 and 3, almond fees have seen the greatest increase, followed by other early-blooming crops, while later-blooming crops have remained stable. The results of the scenario analysis on the calibrated model suggest that the increase in almond acreage over the past decade is more responsible for the rise in early non-almond pollination fees relative to other prices than are loss rates.

6. CONCLUSION

Both native pollinators and commercial honey bees have faced threats in recent years. This research investigated the effects of a change in the number of honey bees required to pollinate almonds, a change in winter colony losses, and a change in summer colony losses on the market for pollination services and honey production. To achieve this, a model of the pollination and honey production market was developed that incorporated multiple sequentially and simultaneously blooming crops and the movement between these crops throughout the year. The model reproduced the observed rise in almond pollination fees and the relative increases of fees for early blooming crops relative to later blooming crops. Results from a scaled-down conceptual version of the model indicate that both increased almond acreage and increased mortality rates play important roles in the observed rise in almond pollination fees relative to others. However, simulations with the calibrated model suggest that the increase in almond acreage over the past decade is a more important cause of the observed price behavior, and that mortality rates and almond acreage have counteracting effects on pollination prices for crops other than almonds.

The validated model was used to predict the impacts of certain future changes on pollination and honey prices. Specifically, the changes investigated were changes in winter survival rates, summer survival rates, and number of hives demanded on almonds, the third of which could result either from increased acreage of almonds or declining populations of wild pollinators in the region. When used to simulate increased demand for hives on almonds, the model predicts a rise in pollination prices for early-blooming crops, and a decline in prices for honey and pollination of late-blooming crops. When simulating changes in survival rates, the model predicts, with some exceptions, a rise in almond pollination fees and late-season pollination fees and a fall in non-almond early pollination fees. Survival rates less than 93% of the base scenario resulted in an inability of the model to reach equilibrium on a 30-year simulation; suggesting a structural change in the market under these conditions that goes beyond the scope of this model.

Because managed colonies are used to replace wild pollinators in terms of crop pollination services, the calibrated model is used to predict economic surplus loss due to a diminishing level of pollination services provided for free by wild pollinators, predicting that crop growers are the most negatively impacted by this change, and that honey consumers actually benefit slightly. The model also predicts that overall economic surplus falls at an increasing rate as summer or winter survival rates fall, but that producer (beekeeper) surplus rises to an extent that is more than offset by the loss in surplus to crop growers.

Humans have been benefitting from the free labor provided by both wild and managed bees for thousands of years. That the public sees the bee as a crucial piece of society is evidenced by the popularization of recent alarms sounded over colony collapse, bee disease, and native pollinator decline and endangerment. Therefore, it is important to understand the potential consequences of threats to both honey bees and native bees, particularly those that are anthropogenic, and this is the primary contribution of this thesis.

6.1 Contributions

The major contributions and findings of this thesis lie in the development of a theoretically consistent and empirically relevant model of the honey production sector and the use of this model to predict the impact of a few specific factors on pollination prices. First, this thesis shows both theoretically and empirically that an increase in honey bees required to pollinate almonds causes prices for early-blooming crops (those that bloom at the same time as almonds) to rise and prices for late-blooming crops to fall. It shows theoretically and empirically that higher loss rates, whether occurring during the summer or winter months, cause almond pollination prices to rise, and that at certain higher levels of loss rates, late-blooming crops see a rise in pollination prices as well. However, the results imply that, at winter or summer colony survival levels below around 93% of 2012 levels, the market would change structurally in a way that cannot be represented by this model. The conceptual model shows that all else being equal, a crop blooming at the same time as almonds will see a similar pollination price increase as winter or summer survival falls, but the calibrated model finds that this is not the case for the specific early-blooming crops included in the model. Finally, this thesis predicts that, relative to the year 2012, if 35% more bees were needed on almonds to achieve the same level of pollination, this would result in a societal cost of around $100 million broken down into a $140 million cost to crop producers and a $40 million benefit to consumers of honey. The model also shows that loss survival rates dropping to 93% of 2012 levels would cost society between $50 and $75 million, but that economic surplus to beekeepers would increase.

Additionally, this thesis contributes to the literature on pollination markets by incorporating elements important for explaining observed pollination prices, including transportation costs and multiple simultaneous and successive bloom times. Empirically calibrating the dynamic model allowed for a structural description of the current pollination and honey-producing sector. Analysis of this dynamic model predicts the impact of changes in colony losses or demand for honey bee hives and evaluates change in economic surplus as the replacement value of a changing abundance of wild pollinators which has not been done elsewhere. Contributions to the literature on pollination are increasingly important as wild pollinators decline and national concern for security of insect-pollinated food crops rises.

6.2 Assumptions and Limitations

Limitations of this work include the assumption of an efficient market, the evaluation of the market in an equilibrium state, the assumption of perfectly inelastic demand for pollination, and the availability of data specific to the parameters in the model.

The model developed for this thesis assumes an efficient market in the pollination industry and no externalities between beekeepers, but there are a few reasons to believe the market is not perfectly efficient. Champetier (2010) points out that externalities arise from the diffusion of pollinators across property lines, and Morse and Calderone (2000) also discuss a "spillover," or free pollination, effect. Champetier et al. (2014) address a crowding effect in the production of honey, but this model assumes no crowding effect because of the smaller scale at which this would occur and because there is no empirical information available on the extent to which crowding would impact production. Because the input data used in this thesis is granular only to the regional level, neither of these issues can be captured in the model; increased granularity in future work may warrant incorporation of these inefficiencies.

Because the model is evaluated at equilibrium, it does not capture the changes that occur when shifting to a new equilibrium, meaning any costs or price changes that arise because of and only during the shift are not captured. In addition, it is unable to reach equilibrium under circumstances of low winter or summer survival, indicating that either some assumptions do not hold or that the market would not reach equilibrium under some circumstances.

A strong assumption that may not hold under all conditions is that of a perfectly inelastic demand for pollination services on major pollinator-dependent crops. In cases where the model was unable to reach equilibrium, a market change outside the scope of the model may associated with the breakdown of this assumption. Though within the neighborhood of current conditions a perfectly inelastic demand may be a reasonable assumption, at some levels of colony loss and when faced with exceedingly high pollination prices, perfectly inelastic demand may not hold. In that case it would be useful to estimate a pollination demand function similar to the theoretical one presented by Rucker et al. (2012).

The calibration of the model is also limited by the data available. First, it is focused only on the western part of the country due to lack of information available on pollination markets elsewhere, and thus is unable to simulate the entire U.S. market for pollination and honey. This does not allow for colonies outside this region to be incorporated, either through sales to beekeepers in the western region or through pollination movement between the east and west. Second, there is not sufficiently granular information available on population changes or honey production expected at various times and locations throughout the year, and data of the required granularity would be difficult to collect. Third, because information such as hive maintenance costs were collected through personal communication, they may not be as reliable as results of a robust survey. Because the USDA NASS is beginning to collect more information on the costs of pollination, improved calibration may be possible in the coming years.

6.3 Implications for Pollinator Biodiversity

When considering the cost of a loss in native pollinators, honey bee management costs are not the only factor. Although the ecosystem service of cultivated crop pollination provided by wild pollinators can, in some cases, be mostly replaced through the use of honey bees, this replacement could cause pollination of wild plant species to decline, resulting in associated societal and ecosystem losses. In addition, pollinator diversity is important in order to maintain ecosystem function and manage risk in the face of potential honey bee disease or other decline.

As Kleijn et al. (2015) point out, ensuring crop pollination is not necessarily a driver to promote pollinator biodiversity. Bees that provide the highest level of ecosystem service in crop pollination are not the threatened bees; they tend to be the more common bees with easily enhanced populations (Kleijn, et al. 2015). Furthermore, managed populations may actually contribute to decline of wild pollinator populations

(Melathopoulos, et al. 2015, National Research Council 2007). For example, transportation of bees over long distances may spread pests and diseases (Champetier de Ribes 2010).

More research is needed on the full impact of a loss in diversity of native pollinators. And because specific ecosystem service preservation or replacement is not necessarily in line with conservation of biodiversity, further work is needed in promoting pollinator diversity for the sake of the other, difficult-to-measure benefits provided by that diversity.

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APPENDIX: POLLEN AND NECTAR INDICES AND PARAMETERS

Table A1: Indices of Availability of Attractive Pollen Sources

Month	Period	CA	OR	WA	MT	ND	SD
End of Feb.	1	9	6	0	0	0	0
Mar	2	8	6	0	0	0	0
	3	16	4	5	1	0	0
April	4	14	4	5	1	0	0
	5	29	23	14	4	8	1
May	6	29	23	10	4	8	1
	7	35	33	24	5	9	2
June	8	28	25	18	4	9	1
	9	32	37	28	4	10	2
July	10	26	28	27	2	5	2
	11	29	31	33	2	12	2
Aug	12	17	21	19	2	12	2
	13	17	21	19	2	12	2
Sept	14	5	8	11	2	5	2
	15	4	8	11	2	5	2
Oct	16	4	3	0	0	2	1
	17	4	3	0	0	2	1
Nov	18	0	0	0	0	0	0
	19	0	0	0	0	0	0
Dec	20	0	0	0	0	0	0
	21	0	0	0	0	0	0
Jan	22	0	0	0	0	0	0
	23	4	3	0	0	0	0
Beg. of Feb.	24	4	3	0	0	0	0

Table A2: Indices of Availability of Attractive Nectar Sources

Month	Period	CA	OR	WA	MT	ND	SD
End of Feb.	1	8	1	0	0	0	0
Mar	2	7	1	0	0	0	0
	3	14	5	6	4	0	0
April	4	12	5	6	4	0	0
	5	17	20	22	7	7	1
May	6	17	20	17	7	7	1
	7	19	38	32	11	8	5
June	8	13	31	28	10	8	4
	9	21	41	38	10	12	8
July	10	19	30	37	8	9	8
	11	21	30	38	8	14	8
Aug	12	17	23	26	8	14	8
	13	17	23	26	8	14	8
Sept	14	13	13	17	8	8	8
	15	9	13	17	8	8	8
Oct	16	8	4	0	0	8	4
	17	8	4	0	0	8	4
Nov	18	0	0	0	0	0	0
	19	0	0	0	0	0	0
Dec	20	0	0	0	0	0	0
	21	0	0	0	0	0	0
Jan	22	0	0	0	0	0	0
	23	5	0	0	0	0	0
Beg. of Feb.	24	5	0	0	0	0	0

Table A3: Population Changes Used in Base Model

Month	Period	Almonds, Kiwis, Watermelons	Apples	Avocados	Blueberries	Cranberries	California Cherries	Cucumbers	Melons	Pears	Plums	Prunes	Squash	Washington Cherries	Vegetable Seeds	ND	SD	MT
End of Feb.	1	0.9986	1.0756	0.998568	1.0909	1.0909	1.0854	1.0854	1.0854	1.0756	1.0854	1.0854	1.0854	1.0756	1.0909	1.0885	1.0885	1.0835
Mar	2	0.996452	1.0756	0.996452	1.0909	1.0909	1.0831	1.0831	1.0831	1.0756	1.0831	1.0831	1.0831	1.0756	1.0909	1.0885	1.0885	1.0835
	3	1.097	1.1148	1.00924	1.0836	1.0836	1.097	1.097	1.097	1.1148	1.097	1.097	1.097	1.025616	1.0836	1.0885	1.0885	1.0986
April	4	1.0547	1.046	1.0547	1.0362	1.0362	1.0547	1.0547	1.0547	1.046	1.0547	0.970324	1.0547	0.96232	1.0362	1.0283	1.0515	1.0521
	5	1.0695	0.980076	1.0695	0.983756	1.0693	1.0695	1.0695	1.0695	0.980076	1.0695	0.98394	1.0695	1.0653	1.0693	1.0745	1.0662	1.0716
May	6	0.98394	0.974004	1.0695	0.983756	1.0693	1.0695	1.0695	1.0695	0.974004	1.0695	1.0695	1.0695	1.0587	1.0693	1.0745	1.0662	1.0716
	7	0.987528	1.0763	1.0734	0.990564	1.0767	1.0734	1.0734	1.0734	1.0763	1.0734	1.0734	1.0734	1.0763	1.0767	1.0767	1.0748	1.0755
June	8	0.983204	1.0704	1.0687	0.98532	0.98532	1.0687	1.0687	0.983204	1.0704	1.0687	1.0687	1.0687	1.0704	1.071	1.0767	1.0662	1.0716
	9	1.0715	1.0795	1.0715	1.0791	0.992772	1.0715	0.98578	0.98578	1.0795	1.0715	1.0715	1.0715	1.0795	1.0791	1.0788	1.0748	1.0716
July	10	0.981824	1.0787	1.0672	1.0733	1.0733	1.0672	0.981824	0.981824	1.0787	1.0672	1.0672	1.0672	1.0787	0.987436	1.0658	1.0748	1.0607
	11	0.87906	0.9469	0.9555	0.9724	0.9724	0.9555	0.87906	0.87906	0.9469	0.9555	0.9555	0.9555	0.9469	0.894608	0.9532	0.9029	0.9703
Aug	12	0.9458	0.9369	0.9458	0.9651	0.9651	0.9458	0.870136	0.9458	0.9369	0.9458	0.9458	0.9458	0.9369	0.9651	0.9532	0.9029	0.9703
	13	0.9458	0.9369	0.9458	0.9651	0.9651	0.9458	0.9458	0.9458	0.9369	0.9458	0.9458	0.9458	0.9369	0.9651	0.9532	0.9029	0.9703
Sept	14	0.9252	0.9274	0.9252	0.948	0.948	0.9252	0.9252	0.9252	0.9274	0.9252	0.9252	0.9252	0.9274	0.948	0.9386	0.9029	0.9703
	15	0.9219	0.9274	0.9219	0.948	0.948	0.9219	0.9219	0.9219	0.9274	0.9219	0.9219	0.9219	0.9274	0.948	0.9386	0.9029	0.9703
Oct	16	0.9806	0.9718	0.9806	0.9814	0.9814	0.9806	0.9806	0.9806	0.9718	0.9806	0.9806	0.9806	0.9718	0.9814	0.9824	0.9568	0.975
	17	0.9806	0.9718	0.9806	0.9814	0.9814	0.9806	0.9806	0.9806	0.9718	0.9806	0.9806	0.9806	0.9718	0.9814	0.9824	0.9568	0.975
Nov	18	0.9496	0.9718	0.9496	0.9545	0.9545	0.9496	0.9496	0.9496	0.9718	0.9496	0.9496	0.9496	0.9718	0.9545	0.9611	0.9436	0.975
	19	0.9496	0.9718	0.9496	0.9545	0.9545	0.9496	0.9496	0.9496	0.9718	0.9496	0.9496	0.9496	0.9718	0.9545	0.9611	0.9436	0.975
Dec	20	0.9496	0.9718	0.9496	0.9545	0.9545	0.9496	0.9496	0.9496	0.9718	0.9496	0.9496	0.9496	0.9718	0.9545	0.9611	0.9436	0.975
	21	0.9496	0.9718	0.9496	0.9545	0.9545	0.9496	0.9496	0.9496	0.9718	0.9496	0.9496	0.9496	0.9718	0.9545	0.9611	0.9436	0.975
Jan	22	0.9496	0.9718	0.9496	0.9545	0.9545	0.9496	0.9496	0.9496	0.9718	0.9496	0.9496	0.9496	0.9718	0.9545	0.9611	0.9436	0.975
	23	0.9806	0.9718	0.9806	0.9814	0.9814	0.9806	0.9806	0.9806	0.9718	0.9806	0.9806	0.9806	0.9718	0.9814	0.9611	0.9436	0.975
Beg. of Feb.	24	0.9806	0.9718	0.9806	0.9814	0.9814	0.9806	0.9806	0.9806	0.9718	0.9806	0.9806	0.9806	0.9718	0.9814	0.9611	0.9436	0.975

Table A4: Honey Production Used in Base Model

Month	Period	Almonds, Kiwis, Watermelons	Apples	Avocados	Blueberries	Cranberries	California Cherries	Cucumbers	Melons	Pears	Plums	Prunes	Squash	Washington Cherries	Vegetable Seeds	ND	SD	MT
End of Feb.	1	0.00	0.00	0.26	0.07	0.07	0.26	1.02	1.02	0.07	0.26	1.02	1.02	0.00	0.07	0.00	0.00	0.00
Mar	2	0.00	0.00	0.22	0.07	0.07	0.22	0.89	0.89	0.07	0.22	0.89	0.89	0.00	0.07	0.00	0.00	0.00
	3	1.78	0.47	0.45	0.35	0.35	0.45	1.78	1.78	0.35	1.78	1.78	1.78	0.12	0.35	0.00	0.00	0.94
April	4	1.53	0.47	1.53	0.35	0.35	0.38	1.53	1.53	0.35	1.53	0.38	1.53	0.12	0.35	0.00	0.00	0.94
	5	2.16	0.43	2.16	0.35	1.41	2.16	2.16	2.16	0.35	2.16	0.54	2.16	1.71	1.41	2.52	0.66	1.64
May	6	0.54	0.33	2.16	0.35	1.41	2.16	2.16	2.16	0.35	2.16	2.16	2.16	1.32	1.41	2.52	0.66	1.64
	7	0.61	2.49	2.42	0.67	2.68	2.42	2.42	2.42	2.68	2.42	2.42	2.42	2.49	2.68	2.88	3.29	2.57
June	8	0.41	2.18	1.65	0.55	0.55	1.65	1.65	0.41	2.19	1.65	1.65	1.65	2.18	2.19	2.88	2.63	2.34
	9	2.67	2.96	2.67	2.90	0.73	2.67	0.67	0.67	2.90	2.67	2.67	0.67	2.96	2.90	4.32	5.26	2.34
July	10	0.61	2.88	2.42	2.12	2.12	2.42	0.61	0.61	2.12	2.42	2.42	0.61	2.88	0.53	3.24	5.26	1.87
	11	0.67	2.96	2.67	2.12	2.12	2.67	0.67	0.67	2.12	2.67	2.67	0.67	2.96	0.53	5.04	5.26	1.87
Aug	12	2.16	2.02	2.16	1.62	1.62	2.16	0.54	2.16	1.62	2.16	2.16	0.54	2.02	1.62	5.04	5.26	1.87
	13	2.16	2.02	2.16	1.62	1.62	2.16	2.16	2.16	1.62	2.16	2.16	0.54	2.02	1.62	5.04	5.26	1.87
Sept	14	1.65	1.32	1.65	0.92	0.92	1.65	1.65	1.65	0.92	1.65	1.65	0.41	1.32	0.92	2.88	5.26	1.87
	15	1.15	1.32	1.15	0.92	0.92	1.15	1.15	1.15	0.92	1.15	1.15	1.15	1.32	0.92	2.88	5.26	1.87
Oct	16	1.02	0.00	1.02	0.28	0.28	1.02	1.02	1.02	0.28	1.02	1.02	1.02	0.00	0.28	2.88	2.63	0.00
	17	1.02	0.00	1.02	0.28	0.28	1.02	1.02	1.02	0.28	1.02	1.02	1.02	0.00	0.28	2.88	2.63	0.00
Nov	18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dec	20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jan	22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	23	0.64	0.00	0.64	0.00	0.00	0.64	0.64	0.64	0.00	0.64	0.64	0.64	0.00	0.00	0.00	0.00	0.00
Beg.of Feb.	24	0.64	0.00	0.64	0.00	0.00	0.64	0.64	0.64	0.00	0.64	0.64	0.64	0.00	0.00	0.00	0.00	0.00