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Economic Effects and Responses to Changes in Honey Bee Health

Peyton M. Ferrier, Randal R. Rucker, Walter N. Thurman, and Michael Burgett

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Abstract

Since 2006, winter losses of managed honey bee colonies in the United States have averaged 28.7 percent, approximately double the 15.0-percent historical rate. These elevated losses have raised concerns that agricultural and food supply chains will suffer disruptions as pollination services become more costly and less available. Despite higher winter loss rates, U.S. honey bee colony numbers have remained stable or risen since 1996, with loss rates showing no correlation with yearly changes in the number of U.S. colonies but being positively correlated with the rate of colony additions. Among pollinated crops, almonds and plums have had the largest increases in pollination service fees, rising about 2.5 and 2.4 times, respectively, in real (inflation-adjusted) terms since the early 1990s, with the largest portion of the increase occurring between 2004 and 2006. For other pollinated crops, real fees have risen at an average rate of 2-3 percent annually and do not show a marked increase since Colony Collapse Disorder appeared in 2006. For most crops other than almonds, the share of farmgate costs attributable to pollination service fees is less than 5 percent at the farm level and less than 1 percent at the retail level.

Keywords: pollination services fees, honey bees, cost of production, Colony Collapse Disorder

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Contents

On May 15, 2018, the report Economic Effects and Responses to Changes in Honey Bee Health was revised to correct the following errors: Table 1 real honey price was incorrectly stated as being in terms of dollars per pound and is corrected to read “(cents/pound).” The Figure 1 title was corrected to read: “U.S. honey bee colonies since 1982.”

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What Is the Issue?

Since 2006, annual winter losses of managed honey bee colonies have averaged 28.7 percent, approximately double the historical winter mortality rate of 15.0 percent. These elevated losses have raised concerns that agricultural and food supply chains will suffer disruptions as pollination services become more costly and less available. This study provides an overview of the pollination services market and the mechanisms by which beekeepers, farmers, and retail food producers adjust to increasing scarcity in the pollination services market. It also examines the empirical data on pollinated crop production, pollination service fees, and annual numbers of honey bee colonies.

What Did the Study Find?

Despite higher winter loss rates, the number of U.S. honey bee colonies has remained stable or risen between 1996 and 2016, depending on which of two data sources is considered. Winter loss rates have no negative correlation with yearly changes in the number of U.S. colonies at the national or State level, and loss rates have a positive correlation with the rate of colony additions, which may reflect strategies used by beekeepers to manage colonies.

Among crops pollinated by honey bees for which data are continuously available, almonds and plums have had the largest increases in pollination service fees, rising about 2.5 and 2.4 times, respectively, in real (inflation-adjusted) terms since the early 1990s, with by far the largest portion of the increase occurring between 2004 and 2006. For most other crops for which pollination fee data are available since 1987, real pollination service fees have risen at an average rate of 2-3 percent annually and have not shown a marked increase since colony collapse disorder appeared in 2006. For a few crops, real pollination service fees are lower now than in 1987.

Between 1988 and 2016, real beekeeper revenue per colony more than doubled. This increase resulted primarily from a doubling of real honey prices over that time span, as well as dramatic growth in both almond acreage and almond pollination service fees. Industry data indicate that in 2016, pollination service income accounted for 41 percent of beekeeper revenue, whereas pollination services accounted for only 11 percent of revenue in 1988. In 2016, 82 percent of all

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pollination service revenue came from almond pollination, implying that almond fees accounted for one-third (82 percent of 41 percent) of total beekeeper revenue in that year. The high share of almond service fees in pollination revenues can be attributed to the following: (1) almond fees are substantially higher than fees for other major crops, and (2) almond pollination accounts for 61 percent of all honey bee colonies rented and 52 percent of all crop acres that pay fees for pollination services. A primary driver of the increased share of pollination fee revenue over time is the dramatic expansion in almond acres—from 419,000 bearing acres in 1988 to 940,000 in 2016.

For most crops other than almonds, the share of total costs attributable to pollination service fees is less than 5 percent at the farm level and less than 1 percent at the retail level. That small share, along with the relatively modest changes in pollination service fees for most crops, will tend to make the effect of increasing pollinator health problems on food prices very small for most crops.

How Was the Study Conducted?

Historical data on pollination service fees were obtained from surveys of beekeepers in the Pacific Northwest since 1987 and California since 1993 and compared with recently released fee data from USDA's National Agricultural Statistics Service's Cost of Pollination Report. Farmgate-level pollination cost shares were compiled from data using two methods. The first method combines pollination fee data with data on yield, crop price, crop production, and stocking density to develop a cost of pollination and revenue per acre from crop production. The second method compiles crop production budgets created by State agricultural extension agents for farmers at the regional level. Retail cost shares were developed by multiplying these figures by estimates of retail-wholesale price spreads. Data on colony losses were obtained from annual data developed by the Bee Informed Partnership, while colony stock figures were obtained from USDA's annual *National Honey Report* and from the Census of Agriculture, which is administered by USDA every 5 years.

Economic Effects and Responses to Changes in Honey Bee Health

Introduction

The function that honey bees (*Apis mellifera*) play as pollinators of agricultural crops is important and has long been under-appreciated. In recent years, amidst rising concerns surrounding pollinator health (Henein and Langworthy, 2009; Walsh, 2013; Winston, 2014), the ability of beekeepers to quickly adapt managerial practices to changing conditions "on the ground" has been frequently overlooked as a way that markets moderate the potentially large economic costs associated with bee mortality. A beekeeper's livelihood relies on the health and productivity of his or her colonies. Beekeepers regularly monitor the size and health of their colonies, provide the colonies with disease and pest treatments, move the colonies to better foraging sources and sheltered environments throughout the year, and alter the genetics of the colonies by selecting for traits such as hardiness, docility, and productivity through purchases of queen stocks.

For beekeepers, management decisions on how many colonies to stock and where to place them depends crucially on the prices of outputs—honey and pollination services—and inputs—transportation costs, equipment, colony replacement costs, and health treatments. Beekeepers adjust the number of colonies they maintain in response to market signals (Muth et al., 2003), splitting or purchasing additional colonies to increase their stock and combining or purging colonies to decrease their stock. According to the most recent examination of the industry, commercial (managed) beekeeping is dominated by large enterprises (Daberkow et al., 2009). Based on data from the 2007 Census of Agriculture, that study found that large beekeepers (2,000 or more colonies) managed 4,095 colonies on average and 50.0 percent of all U.S. colonies; medium-sized beekeepers (300 to 1,999 colonies) managed 762 colonies on average and an additional 37.7 percent of all U.S. colonies.[1]

The role of beekeepers in providing pollination services to agriculture is not new—crop producers have been charged fees for hive rentals for at least 100 years. Now, however, pollination services account for a much larger share of beekeeper revenue than a century ago. In 1988, pollination revenue accounted for 11 percent of all beekeeper revenue (which includes Government payments, sales of beeswax, and sales of queens, nucs (replacement colonies), and packages to other beekeepers) and 17 percent of (the sum of) honey and pollination services revenue. In 2016, pollination services revenue accounted for 41 percent of all beekeeper revenue percent and 50 percent of honey and pollination services revenue (USDA-NASS, 2017a; Hoff and Willet, 1994).

Historically, beekeepers have addressed honey bee health challenges as a part of routine management. Pathogen transmission among honey bees is particularly easy because honey bees live densely in large numbers, forage across broad ranges of wild spaces, and interact regularly with bees from

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[1] In contrast, small beekeepers (25 to 299 colonies) managed 85 colonies on average in 2007. Based on average honey and pollination services revenue of $244 per colony (revenues of $340.3 million for honey sales plus $335.9 million for pollination services divided by 2.775 million colonies, USDA-NASS, 2017a), large, medium, and small beekeeping operations earned, on average, $998,000, $187,000, and $21,000 in annual revenue in 2016.

other colonies. Further, as a diseased colony's population declines, bees from other colonies may rob it of honey stores and contract disease in the process. In fall 2006 and over the ensuing winter and spring, a new health threat to honey bees emerged with a mysterious set of diagnostic symptoms in lost colonies. Entomologists soon termed this new threat colony collapse disorder (CCD). Between 2007 and 2015, winter colony loss rates averaged 28.8 percent, almost twice the 15.0 percent rate considered to be "normal" (Burgett et al., 2009; Lee et al., 2015; Pernal, 2008; Spleen et al., 2013; Steinhauer et al., 2016; Steinhauer et al., 2014).

This study provides an overview of the pollination services market and the mechanisms by which beekeepers, farmers, and retail food producers adjust to increasing scarcity in the pollination service market. It also surveys the empirical data on crop production, pollination service fees, and annual colony figures.

Background on the U.S. Beekeeping Industry

Beekeeping and Honey Bee Biology

A healthy honey bee colony is frequently termed a "super organism" because the helplessness and extreme interdependency of individual members result in the colony being able to survive only as a collective entity (Delaplane, 2016). Sterile female worker bees, which make up the majority of the colony's population, typically live from 5 to 7 weeks and provide nearly all the colony's nonreproductive labor. Worker bees progress through different behavioral stages in which they perform distinct tasks—initially cell cleaning, brood feeding, and comb building, and then progressing to foraging for sustenance and water. Comparably fewer in number, other bees in the colony include a single egg-laying queen and several hundred males (drones) that exist primarily to reproduce.

Although tending to stay close to the hive, worker bees will forage on flowering plants up to 3 miles away (Seeley, 2010). Flowering plants provide nectar that bees convert into honey and pollen that bees consume for protein. Within the hive, bees store honey and pollen in the hexagonal cells of the comb. Bees raise their young in brood combs, with each cell containing a fertilized egg (worker) or an unfertilized egg (drone) laid by the queen. During the summer season, an established managed bee colony typically consists of 30,000 to 50,000 bees with a single queen, honey and pollen stores, and multiple frames of new brood in different stages of development, all residing in the physical structure of the hive. To measure a colony's health and maturity, a beekeeper visually assesses the number and quality of frames of comb filled with pollen or honey or brood, assigning to the colony a "frame count."

In wild settings, healthy growing honey bee colonies reproduce by swarming in the spring and early summer, a process in which approximately half the colony's bees, including the already fertilized queen, spontaneously search out and relocate to a new prospective hive site (Seeley, 2010). Meanwhile, in the original colony, the remaining bees tend to the developing brood and build several specialized queen brood cells to replace their departed queen. The first of the new queens to emerge kills the other developing queens in their cells and then departs the hive to mate with nearby drone bees over the next week or so. After returning to the colony, the queen's stored semen enables her to lay eggs for about 2 years, in which time the colony might again swarm. Eventually, the queen becomes a poor egg layer. At this point, the colony typically kills and replaces her with a new queen.[2]

In cold weather, honey bees do not hibernate. Instead, they cluster within the hive to conserve heat while drawing down honey and pollen stores. Despite this survival mechanism, some winter mortality regularly occurs across colonies, and beekeepers have historically reported local winter loss rates as a way to gauge management challenges and market conditions. Trade publications have long discussed ways that beekeepers might reduce winter mortality rates, including moving colonies to warmer areas, enhancing the hive's protection against cold weather (e.g., moving bees underground or covering hives with insulation), and harvesting less honey in the fall.

Beekeepers intervene in other ways to improve the colony's health and facilitate honey collection throughout the year. They provide the colony with standardized pre-fabricated hives ("bee boxes")

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[2] In some cases, an exhausted queen will lay only unfertilized eggs that emerge as male drones. Shortly thereafter, the colony itself will collapse for lack of workers.

that contain regularly spaced, artificial frames upon which bees build their wax comb.[3] They also split a colony before it swarms. The new nucleus colony, or “nuc,” contains a queen, workers, and brood frames and is functionally similar to the original colony after 6 to 8 weeks. A beekeeper may use these nucs to bolster weak hives or to increase colony numbers. Alternatively, the beekeeper may sell nucs to other beekeepers seeking to replace their lost colonies or expand their colony numbers. Beekeepers may also separate out 3 to 5 pounds of the workers from a large colonies to sell them as “package bees” that can be combined with an existing colony or used to form a new colony. Beekeepers will also typically replace a queen nearing exhaustion with a new (fertilized) queen that they either reared themselves or purchased from queen breeders. Installing replacement queens enables beekeepers to improve a colony’s genetics and substantially reduce the lag time and mortality risk associated with a newly hatched queen leaving the hive to mate.

Migratory Beekeeping and Contracting for Pollination Services

Migratory beekeepers move colonies among distant locations to pursue better forage locations and to receive pollination services fees. Across agricultural enterprises, migratory beekeeping is unique in several regards. First, a beekeeper’s revenue comes from the sale of two co-products—pollination services and honey. In the Pacific Northwest, beekeepers managing more than 300 colonies earn about 63 percent of their income from pollination services, whereas beekeepers with 300 or fewer colonies earn about 32 percent (Burgett et al., 2010). According to data from USDA, National Agricultural Statistics Service (NASS) (2017a), at the national level, the shares of beekeeper income from honey and pollination services are about equal, with beekeepers with more than five colonies earning total revenues of $338 million from pollination services and $335 million from honey in 2016.[4] Second, in light of its super-organism biology, a bee colony is managed as a unit rather than as individual bees. The population of an individual colony varies seasonally and in response to environmental factors, with the individual bees continually dying and being replaced by the colony. Third, to provide pollination services to seasonal crops, beekeepers and their colonies must be highly mobile and will often travel several thousand miles over the course of a year. On average, a commercial beekeeper in the Pacific Northwest pollinates 5.5 crops per year over 6.8 counties, with each colony servicing 2.4 crops (Burgett et al., 2010). Fourth, unlike many other agricultural producers, beekeepers often neither own nor rent the land on which their bees forage (Daberkow et al., 2009). Finally, bees move easily across land boundaries and interact with both feral bees and other nearby managed bee colonies. This limits the extent to which beekeepers can maintain arthropod pest and disease management strategies common in other livestock management contexts.

Crop farmers typically contract for pollination services on a per colony basis, with an agreement that often specifies the colony quality (based on a frame count metric), the delivery date, the time span over which the colonies will remain in the field, and other factors[5] (Woodcock, 2012; Skinner, n.d.). Almond pollination in California has by far the largest demand for pollination services and also has

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[3] Developed and patented in 1852, Langstroth hive (named for its inventor, Reverend Lorenzo Lorraine Langstroth) arranged the space between frames to the enable beekeepers to more easily inspect and remove a comb without damaging it.

[4] In 2016, beekeepers also reported $148 million in “other income,” which includes sales of specialty bee products (beeswax, propolis, venom, pollen) and breeding stock (queen bees, packages, nucs). To the extent that breeding stock is sold to other beekeepers, it represents an internal transaction to the industry and should not be viewed as outside income, a distinction that might be important if beekeepers are now more likely to purchase queens or nucs from other beekeepers following large colony losses. Unfortunately, current USDA-NASS data on other income do not distinguish between shares of sales within and outside the industry.

[5] In contrast to the concentrated placement of colonies when honey is produced, farmers typically require beekeepers to distribute their colonies as close to crops as possible to maximize the pollination benefit.

one of the earliest blooms, beginning each year in February. Bee brokers often serve to intermediate the beekeeper and almond-grower transaction across thousands of miles. Beekeepers whose colonies are transported to California to pollinate almonds will usually place their colonies in nearby bee yards prior to the almond bloom so their bees can become active after their winter torpor. In some cases, bee brokers will provide staging areas and other services, such as winter locations that include comprehensive health management and feeding.

Regardless of whether the beekeeper is being compensated for providing pollination services, he or she always retains the colony's honey stores, an institutional arrangement in place since the emergence and development of migratory beekeeping (see box "The Emergence and Development of Migratory Beekeeping"). To harvest the honey, the beekeeper removes excess frames of honeycomb, uncaps them, and removes their contents with a centrifuge. Then, the honey is strained and bottled. This process is normally undertaken at the end of major honey flows. Although honey bees will produce honey from a wide range of blooms, the honey's quality and volume varies by crop. Almonds and cranberries, for example, are associated with poor honey quality, while basswood and clover are excellent.

The Emergence and Development of Migratory Beekeeping

Although evidence suggests that beekeeping dates as far back as the seventh century BCE (Toussaint-Samat, 1992, p. 28),[6] the development of markets for pollination services is much more recent (Burgett et al., 2010; Rucker and Thurman, 2010). In 1898, Doolittle references contemporaneous evidence showing the value of bees in improving the yields of clover, squash, buckwheat, and most fruits. Johnson (1973) suggests that the first recorded renting of colonies for pollination in North America was in 1910, while Lindquist (2016) states that the first bees were rented for pollination in New Jersey in 1909. Olmstead and Wooten (1987) indicate that plum and prune growers started renting hives for pollination services "beginning around World War I" and that their success led to the development of similar practices by growers of other fruits and nuts. Rucker and Thurman (2010) provide accounts of migratory beekeeping for the purpose of following the bloom and producing honey going back to the 1870s and suggest that there were commercial beekeepers who "were mobile, migratory, and large by the 1920s" (p. 9). They also provide several accounts of the provision of pollination services for pay in the 1920s, noting that many of the accounts are from California, and the extent to which the practice was widespread at that early date is unclear.

Olmstead and Wooten (1987) describe the rapid development of pollination markets in the early 1950s to service alfalfa seed after USDA research documented the yield benefits of honey bees. Cheung (1973) describes contemporary for-pay pollination arrangements between beekeepers and farmers in Central Washington. He also indicates that some of the beekeepers with whom he consulted were transporting a portion of their colonies to California each year to pollinate almonds in February and March. At the time, the pollination fees for almonds were a bit less than

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[6] Given its widespread referencing in ancient art and literature, honey was likely available to humans through foraging prior to recorded history. Evidence of apicultural management and bee breeding, as noted by Toussaint-Samat (1992), appears as manmade pottery hives showing on Egyptian wall frescoes dating from the seventh century BCE. The authors note, however, that until the 1700s, most honey harvesting likely destroyed the colony itself.

> those for local apples and cherries, which are among the first crops pollinated in Washington in the spring. Cheung (1973) suggests that the Washington beekeepers were compensated for the extra costs of transporting their bees to and from California through greater brood gains in their hives from placement in almond orchards.

As California's almond acreage has grown since the 1980s, almond pollination fees have increased as well, attracting distant beekeepers with home bases located far from the State's almond groves. In recent years, 60 to 75 percent of the honey bee colonies in the United States have been transported to California—some from as far away as Florida and North Carolina—to provide pollination services for the February and March almond bloom (Bond et al., 2014; Horn, 2005; Souza, 2011).

Increasing pollination services fees have resulted in a substantial increase in real beekeeper revenue per colony (see **table 1**). In 1988, revenue per colony was $63.85 in nominal terms and $111.25 in 2016 dollars (Hoff and Willett, 1994). Of this revenue, 52.7 percent came from honey sales, 10.9 percent from pollination services fees, and 36.4 percent from other sources (including Government payments and sales of queens, nucs, and beeswax.) In 2016, revenue per colony was $258.55 in 2016 dollars (USDA-NASS, 2017a). Of this revenue, 39.2 percent came from honey sales, 41.1 percent came from pollination services fees, and 19.9 percent came from other sources. Because 82.2 percent of all pollination services fees paid is from almonds (USDA-NASS, 2017a), pollination services revenue from almonds now accounts for over a third (33.7 percent) of all beekeeper revenue. Even if pollination services revenue is excluded from the calculations, current revenue per colony is still higher than its level in 1988. This stems primarily from the large increase in real honey prices rather than an increases in honey yields.

Table 1

Increases in per colony revenue and changes to revenue shares between 1988 and 2016

			Revenue per colony (dollars)				Shares of total revenue for:		
Year	Number of all colonies[1]	Number of honey-producing colonies[2]	All sources[3]	Excluding pollination services	Honey yield per colony (pound/colony)	Real honey price (cents/pound)	Honey (percent)	Pollination services (percent)	Other[4] (percent)
1988	NA	3,370,000	111.25	99.17	66.1	87.12	52.7	10.9	36.4
2015	3,132,880	2,660,000	260.50	153.97	58.9	204.26	39.2	40.0	19.9
2016	3,181,180	2,775,000	258.55	152.30	58.3	207.50	40.8	41.1	18.1

NA=Not available. 1. Third quarter number of colonies from the NASS *Honey Bee Colony Report* (which first reports data in 2015). 2. The number of colonies from the NASS *Honey Report,* which only counts colonies from which honey is pulled. 3. Prices are adjusted to their 2016 (real) values using the Producer Price Index. 4. "Other" includes sales of queens, nucs, or packages; beeswax, venom, and propolis sales; and Government payments.

Sources: USDA, Economic Research Service using data from Hoff and Willett (1994); USDA, National Agricultural Statistics Service (NASS), *Honey Report* (2017a); and USDA, NASS, *Honey Bee Colonies Report* (2016e).

Recent Colony Loss Rates and Colony Collapse Disorder

Beekeepers have long been concerned with the causes of bee colony losses. While colony loss can occur for many reasons, key factors include loss of forage and, consequently, poor nutrition (see Hellerstein et al., 2017); insecticide exposure; and biotic stressors, including diseases and parasites (see table 2). In fall 2006 and the ensuing winter, large numbers of honey bee colonies perished with distinctive diagnostic symptoms—brood stock and queens were both present, as were adequate food supplies, but the worker bees were absent entirely. This affliction was designated colony collapse disorder (Nordhaus, 2011).

At around the same time, general awareness of pollinator health problems was increasing and the Bee Informed Partnership—a collaboration involving leading research organizations in agriculture and science—began to collect data on winter colony losses at the national level. In the 10 years since 2007, U.S. winter loss rates have averaged 28.7 percent, ranging from 21.9 percent in winter 2011-12 to 35.8 percent in winter 2007-08 (table 3). Although no nationwide data are available before this 10-year period, several sources indicate that winter mortality rates were around 15 percent in previous decades (Burgett et al., 2010, Pernal, 2008, Rucker et al., 2016, Van Engelsdorp et al., 2007).[7] Most industry observers agree that current winter losses are roughly double their historic rate, although there is growing agreement that much of the recent mortality does not fall within the specific CCD diagnostic criterion (Bucciere, 2014).

Researchers have yet to identify a single specific cause of CCD.[8] In recent years, rates of loss attributable to CCD have declined, despite continued high rates of summer and winter loss. Although winter loss rates have fallen somewhat from their high levels between 2007 and 2010, they remain elevated. Moreover, data collected since 2011 suggest that colony loss rates are also high during the summer, a period in which nutrition is abundant and colonies are thought to be more resilient (although there is less historical data for comparison) (USDA-NASS, 2016e Steinhauer et al., 2016).

Although the higher mortality rates for managed honey bees over the last decade have increased beekeeper costs, the increased mortality rates have not been associated with concomitant declines in U.S. colony numbers (**table 2**). As discussed later in this study, the lack of correlation between winter losses and the number of colonies may be attributable to the ability of beekeepers to replace lost colonies (Rucker et al., 2016; Van Engelsdorp and Meixner, 2010). While remaining higher than historical averages, winter losses have abated somewhat in recent years (Entine, 2015; Rucker et al., 2016). Moreover, recent beekeeper-reported losses attributed to queen failure, starvation, Varroa

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[7] Pernal (2008) estimates that prior to the appearance of colony collapse disorder (CCD,), normal winter mortality was 15 percent, and VanEnglesdorp et al. (2007) report that during winter 2006-07, beekeepers experiencing normal losses had a mortality rate of 15.9 percent, on average. In the mid-to-late 1980s, colony losses for North American beekeepers were severely elevated following the arrival of the two species of honey bee mite parasites: Acarapis woodi and Varroa destructor. Prior to that time, skilled beekeepers maintained their average winter losses below 10 percent. After the arrival of the mites, for the 10-year period 1989-98, the average annual colony loss for commercial beekeepers in the Pacific Northwest was 22.6 percent (Burgett, 1998).

[8] De Miranda et al. (2010) note that “One highly diagnostic feature of CCD, and other historic “disappearing” disorders, is the absence of dead adult bees in or near the hive or signs of a diseased brood, which is highly atypical for a monocausal infectious disease and more symptomatic of acute poisoning or possibly a prolonged brood-free spell that upsets the age distribution of the worker bees in the colony. However, neither direct poisoning nor brood rearing problems were associated with CCD.”

mites (*Varroa destructor*), nosema, and small hive beetle (*Aethina tumida*) have, at times, all been greater than losses attributed to CCD (Lee et al., 2015; Spleen et al., 2013; Steinhauer, et al., 2014).[9]

Table 2

Winter loss rates for managed honey bee colonies in the United States and annual percentage change in colony numbers

Period ending	Winter loss rates (percent)	Honey colonies (thousands)	Year-to-year change in colonies (percent)
2006	NA	2,393	NA
2007	31.8	2,443	2.1
2008	35.8	2,342	-4.1
2009	28.6	2,498	6.7
2010	34.4	2,692	7.8
2011	29.9	2,491	-7.5
2012	21.9	2,539	1.9
2013	30.6	2,640	4.0
2014	23.7	2,740	3.8
2015	23.1	2,660	-2.9
2016	28.1	2,775	4.3
Average	28.7	2,544	1.2

Note: Averages for winter loss rates and percent change in colonies are the arithmetic averages weighted by the number of colonies. NA = not available.

Source: USDA, Economic Research Service using data from Bee Informed Partnership (2016), de Lange et al. (2013), Spleen et al. (2013), Steinhauer et al. (2016), and Steinhauer et al. (2014) for winter loss rates; USDA, National Agricultural Statistics Service, National Honey Report (2016d) for honey colonies; and Bee Informed Partnership (2016), de Lange et al. (2013), Spleen et al. (2013), Steinhauer et al. (2016), and Steinhauer et al. (2014) for percent change in colonies.

Honey Bee Mortality Rates and Colony Numbers

Despite the increase in winter loss rates, over the last 20 years, the number of managed colonies in the United States has either remained relatively stable (USDA-NASS, 2017a) or has grown (USDA-NASS, 2012) (fig. 1). Many studies have reported on the decline in the number of managed colonies from a historic high of 5.9 million in 1946 to the 2016 level of 2.8 million in the USDA *Honey Report* (HR) data (Walsh, 2013; USDA-NASS, 2017a). Despite the focus on recent bee health problems, the bulk of this decline occurred by 1982, before the Varroa mite and the several viruses it vectors had arrived in the United States. The drop in the earlier period likely stems from changes in the market for honey as a sweetener and the increased availability of imported honey (Muth et al., 2003).

The Honey Report and Census of Agriculture (Census) datasets have key differences. With the exception of 1982 to 1985, HR data have been collected continuously since 1946. VanEngelsdorp and Meixner (2010), Highland and James (2016), and Rucker et al. (2016) note that National Honey Report (NHR) data potentially double-count honey bee colonies that have been located in multiple States in one year. On the other hand, because the focus of the annual surveys is to measure U.S.

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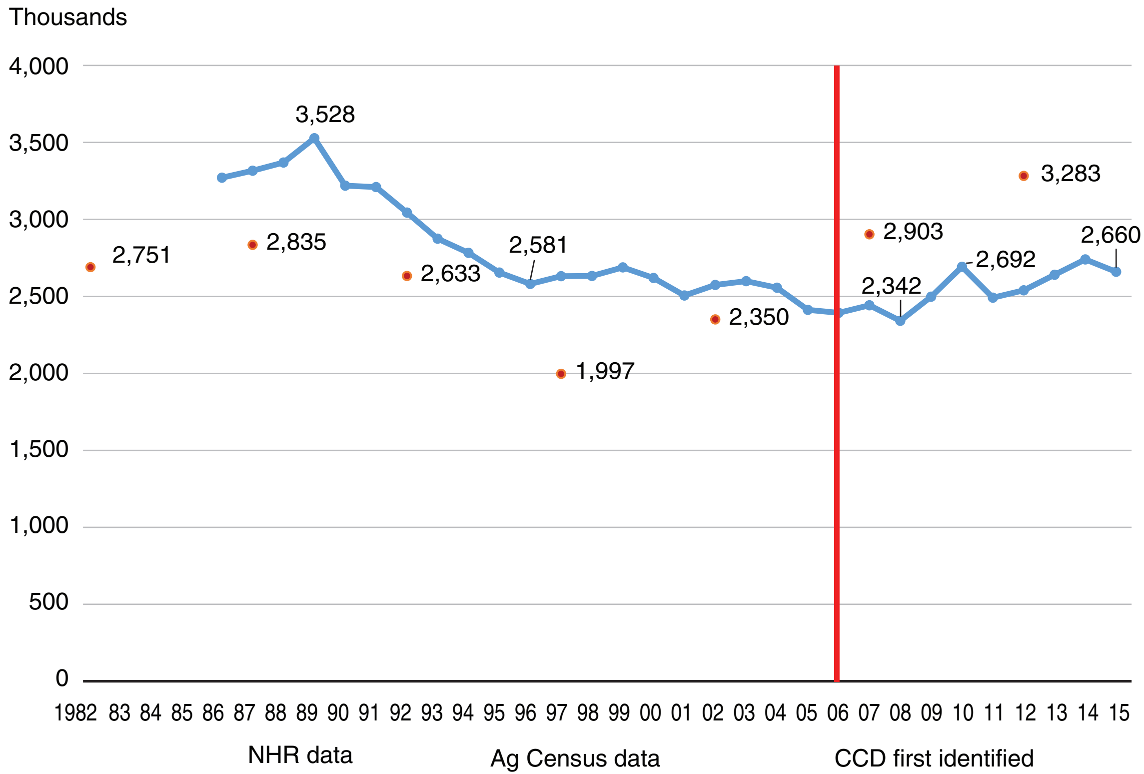
[9] Data from USDA-NASS (2016e) indicate that in 2015 and the first quarter of 2016, beekeepers self-reported that 20.4 percent of colony losses showed the specific diagnostic symptoms of CCD, although NASS does not independently verify the accuracy of the beekeepers' diagnoses.

honey production, the HR data do not count colonies not producing honey. After 1985, the annual HR survey stopped counting operations with five or fewer colonies. In contrast, Census data exclude beekeepers that do not produce or sell at least $100 worth of honey per year. Daberkow et al. (2009) and Highland and James (2016) note that because the Census counts bee colonies owned by farm operations on December 31, its total may not reflect the number of colonies actually producing honey in the summer.[10] The HR data show that colonies dropped from 3.5 million to 2.6 million between 1989 and 1996 and then ranged from 2.3 million to 2.8 million colonies through 2016. The Census data show a similar initial decline as colonies fell from 2.8 million in 1987 to 2.0 million in 1997 but then rose to 3.3 million in 2012, the highest year on record. Although the HR and Census counts on honey bee colonies have not tracked each other closely in recent years (Highland and James, 2016), it should be noted that neither dataset suggests that colony numbers have fallen dramatically since the appearance of CCD and the reported increase in pollinator health problems in the mid-to-late 2000s. Highland and James (2016) attribute the difference between the two datasets' colony counts primarily to the NHR data omitting colonies that do not produce honey, leading to an undercounting of the total number of colonies in that dataset.

Figure 1

U.S. honey bee colonies since 1982



Notes: CCD = Colony Collapse Disorder. NHR = National Honey Report.

Sources: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service (NASS); National Honey Report (2016c); and USDA-NASS (2014).

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[10] In the Census of Agriculture data, farms are defined as agricultural businesses that have the potential to sell $1,000 or more of a product in a given year. For beekeepers, this production includes earning revenue from sales of honey, queens, nucs, or pollination services.

An issue that arises when considering the impacts of pollinator health on honey bees and beekeepers is the nature of the relationship between winter mortality rates and colony numbers. Much of the public discussion of this topic assumes that increased winter loss rates lead to reductions in colony numbers. However, findings show no systematic relationship between winter loss rates and subsequent annual changes in the number of managed colonies (calculated from the annual NHR data) since loss-rate data were first collected for winter 2006-07 (**table 3**). The calculated correlation coefficient between the winter loss rate and the year-to-year percentage change in the number of colonies reported in the NHR data for the 10 available periods is -.0019, which is small and not statistically significant.[11] We also estimate the correlation between State-level annual changes in colony counts from the NHR and loss rates reported by the Bee Informed Partnership for the years 2008-15. Because the Bee Informed Partnership only began reporting summer loss rates in 2010, of the 280 total observations, only 190 include both summer and winter loss rates. All estimated correlation coefficients are positive and not statistically significant (**table 3**).

Table 3

Correlation between annual change in colony numbers and winter loss rates by State (NHR and BIP data, 2008-16)

Variable 1	Variable 2	Correlation statistics	Weighted[1]	Unweighted
Annual change in colony numbers	Winter loss rate	Coefficient est. (ρ)	0.0780	0.0014
		t-stat (H_0: ρ > 0)	0.0047	0.0001
		p-value (H_0: ρ > 0)	0.4981	0.5000
		Observations (n)	270	270
Annual change in colony numbers	Summer loss rate	Coefficient est. (ρ)	0.0402	0.0030
		t-stat (H_0: ρ > 0)	0.0024	0.0002
		p-value (H_0: ρ > 0)	0.4990	0.4999
Annual change in colony numbers	Sum of summer and winter loss rate	Estimate (ρ)	0.0796	0.0133
		t-stat (H_0: ρ > 0)	0.0048	0.0010
		p-value (H_0: ρ > 0)	0.4981	0.4996
		Observations (n)	190	190

Notes: 1. State colony counts are used to weight the correlation coefficient estimates.

Sources: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, National Honey Report (2007-16) and Bee Informed Partnership (2007-16). The Honey Report data are used to calculate the year-to-year change in the number of colonies for which honey is pulled at the State level (variable 1). Bee Informed Partnership (BIP) data provide rates of overwintering loss beginning, for some States, in the winter period from 2007 into 2008. After 2010, BIP data also report summer loss rates. Estimated correlation coefficients ($\hat{\rho}$) are calculated between the annual change in colony numbers and the winter loss rate, summer loss rate, and sum of the summer and winter loss rates, respectively.

The finding that the correlation coefficient between either winter or summer colony losses and year-to-year changes in colony counts is not significantly different from zero is further tested with data from the NASS Honey Bee Colonies report (USDA-NASS, 2016e). The NASS report provides State-level colony counts, colony loss rates, and colony addition rates (the number of colonies added through either splits or purchases of colonies) for the five quarters starting first quarter 2015 and through first quarter 2016. Data were collected through a nationwide survey of nearly all U.S.

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[11] Specifically, the Pearson Product-Moment Correlation Coefficient (r) can be tested as being significantly less than zero using a Student t-test with n-2 degrees of freedom, where t equals r/(((1-r^2)/(n-2))^0.5) or -0.0000302. Because the absolute value of estimated t-statistic is not greater than the critical value of 1.415 for significance at the 10-percent level, the null hypothesis of no correlation between the two datasets cannot be rejected.

beekeepers.[12] **Table 4** presents this information and also displays the 2015 annualized loss rates (which we calculate as the sum of quarterly losses divided by the sum of quarterly colony counts for each period in 2015), as well as the addition rates.

Table 4

Number of colonies (in thousands), annual change loss rates, and addition rates by State

	State	Q1-2015 number of colonies	Q1-2016 number of colonies	2015 average number of colonies	Annual change in colonies (2015-16) (percent)	Loss rate (2015) (percent)	Addition rate (2015) (percent)
1	Alabama	7.0	7.5	7.8	7.1	15.2	15.9
2	Arizona	35.0	30.0	36.0	-14.3	19.0	21.0
3	Arkansas	13.0	27.0	18.1	107.7	17.0	20.8
4	California	1,440.0	1,140.0	990.0	-20.8	12.2	12.6
5	Colorado	3.5	6.0	17.1	71.4	11.9	16.1
6	Connecticut	3.9	2.7	3.5	-30.8	8.8	11.7
7	Florida	305.0	245.0	224.8	-19.7	14.5	18.4
8	Georgia	104.0	100.0	109.0	-3.8	15.1	22.0
9	Hawaii	10.5	15.0	12.9	42.9	7.7	16.3
10	Idaho	81.0	90.0	86.0	11.1	10.4	8.8
11	Illinois	6.0	7.0	10.9	16.7	13.4	22.1
12	Indiana	9.0	6.5	10.9	-27.8	12.8	15.9
13	Iowa	12.5	16.5	22.3	32.0	10.7	10.0
14	Kansas	4.6	4.7	7.0	2.2	21.5	12.1
15	Kentucky	7.5	7.0	8.4	-6.7	18.6	12.1
16	Louisiana	51.0	68.0	50.0	33.3	7.9	6.5
17	Maine	3.1	2.2	4.6	-29.0	6.6	24.2
18	Maryland	7.5	6.5	7.5	-13.3	15.2	16.4
19	Massachusetts	2.9	3.0	4.8	3.4	8.4	8.0
20	Michigan	16.5	25.0	57.6	51.5	10.7	10.6
21	Minnesota	28.0	37.0	84.0	32.1	15.1	6.5
22	Mississippi	34.0	24.0	44.3	-29.4	10.1	16.0
23	Missouri	12.0	11.5	12.8	-4.2	8.2	5.6
24	Montana	8.5	15.5	75.1	82.4	6.8	6.5
25	Nebraska	10.0	10.5	44.5	5.0	8.5	9.1
26	New Jersey	6.0	8.5	10.3	41.7	4.9	7.0
27	New Mexico	7.0	6.0	6.5	-14.3	13.1	12.6
28	New York	27.0	31.0	35.0	14.8	12.1	11.5
29	North Carolina	24.0	18.5	22.4	-22.9	14.7	16.2
30	North Dakota	57.0	82.0	217.0	43.9	14.4	6.3
31	Ohio	18.0	16.0	19.4	-11.1	19.2	22.6

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[12] Although data were collected from all 50 States, information is only reported for 45 individual States. Information from the other five States (all of which are small honey producers and have relatively few honey bee colonies) is combined, as can be seen in the last entry in table 4.

Table 4

Number of colonies (in thousands), annual change loss rates, and addition rates by State - *continued*

	State	Q1-2015 number of colonies	Q1-2016 number of colonies	2015 average number of colonies	Annual change in colonies (2015-16) (percent)	Loss rate (2015) (percent)	Addition rate (2015) (percent)
32	Oklahoma	9.5	6.0	14.8	-36.8	7.5	14.5
33	Oregon	77.0	70.0	81.8	-9.1	15.1	8.3
34	Pennsylvania	14.0	12.5	19.1	-10.7	12.7	15.6
35	South Carolina	17.0	16.5	14.1	-2.9	12.0	9.4
36	South Dakota	50.0	30.0	159.8	-40.0	11.0	6.3
37	Tennessee	9.5	9.0	8.9	-5.3	13.7	14.6
38	Texas	191.0	240.0	174.3	25.7	10.7	25.3
39	Utah	6.0	12.0	22.3	100.0	14.3	15.8
40	Vermont	5.5	5.5	6.0	0.0	7.8	7.6
41	Virginia	8.0	6.5	7.8	-18.8	12.9	11.0
42	Washington	52.0	78.0	82.0	50.0	8.3	9.3
43	West Virginia	4.7	6.5	5.9	38.3	12.3	16.9
44	Wisconsin	16.5	22.0	37.4	33.3	14.8	9.8
45	Wyoming	5.5	2.7	17.6	-50.9	8.1	13.9
46	5 States (DE, NH, AK, NV, RI)	3.4	7.3	8.9	113.8	6.7	17.3
	United States	2,824.6	2,594.6	2,920.4	-8.1	14.7	12.8

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, Honey Bee Colonies (2016).

Table 5

Correlation between State average quarterly loss rates and year-to-year changes in colony counts (NASS, 2016)

Variable 1	Variable 2	Correlation statistics	Weighted[1]	Unweighted
Annual change in colony numbers	Loss rate	Coefficient est. (ρ)	-0.0985	-0.1688
		t-stat (H_0: $\rho > 0$)	-0.6568	-1.1359
		p-value (H_0: $\rho > 0$)	0.2573	0.1309
Annual change in colony numbers	Added rate	Coefficient est. (ρ)	-0.0417	-0.1289
		t-stat (H_0: $\rho > 0$)	-0.2767	-0.8620
		p-value (H_0: $\rho > 0$)	0.3916	0.1966
Loss rate	Added rate	Coefficient est. (ρ)	0.3040**	0.2213*
		t-stat (H_0: $\rho > 0$)	2.1168	1.5054
		p-value (H_0: $\rho > 0$)	0.0199	0.0695
		Observations (N)	46	46

Notes: 1. State colony counts are used to weight the correlation coefficient estimates. *Significant at the 10-percent level. **Significant at the 5-percent level.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service (NASS), Honey Bee Colonies (2016).

Table 5 provides additional estimates of the correlation coefficients. To address the possibility that States with few colonies may drive the results, correlation coefficients are calculated first with observations unweighted and then weighted by the yearly average number of colonies in each State. While the correlation coefficient between the annual change in colony numbers and the loss rate is negative, it is not significantly different from zero. Similarly, the correlation coefficient between annual changes in colony numbers and addition rates is not statistically significant either. This lack of correlation is likely attributed to efforts of beekeepers to replace lost colonies over the course of a year. Supporting this premise, the correlation coefficient between the loss rate and the addition rate is positive and statistically significant (see **table 5**).

Pollination Fees

The only comprehensive data that report U.S. pollination services fees are from the NASS Cost of Pollination report, which was released (for the first time) in December 2016. These data are obtained from a survey of farmers who pay beekeepers rental fees for honey bee colonies that provide pollination services. The survey collected information on crop type and acreage amount pollinated, the number of colonies, and the total amount paid per rental. Prior to December 2016, the only data available on the fees charged for pollination services were those collected through two related surveys of beekeepers in the Pacific Northwest (PNW) and California. The survey of beekeepers in the PNW extends back to 1987, while the first survey of beekeepers in California was in 1996. Note that beekeepers can and do travel outside their respective regions over the course of the year to provide pollination services and produce honey. For example, in 2015, 76.8 percent of pollination services fee revenue for beekeepers in the PNW came from almonds, which are produced exclusively in California's Central Valley (Sagili and Caron, 2016).

In the discussions and analysis of pollination services markets, an important consideration is the extent to which historical regional price data from the PNW and California surveys can be used to gain insights into pollination markets in other regions in the United States, especially because nationally representative data are only available for 2015 (with the release of NASS's Cost of Pollination report). The NASS data in **table 6** show that almond pollination fees accounted for 82.2 percent of all paid pollination service fees in the United States in 2015, which is close to the 76.8-percent rate based on prices in the survey of PNW beekeepers.

Table 6 also shows that the average cost of a colony rental for non-almond acres in the PNW ($54.12) differs by 1.3 percent from the cost in the NASS data ($54.80) and by 15.3 percent from the cost in California. This larger difference is explained (at least in part) by the much earlier bloom time of (early) cherries and plums in California, which forces those growers to pay California beekeepers pollination fees that are roughly equivalent to those paid for the simultaneously blooming almonds. Average per colony pollination fees fall from $121.4 to $54.8 when almonds are excluded from the calculation of average price. Even after price effects are excluded, the almond crop's share of acres pollinated and rentals of pollination services is large. Almonds account for 52.8 percent of all colony rentals and 60.5 percent of all acres on which rented colonies are placed.

U.S. crops are also serviced by other pollinators, notably the alfalfa leafcutter bee from Canada (see box "Leafcutter Bees in Alfalfa Seed Production"). The costs of importing this bee are primarily incurred by alfalfa seed producers and are excluded from NASS's Cost of Pollination report, which only covers payments for honey bee colonies.

Table 6

Price, colonies used, acreage, and cost-share statistics for pollination service fees by crop in 2015

Crop	1. Pollination fee per colony (dollars)	2. PNW survey pollination fee per colony (dollars)	3. CA survey pollination fee per colony (dollars)	4. Colonies used (thousands)	5. Paid pollinated acres (thousands)	6. Stocking density (5/4)	7. Pollination service fees paid (thousand dollars)	8. Pollination fees paid per acre (7/5) (dollars)	9. Crop's share of all acres paying pollination fees (percent)	10. Crop's share of all colonies rented (percent)	11. Crop's share of all pollination service fees paid (percent)
Alfalfa[5]	48.80	53.70	57.61	46.0	27.9	1.65	2,245	80.20	1.60	1.58	0.64
Almond	165.00	173.25	175.57	1,760.0	921.2	1.91	290,400	313.00	52.80	60.47	82.17
Apple	53.13	51.20	25.00	148.6	212.3	0.70	7,895	37.20	12.17	5.11	2.23
Avocado	27.70	NA	30.00	52.0	8.6	6.05	1,440	74.20	0.49	1.79	0.41
Blueberry[1]	72.79	64.00	NA	174.5	82.4	2.12	12,701	154.14	4.72	6.00	3.59
Cantaloupe	45.10	NA	NA	28.0	27.3	1.03	1,263	46.30	1.56	0.96	0.36
Cherry[1,2]	54.16	51.30	121.63	135.2	97.7	1.38	7,323	74.95	5.60	4.65	2.07
Clover	35.70	NA	NA	10.0	7.6	1.32	357	38.80	0.44	0.34	0.10
Cranberry	70.37	65.00	NA	80.5	35.8	2.25	5,665	158.46	2.05	2.77	1.60
Cucumber	51.82	30.00	NA	49.5	60.2	0.82	2,565	42.64	3.45	1.70	0.73
Honey dew	49.90	NA	NA	8.0	8.7	0.92	399	45.80	0.50	0.27	0.11
Kiwi	33.60	NA	NA	6.5	2.5	2.65	218	86.80	0.14	0.22	0.06
Pear	52.00	51.00	NA	30.0	27.8	1.08	1,560	56.00	1.59	1.03	0.44
Plum[1,3]	85.50	NA	165.57	20.0	13.0	1.54	1,710	117.00	0.75	0.69	0.48
Pumpkin	72.56	46.80	NA	12.5	17.6	0.71	907	51.53	1.01	0.43	0.26
Raspberry	86.21	NA	NA	14.5	9.8	1.48	1,250	127.55	0.56	0.50	0.35
Squash	49.82	46.80	NA	21.9	21.6	1.01	1,091	50.51	1.24	0.75	0.31
Sunflower	35.60	25.00	38.84	36.0	21.4	1.68	1,282	53.30	1.23	1.24	0.36
Watermelon	58.20	65.00	44.27	75.5	72.1	1.05	4,394	60.94	4.13	2.59	1.24
Other crops [4]	43.61	NA	NA	201.1	69.4	2.90	8,769	126.35	3.98	6.91	2.48
All crops with almonds	**121.44**	**135.70**	**153.70**	**2,910.3**	**1,744.7**		**353,434**	**202.58**			
Crops without almonds	**54.80**	**54.12**	**63.16**	**1,150.3**	**823.5**		**63,034**	**$6.54**	**47.2**	**39.5**	**17.8**

Notes: NA = not available. PNW = Pacific Northwest. CA = California. 1. Total acreage and sales for blueberries includes tame varieties only, for cherries includes sweet varieties only, and for plums does not include prunes. 2. CA price refers to early cherries only. Late cherries pay $37.56 per colony. 3. CA plums price refers to plums only. Prunes pay $18.00 per colony. 4. In addition to the the 19 crops listed, the Cost of Pollination Services Survey targeted 14 other crops (apricots, caneberries, boysenberries, buckwheat, canola, grapes, macadamia nuts, mangoes, nectarines, oranges, peaches, prunes, strawberries, and turnips) and also allowed surveyed producers to write in payment values for crops other than the 33 target crops. Data are reported across six regions. In regions where the sample response for a specific crop was not large enough to protect confidentiality, the response was aggregated into an "other crops category." For this reason, "Other crops" can potentially include the 19 crops listed in this table if paid pollination for that crop a particular region is so small that NASS cannot report statistics on it without violating its data confidentiality rules. 5. See box "Leafcutter Bees and Alfalfa Seed Production" for a discussion of pollination costs that alfalfa seed producers are likely to pay for leaf cutter bees but are not ennumerated in the Cost of Pollination Survey.

Sources: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service (NASS), Cost of Pollination Report (2016b) for columns 1, 4, 5, and 7; and Caron and Sagili (2016) for columns 2 and 3. Columns 9-11 derived using NASS (2016b).

Leafcutter Bees in Alfalfa Seed Production

While the honey bee pollinates a wide variety of crops, in certain applications, other pollinators are preferred. Notably, the alfalfa leafcutter bee (ALCB, *Megachile rotundata*) is used widely as a pollinator in commercial alfalfa seed production owing, in part, to its different physiology (Pitts-Singer and Cane, 2011). The alfalfa flower includes a trigger that a pollinator must trip to release its pollen. Compared to ALCB, honey bees are small and averse to the strike of the trigger mechanism. Often, honey bee nectar foragers (which greatly outnumber pollen foragers) learn to avoid the trigger by boring through the flower from the side to avoid the trigger mechanism, thereby reducing their pollen exposure (Bohart, 1957).

ALCB are sold in their pre-pupal stage, and the bees' maturation and emergence as an adult insect are managed with temperature to coincide with the alfalfa bloom (Pitts-Singer and Cane, 2011). When sold in gallon quantities (roughly 10,000 live bees per gallon), typical stocking rates are 1 to 4 gallons per acre, but leafcutters are also sold in other format measurements and may also be used in conjunction with less expensive, less technically demanding honey bees (Mueller, 2008). In 2015, Montana alfalfa seed producers used ALCB at a stocking rate of 2.9 gallons per acre on 92 percent of the 7,400 irrigated acres (USDA-NASS, 2016a). The most recent data indicate that 121,000 alfalfa acres were harvested for seed in 2012 (USDA-NASS, 2012) while 27,900 alfalfa acres were pollinated by honey bees in 2016 (23.1 percent if acreages are similar across these years).

While ALCB are raised domestically, in 2016, the United States imported $18.8 million worth from Canada,[13] the sole import source. The extent to which one year's imports of ALCB are used in future years is unclear. Recapture of ALCB after alfalfa seed pollination is possible but technically difficult since the bees are solitary and nest in the ground. Since 2012, ALCB imports have grown steadily in volume terms, suggesting that imported bees are not being recovered to use in subsequent years. If recent ALCB import values exceeding $18.8 million over each of the last 3 years represent single-use purchases of pollination services, then the alfalfa seed crop represents the second-largest user of paid pollination services by value after almonds.

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[13] This corresponds to 745,000 pounds, or 314,000 gallons, of bees at a conversion rate of 2.37 pounds per gallon based on JWM Inc. (2017).

Table 7

Changes in real pollination service fees through 2015

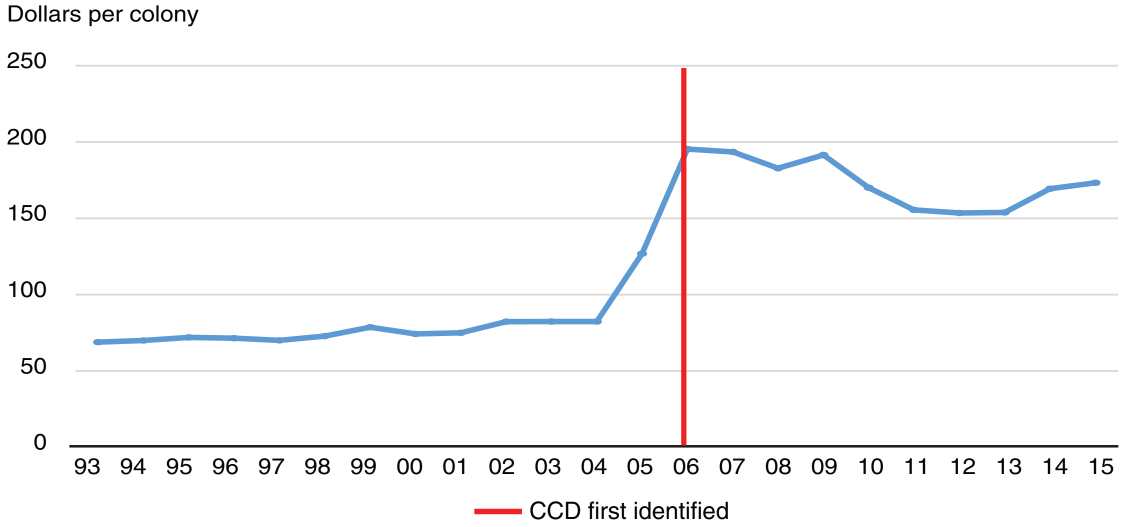
	Crop	Earliest year	Earliest fee (dollars per colony)	2015 fee (dollars per colony)	Ratio of earliest fee to 2015 fee	Annual rate of fee increase (percent)
Based on surveys of Pacific Northwest beekeepers	Almonds	1993	67.71	173.25	2.56	4.4
	Sweet cherries	1987	51.04	51.30	1.01	0.0
	Cranberries	1987	69.79	65.00	0.93	-0.3
	Blueberries	1987	33.37	64.50	1.93	2.4
	Clover seed	1987	35.36	53.70	1.52	1.5
	Pears	1987	46.52	51.00	1.10	0.3
	Apples	1987	47.73	51.20	1.07	0.3
Based on surveys of California beekeepers	Alfalfa seed	2002	48.22	57.61	1.19	1.4
	Almonds	1995	72.06	175.52	2.44	4.6
	Apples	1995	27.17	25.00	0.92	-0.4
	Avocados	1996	38.17	30.00	0.79	-1.3
	Cherries, early	1995	73.71	121.63	1.65	2.5
	Cherries, late	2002	28.61	37.59	1.31	2.1
	Melons, other	1998	39.59	47.44	1.20	1.1
	Plums	1995	70.22	165.57	2.36	4.4
	Prunes	1995	15.77	18.00	1.14	0.7
	Sunflowers	1995	29.50	38.84	1.32	1.4
	Vegetable seed	1995	39.44	61.18	1.55	2.2
	Watermelon	1998	44.82	44.27	0.99	-0.1

Source: USDA, Economic Research Service using Burgett et al. (2010) for pollination fees prior to 2008; Sagili and Caron (2016) for Pacific Northwest pollination fees after 2008; and California State Beekeepers Association (2016) for California pollination fees after 2008. Pollination fees are adjusted to their real values for the 2015 base year using the Farm Producer Price Index available on the USDA, National Agricultural Statistics Service website.

As shown in **table 7**, fees for pollination services as reported by beekeepers based in the Pacific Northwest and California have risen for most crops since the first period in which data were recorded. In California, real (inflation-adjusted) fees for pollinating almonds and plums increased 2.44 and 2.36 times, respectively, from 1995 to 2015. For most of the other crops for which pollination fee data have been available since 1987, real fees have risen at an average rate of 2-3 percent annually and have not shown a marked increase since the emergence of CCD in 2006. For some crops, such as cranberries, real pollination fees were actually lower in 2015 than in 1987. Almonds are heavily dependent on pollination services provided by managed honey bees, and the revenues from these services account for over 90 percent of total pollination service revenue for beekeepers in the PNW (Burgett et al., 2010) and 82 percent nationally (USDA-NASS, 2016f). Almond pollination service fees rose sharply in the winters of 2004-05 and 2005-06, which coincides roughly with the identification of CCD and the continued growth in almond acreage and demand for pollination services in California's Central Valley (**fig. 2**). Over the same period, the growth in pollination services fees for other crops was more muted (**fig. 3**).

Figure 2

Real pollination service fees for almonds based on surveys of Pacific Northwest beekeepers

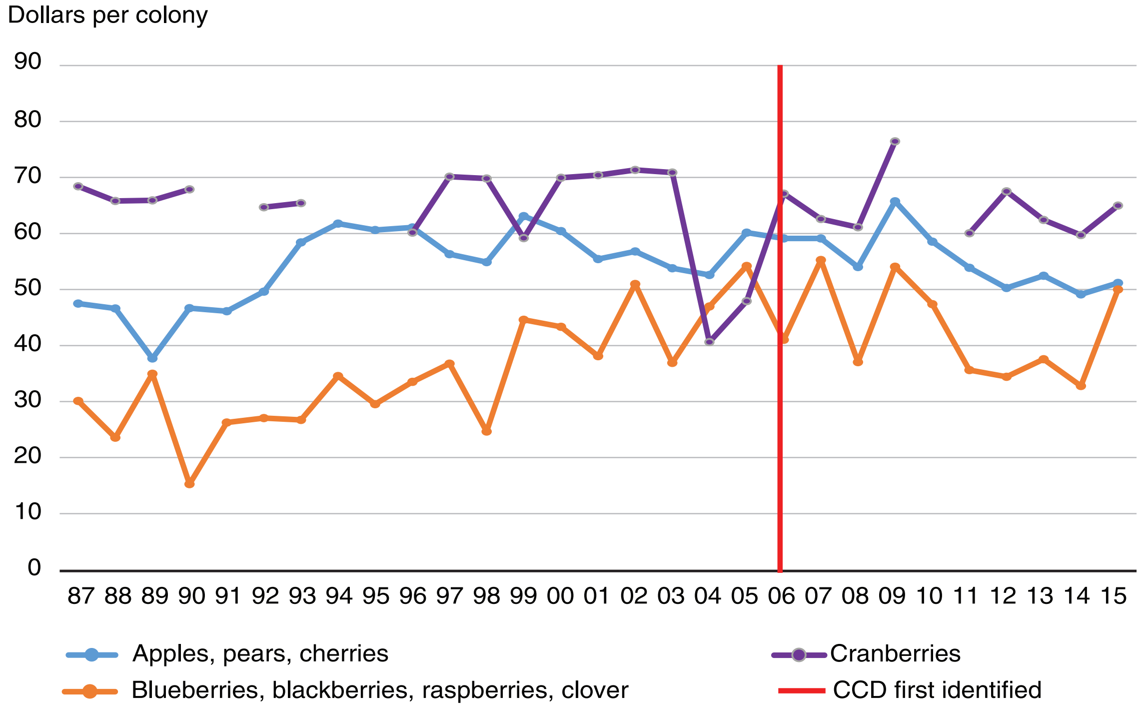


Note: CCD = Colony Collapse Disorder.

Source: USDA, Economic Research Service using data from Burgett et al. (2010a). All prices adjusted to 2015 (real) values using the Producer Price Index.

Figure 3

Real pollination service fees for other crops based on surveys of Pacific Northwest beekeepers



Note: CCD = Colony Collapse Disorder.

Source: USDA, Economic Research Service using data from Burgett et al. (2010a). All prices adjusted to 2015 (real) values using the Producer Price Index.

Whatever the long-run market impacts of higher colony loss rates in the mid-2000s, it seems likely that the immediate effect following the winter of 2006-07 was more severe. That period had one of the three highest recorded loss rates in history (see **table 3**). Moreover, these losses were likely neither anticipated nor evenly distributed across beekeepers. Anecdotal accounts suggest that some individual beekeepers suffered losses exceeding 50 percent, which left them scrambling to meet contract commitments for the California almond bloom. As expectations about loss rates adjust, however, beekeepers can increase their splits and colony numbers in the spring and summer and can also arrange to buy or swap hives with each other in anticipation of higher loss rates. And, as discussed in this study, beekeepers can adjust other management practices to actively reduce colony losses.

Supply-Side Colony Management Responses to Disease and Parasites

Beekeepers consider a variety of economic factors in making their decisions regarding colony numbers, including management and labor costs, transportation and pollinator health treatment expenses, and output prices of honey and pollination services. In general, the bee's reproductive life-cycle, as well as regulatory limitations on honey bee imports, constrain beekeepers to adding or re-stocking colonies in spring and summer.

Methods of Increasing Colony Numbers

When pollination fees or honey prices rise, the profitability of managing bee colonies increases, and beekeepers may choose to increase their colony stock using any of several methods. First, beekeepers can opportunistically capture swarms from existing hives, although this likely plays a minor role in most operations (Ellis, 2015). Second, beekeepers can purchase mature or functionally complete nucleus colonies ("nucs") from other beekeepers. Third, they can create a new colony using packaged bees (which also contain a newly fertilized queen) that they purchase from firms that specialize in these products. The packages contain bees but lack comb, brood, and hive structure.[14] Fourth, beekeepers can split their own colonies, in which case they often purchase newly fertilized queens through the mail. Burgett et al. (2009) find that commercial beekeepers in the Pacific Northwest used splits in 78 percent of their hive replacements. The next most common methods were nuc purchases (16 percent of replacements), whole colony purchases (3 percent), and purchases of packaged bees (3 percent).

Colonies that are split are typically divided into two parts. This process, which is also referred to as "making increase," has been a common industry practice for many years. To make increase, the beekeeper moves a portion (typically less than half) of the healthy hive's population of adult bees and brood to a new hive to form a nuc. The queen of the "parent" colony is normally left in place. For the nuc, beekeepers may install a queen cell that they produce or they may purchase a newly fertilized queen from a commercial queen breeder (in aggregate, these breeders annually produce hundreds of thousands of queens for sale, Essoyan, 2012). Following the split, the original hive (now with a diminished population) will be strong enough to pollinate crops within 3 weeks, if not immediately, and the new hive (nuc) will be able to provide pollination services in about 6 weeks.

In California, splitting typically begins in March, after almond pollination is complete. In Oregon and Washington, beekeepers usually start making increase in April, with the difference in timing dictated by weather considerations. In addition, commercial beekeepers will make nucs at various points in the season to rejuvenate declining colonies and in anticipation of winter colony losses. As mentioned earlier, a typical split generates two colonies from a single colony.[15] Further, in the course of a summer, a beekeeper can split a strong colony two or three times. If a hive is split twice, a single healthy colony can be increased to four colonies in a season, and so forth. In describing alterna-

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[14] For several years following the appearance of CCD, Australia was a leading source of packaged bees, largely because it could provide packages in time for almond pollination. Disease concerns led the United States to prohibit the importation of these packages in December 2010.

[15] Beekeepers will occasionally split colonies to create three, or even four, colonies from a single healthy colony but only if the parent colony has considerable excess brood and adult bees.

tive methods of splitting colonies, Bush (2006) states that, while sacrificing most honey production, splitting a strong colony five times in a year is feasible.[16] Having a previously fertilized (typically purchased) queen in hand at the time of each split (as compared to letting the bees in the nuc produce their own queen) expedites the colony's formation of brood by shortening the time needed before the colonies are strong enough to be split again.

Using a bioeconomic model in which beekeepers manage colonies to optimize revenue from honey collection and pollination service fees, Champetier et al. (2015) show that, as long as beekeepers collect honey, the steady-state level of managed colonies is lower than the maximum total number of colonies that can be supported on bee forage acreage.[17] In this model, bee populations can be reorganized across colonies by having the beekeeper move brood frames between bee hives, but the ability of the colony to sustain itself through dormant periods depends on its honey and pollen stores.[18] When beekeepers collect excess honey, they potentially reduce the nutrition available for bees to survive overwintering periods. If beekeepers collect less honey, they can maintain a larger bee population (either by splitting colonies to maintain more of a fixed size or by having a fixed number of colonies with large bee populations). Beekeepers manage their annual honey harvesting rates to maximize their sum of near-term profits from honey collection and future discounted profits from their stock of colonies earning both pollination service and honey revenue.

In addition to enabling beekeepers to expand their colony stock, splitting colonies provides beekeepers with a way to respond relatively quickly and economically to colony losses. Splitting is seasonal in temperate areas because queen egg laying and hive activity diminish greatly during cold winters. Until temperatures rise in the spring, neither queens nor drones survive outside the colony so that new queens cannot mate. For this and other reasons, beekeepers may purchase fertilized queens relatively early in the spring to split colonies earlier than would be possible if they choose to use their own bees to produce queens (Essoyan, 2012).

Splitting to replace lost colonies involves relatively few explicit costs beyond the usual costs of maintaining a colony. Burgett et al. (2009) estimate costs in the late 2000s to be about $19, and Rucker et al. (2016) update those calculations and find the costs to splitting to be $23 in 2016 dollars. This amount comprises $18 for a replacement queen and $5 in labor costs to perform the splitting itself

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[16] Similarly, Champetier et al. (2015) find that bee populations grow about 2 percent daily throughout their 180- to 200-day period of seasonal activity, a growth rate corresponding to the colonies' capacity to double in size over five times in a season.

[17] The steady-state level is the number of colonies that beekeepers will optimally desire to maintain. This level is determined by various market factors, including honey prices, pollination service fees, loss rates, and management costs. Unexpectedly higher or lower loss rates can move the current level of colonies away from its steady-state level over the short run, but beekeepers will seek to move their colonies' holdings back to their optimal targeted number if they view long-run market conditions as unchanged.

[18] Champetier et al. (2015) argue that the common metric of colonies available on farms for pollination fails to account for differences in bee populations across colonies, which affect pollination service fees. Goodrich and Goodhue (2016) document that pollination service contracts for almonds specify higher payments for larger colonies (as measured by frame counts).

(assuming an hourly wage rate of $15), which takes a skilled beekeeper 20 minutes or less.[19, 20] In contrast, Burgett et al. (2009) estimate the cost of replacing colonies with packaged bees at about $52, with $50 for the package itself and $2 for the labor to install the package in an empty colony. Alternatively, Ellis (2015a, 2015b) lists the cost of queens at $20 to $30, and packages with queens at $70 to $120, with the prices of both queens and packages generally decreasing as the quantity purchased increases. Separately, the NASS Honey Bee Colony Survey (2017) reports national average costs of queen bees at $19 and package bees at $89 for beekeepers with more than five colonies and $33 and $109 for beekeepers with five or fewer colonies.[21]

The timing of splitting is such that it is unlikely to affect the beekeeper's opportunities to earn pollination service fees with the parent colony. As mentioned earlier, a common time to split colonies is shortly after the completion of almond pollination, the primary source of pollination revenue for beekeepers. After beekeepers transport their colonies back to their home bases, the time lag between almond pollination and other crop pollination (e.g., apples, cherries, and pears) is enough that beekeepers can split the colonies without foregoing other pollination income. In anticipation of winter mortality, beekeepers may also make increase (split their colonies) in late July and August—another time when pollination opportunities are limited and surplus honey has been removed.[22]

The extent to which splitting colonies reduces honey production is unclear. The timing of splitting in the spring also coincides with a period of relatively low honey flow, and the parent colony—if it is strong and healthy before the split—is capable of producing honey relatively quickly after the split. However, between two bee populations of equal size, a single large colony produces more honey than multiple small colonies (Farrar, 1968; Bhusal et al., 2011; Taha and Al-Kahtani, 2013). In other words, 1 large colony with 10 frames is often more efficient at honey production than two 5-frame colonies. Splitting may then reduce honey production later in the season, an outcome that may be reflected in reduced per colony honey yields. If present, this effect is likely to be limited only to the year in which a new colony is created, as beekeepers remove less excess honey to leave sufficient energy for the colony to survive the winter, a period in which the colony's population generally declines. Honey yields are highly variable across geographic regions and local climate conditions. We are not aware of any study that directly links splitting colonies (or colony loss) to reported honey yields using regional or national data.

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[19] These calculations follow the same methodology described in Rucker et al. (2012) and Burgett et al. (2010). The replacement queen cost is the average cost of 100 queens (as advertised in the March 2017 American Bee Journal) across the four queen breeders whose prices have been available continuously since the mid-1980s. Across all queen producers who advertised in the March 2017 *American Bee Journal*, the average is slightly higher at $23.11. Based on conversations with industry sources, we estimate shipping costs to be about $0.30 per queen.

[20] An additional cost of less than $1 per colony may arise if beekeepers need to physically move the newly created hive several miles from the parent hive to ensure that the relocated bees in the new colony do not migrate back to their original hive.

[21] Like splitting, the availability of beekeeping inputs and their prices are highly seasonal. Fertilized queens are most scarce in February in the United States because it is too cold for commercial queen production in most parts of the country. Whole colonies are cheapest immediately following the almond pollination seasons in March (Ellis, 2015). Nucs and fertilized queens are cheaper and more readily available in late spring and early summer than at other times.

[22] The normal costs of splitting can be contrasted with splits done under abnormal circumstances. Suppose, for example, a beekeeper suffers larger-than-expected winter losses and in early spring finds that he or she does not have enough colonies to meet almond pollination contracts. If the remaining colonies are split immediately, they will not be of sufficient strength to provide adequate pollination services and substantial pollination revenues will be foregone. In this case, the beekeeper is likely to immediately fill a portion of the almond obligations with the remaining healthy colonies and then find other ways to fill the obligations. For example, prior to 2010, packaged bees from Australia could be imported and combined into existing colonies. Also, arrangements might be made to exchange colonies with other beekeepers who have excess colonies.

Pollinator Health Risk and Pesticide Exposure

Pollination fees differ across crops and from farmer to farmer (Burgett et al., 2010; Cheung, 1973; Muth et al., 2003). For crops in which little marketable honey is produced, pollination fees are higher. Moreover, beekeepers may avoid or charge higher pollination fees for crops associated with increased risks to the colonies. In reporting on specific industry practices, Weaver and Weaver (2015, 2016) note that a Texas beekeeper oriented toward queen and package bee production avoids California almond pollination because the monoculture diet lacks sufficient protein for bees, and a Wisconsin beekeeper oriented toward honey production allows his bees to pollinate almonds but not cranberries, cherries, blueberries, and apples because of the use of insect growth regulators on these crops.

Honey bees can be exposed to agricultural insecticides through a number of channels (see box "Channels of Exposure of Honey Bees to Agricultural Insecticides"). It is beyond the scope of this report to provide a comprehensive review of the extensive literature on the effects of pesticides on pollinators and the rationale for, and impacts of, Federal and State regulations regarding their use. Through its statutory authority to set conditions for pesticide use through labeling restrictions, the U.S. Environmental Protection Agency (EPA) currently prohibits certain uses and methods of application of pesticides to prevent harm to pollinators. For example, the EPA restricts the spraying of some pesticides while flowers are in bloom (EPA, 2013) and has proposed prohibiting the use of a large array of pesticides on lands where farmers have contracted for pollination services and flowers are in bloom (EPA, 2015). States can also restrict certain pesticide application practices. In Iowa and California, pesticide applicators are required to notify beekeepers within a certain radius of a registered apiary prior to spraying. Other States facilitate voluntary notification. Eleven States sponsor Fieldwatch, a nonprofit that operates the BeeCheck website where beekeepers register and map their apiaries so that applicators may notify them prior to spraying (Fieldwatch, 2016).

Channels of Exposure of Honey Bees to Agricultural Insecticides

Insecticides are primarily used in two ways in agriculture. In foliar applications, the pesticide is sprayed on the plant surface to kill targeted insect pests. In seed treatments, a coating of hydrophilic pesticides (typically, neonicotinoids) is attached to the seed and is later absorbed into the plant. As the seed germinates, the pesticide is transported into the plant's stem and leaves. In planting, farmers often inject the seeds into the ground with a pneumatic (air-powered) seed drill that can eject exhaust dust containing the insecticide. Creswell (2016) describes how honey bees and other pollinators can be exposed to agricultural insecticides through five channels: (1) *insecticidal dust*, originating from seed treatment coatings; (2) *guttation fluid*[23] *and puddles*, which may contain pesticide residues and from which bees sometimes collect water for hive activity; (3) *direct contact with insecticidal sprays used on mass-flowering crops*; (4) *contact with insecticide residues on sprayed foliage and flowers*; and (5) *ingestion of insecticide residues in sprayed foliage and flowers.*

In reviewing the risk imposed on honey bees by pyrethroids and neonicotinoids (both widely used agricultural pesticide classes), Creswell (2016) notes that the effects of pesticides are

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[23] Guttation fluid is xylem sap on the tips or edges of plant leaves that has typically been forced up from that ground by root pressure when the soil has a high moisture level.

highly dose dependent, with several mechanisms affecting the dose to which pollinators might be exposed. These include the extent of overlap between spring seed planting periods and the bee's emergence from winter dormancy, the proximity of pollinator nesting and foraging sites to treated fields, and the diversity of alternative untreated local forage that can dilute the pollinator's level of exposure. Insects can metabolize small dosages of pyrethroids and neonicotinoids and, for this reason, these pesticides typically do not accumulate in the environment as did previously common insecticides including DDT (dichloro-diphenyl-trichloroethane). At the same time, sublethal doses can affect various aspects of honey bee behavior (learning, orientation, foraging, and feeding) and immunocompetence. Creswell further notes that the effects of pyrethroids and neonicotinoids will vary between managed honey bees and wild pollinators.

Biotic Stressors of Bees and Their Treatment

Bee pathogens can be fungal, viral, or bacterial. Certain insects and mites act as parasites and often serve as vectors of pathogenic viral diseases (see **table 8** and box "Biotic Stressors of Honey Bee Colonies"). In the classification by Ellis (2016), "significant" threats are widespread and likely to kill colonies if not actively managed, while "moderate" threats are common and will cause significant damage if not appropriately addressed.

Table 8

Biotic stressors of honey bee colonies

Name	Type	Threat assessment	First detection in U.S.
Varroa	Mite	Significant	1987
American foulbrood	Bacteria	Significant	Before 1920
Deformed wing virus	Virus	Significant	1980s
Nosema ceranae	Fungi	Significant	2006
Small hive beetles	Insects	Moderate	1996
Bears	Mammal	Moderate	Continually present
Viruses acting synergistically (ABPV, IAPV, KBV, sacbrood virus, black queen cell virus, chronic bee paralysis virus)	Virus	Moderate	1980s
European foulbrood	Bacteria	Moderate	Before 1920
Greater wax moth	Insects	Moderate	Before 1840s
Nosema apis	Fungi	Moderate	Before 1920
Lesser wax moths	Insects	Moderate	Before 1980
Tracheal mites	Mites	Moderate	1980s
Chalkbrood disease	Fungi	Moderate	1960s

Sources: USDA, Economic Research Service using Jamie Ellis (2016).

Timeline for the Introduction of Biotic Stressors of Honey Bees

Some of these biotic stressors are long established, while others have only arrived recently. Bears have, of course, always been present in the United States. For greater or lesser wax moths, Shimanuki et al. (1980) indicate that U.S. patents were being granted for traps to control the moths as early as the 1840s. Prior to World War I, U.S. beekeeping operations were exposed to American and European foulbrood, and researchers had started studying *Nosema apis,* a fungal pathogen. In the 1960s, chalkbrood—another fungal disease—was first discovered in Utah and by 1975 had been detected in 34 States. In the early 1980s, the complex of three related viruses—Acute Bee Paralysis Virus (ABPV), Kashmir Bee Virus (KBV), and Israeli Acute Paralysis Virus (IAPV)—was identified in the United States (De Miranda et al., 2010). In 1987, Varroa mites were detected in the United States and then spread across the country within a few years (Rosenkranz et al., 2010). Ellis (2016) describes the Varroa mite as currently being the greatest biotic stressor of bees, both in its capacity as a parasite and by acting as a vector for viruses, including the ABPV, KBV, and IAPV virus and the Deformed Wing Virus. In fact, Ellis (2016) argues that control of the Varroa mite should be the primary approach for prophylactically preventing the spread of most viruses. The small hive beetle arrived in 1996 (Hood, 2000), and the fungal pathogen *Nosema ceranae* (originally endemic to *Apis cerana*, Asian honey bees) was detected in the *Apis mellifera* populations as far back as 1996 (Chen et al., 2008).

Ellis also describes prophylactic and remedial health measures to control biotic stressors of bee colonies.[24] Prophylactic measures are designed to prevent pollinator health problems before they arise, whereas remedial health measures involve treatment of diseases and parasites that are already in the hives.

Bacterial diseases, in particular American and European foulbrood (*Paenibacillus larvae, Melissococcus plutonius*), can be treated prophylactically by dusting the top of the colony with antibiotics (terramycin, tyrol) several times over a 5-day period. Because American foulbrood is highly contagious, most colonies (and the physical hives that contain the foulbrood) are destroyed if found to be infected. Varroa and tracheal mites (*Varroa destructor, Acarapis woodi)* are treated both prophylactically and remedially with miticides (coumaphos, amitraz, thymol) that are placed as wafers or strips in or below the hive. Early in the season, bees can also be sprayed with oxalic acid, which is more toxic to mites than to bees. Control of Varroa mites is also the primary way to prevent the spread of viruses that typically have no direct treatments. In addition to Varroa treatments, tracheal mites can be treated with menthol crystals that evaporate to form a gas that kills the mite, or with sugar and vegetable oil patties that once eaten by the bee prevent the mites from moving to new bees. The fungal diseases, *Nosema apis* and *Nosema ceranae*, are both treated with fumagillin, a fungicide consumed by bees through a medicated syrup (Mussen, 2011a). Chalkbrood disease (*Ascosphaera apis*), another fungal disease, as well as insect pests, such as greater and lesser wax moths (*Galleria mellonella, Achroia grisella*), are controlled without chemical treatments. The small hive beetle (*Aethina tumida*), a different insect pest, can be managed nonchemically with traps or controlled with certain Varroa treatments (coumaphos

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[24] The commercial website Brushy Mountain Bee Farm (2016) also provided some information on bee health treatments discussed here.

miticides) in addition to administering a soil treatment (permethrin) to kill burrowing larva in the area surrounding the apiary (Mussen, 2011b).

Bees also have behavioral defenses to fight pathogens and parasites, and beekeepers frequently try to improve the genetics and hardiness of their colonies through breeding and the use of survivor stock (see box “Breeding and the Use of Survivor Stock in Combating Bee Disease”). Migratory beekeeping—along with the difficulty in limiting the interaction between managed and native bee populations—has likely exacerbated problems of disease transmission and general environmental stress (Simone-Finstrom et al., 2016). Moreover, the major expansion of almond acreage over the last 20 years has encouraged a massive co-location of otherwise geographically dispersed colonies to California’s Central Valley in the early spring, thus encouraging the spread of disease.

Breeding and the Use of Survivor Stock in Combating Bee Disease

The role of genetics in enhancing colony health is multifaceted. Bees maintain behavioral defenses such as grooming and hive defense to protect their colonies from many health problems. Also, as described by Harbo and Harris (2009), colonies displaying hygienic behavior have specialized bees (nest-cleaning bees) that uncap cells and remove brood (pupae) that have been punctured or infested with brood mites, small hive beetles, wax moths, and Varroa mites. In recent years, specialist beekeepers have begun breeding and selling queens displaying the Varroa Sensitive Hygiene (VSH) trait, a specialized form of hygienic behavior whereby colonies specifically detect and kill brood with viable and reproducing Varroa mites (Glenn Apiaries, 2014; Harbo and Harris, 2009; Harris, 2007; Spivak and Reuter, 2001; Villa et al., 2009). The VSH trait was developed primarily at the USDA Bee Research Lab in Baton Rouge, LA, one of four bee labs that USDA operates nationally.

Survivor stock refers to those colonies that survive the various biotic stressors that afflict honey bees. Historically, breeding from the pool of survivor stock represented a key tool for beekeepers to improve colony genetics. Through this process, beekeepers selected for healthy colonies entering winter periods and were more likely to split their healthiest colonies in the spring and summer.[25] Spivak and Reuter (2001) argue that reliance on nonlocal queen bees purchased from breeders selects for genetics that are not necessarily well adapted to the ecological and disease conditions of a locality. Furthermore, prior to the first discovery of the Varroa mite (*Varroa destructor*) in the United States in 1987, survivor stock may have been more robust than today because of the potential for genetic exchange between feral honey bees and managed honey bees when new queens are fertilized. Because feral bees were not managed and treated for health problems, they faced evolutionary pressure that selects for pathogen resistance and heartiness. With the appearance and spread of the Varroa mite, feral honey bee populations were largely annihilated, and the extent to which they have recovered today is not well understood.[26]

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[25] A colloquial term for the strategy of eschewing chemical treatments in Varroa-infested colonies with the purpose of selecting for bees resistant to Varroa mite is the (James) Bond Method, a reference to the 1973 movie Live and Let Die. Because the Bond Method leads to elevated short-run losses as densities of Varroa mites increase during the time when colonies develop resistance, beekeepers employing this method should keep those colonies isolated from colonies of neighboring beekeepers (Oliver, 2017; McNeil, 2016).

[26] Mikheyev et al. (2015) find evidence that feral honey bees have evolved rapidly following the massive losses from Varroa infestations to acquire some resistance to the parasite.

Demand-Side Responses to Increases in Pollination Costs

The supply of managed honey bee colonies is determined in part by the cost of operating a commercial beekeeping operation, with pollinator health problems increasingly having an effect on costs in recent years. The demand for colonies, on the other hand, reflects their value to farmers through increased crop yields and value.[27] From this perspective, pollination services provided by managed honey bees are an agricultural input in the same manner as land, fertilizer, irrigation water, and machinery. Basic economic intuition, supported by a large body of economic literature, suggests that a farmer's demand for an input depends on a variety of market factors (Hicks, 1963; Marshall, 1920). In the current context, the quantity of pollination services demanded is expected to depend on the price of the services (the pollination fee), the price of the fruit (or other crops) produced using those services, and the importance of pollination services in determining the quantity and quality of the fruit being produced.

Farmer-Level Substitution for Pollination Services

Bee health problems that result in unexpected reductions in the number of colonies available for pollination will cause the price of pollination services to increase. As the price of this input rises, profit-maximizing farmers will have an incentive to purchase fewer pollination services. It is useful here to break the farmer's response to the increased input price into two components.[28] First, for any given level of production, the farmer will substitute other inputs for pollination services—the substitution effect. For example, farmers may replace current seed varieties with more expensive varieties that have a greater tendency to self-pollinate and are less dependent on honey bees for pollination. Second, farmers will reduce production in response to the higher input costs even while keeping the relative shares of inputs the same—the output effect. The output effect is the change in the quantity of pollination services demanded because the increased price of pollination services will induce the farmer to produce less output.[29] For example, farmers might reduce the number of acres planted to crops that require pollination.

Two industry terms provide useful insights into the productive relationship between honey bees and specific crops at the farm level. *Stocking density* is the number of colonies placed on one acre of crop land to supply pollination services. While Rucker et al. (2012) show that stocking density varies systematically with crop type, they find that this rate exhibits almost no variation in response to changes in the cost of renting colonies for almonds or other crops considered. *Bee dependency* is a ratio that describes the reduction in a crop's yield that would occur if no bees were present for pollination. For example, a crop that has a bee dependency of 0.9 would see a 90-percent reduction in yield in the absence of bees. One key shortcoming of the bee dependency metric is its inability to account for the yield response to partial reductions in the number of colonies placed per acre.

In addition to yield response, other economic factors affect the farmer's demand for pollination services. A commonly used indicator of the responsiveness of the demand for an input to changes in

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[27] Cross-pollination facilitates hybrid vigor, which can increase both crop yield and uniformity.

[28] Here, as elsewhere in discussions of the concept of demand, we distinguish between movements along demand curves (changes in quantity demanded) and shifts in demand (changes in demand). The former results from changes in the price of the good in question. The latter results from changes in other factors that affect demand.

[29] Note that as farmers reduce output, the price of that output may increase, which will tend to moderate the decrease in the quantity of pollination services demanded.

its price is the price elasticity of input demand.[30] If responsiveness to a price change is small (i.e., demand is inelastic), farmers will only curtail their use of the input slightly as the price of the input rises. For pollination services, the elasticity is determined by three main factors: (1) the share of total farm production costs attributable to pollination services; (2) the availability of substitutes for pollination services (hybrid seed varieties, other pollinators, hand pollination, alternative inputs to increase yield); and (3) the responsiveness of demand for the crop itself to price. While (1) and (2) are determined primarily by farm-level production relationships, (3) is determined by retail buyers (and ultimately consumers) who combine the wholesale crop with other inputs to produce retail food goods. In general, as demand for the crop itself becomes less responsive to price increases (more inelastic), crop producers are better able to pass along the higher cost of pollination services to their buyers. In turn, this ability of crop producers to pass along a higher cost of pollination services makes them less responsive to increases in the price of pollination services when they make their pollination rental decisions.

The Farm Cost Share of Honey Bee Pollination

A farm's cost share of pollination services is the share of total farm costs attributable to the input. This share will vary with the crop-specific pollination services fees paid by the farmer, the stocking density per acre, the cost of other farm inputs, the farm's yield, and agricultural output prices. As suggested previously, pollination services fees vary across crops primarily for two reasons. First, crops that yield marketable honey pay lower pollination fees because the honey acts as a payment in kind to the beekeeper (Burgett et al., 2010; Cheung, 1973; Muth et al., 2003; Rucker et al., 2012). Second, pollination fees are substantially higher early in the pollination season because the demand for pollination services by almond producers dwarfs that from any other crop producers.

Table 9 provides 2015 estimates of pollination's share of (1) total costs at the farm level and (2) the retail price of food. The stocking density ratio, which affects both shares, is calculated as the total number of colonies used for pollinating a crop divided by the total number of pollinated acres for that crop. Avocados had an unusually high stocking density of 6.05 colonies per acre in 2015 (see table 6), but only a small share (14.5 percent) of total avocado acreage was pollinated commercially. Kiwi had the next highest stocking density at 2.65 colonies per acre; most crops stock at 2.00 colonies or less per acre. The first three columns in **table 9**—harvested acres, pounds produced, and total value of farm production—are obtained from NASS Farm Production Data. For most foods, the retail price per pound is obtained from ERS's Fruit and Vegetable Prices dataset (2015).[31] Pollination's share of costs at the farm level is calculated as the ratio of the pollination fee per acre to the value of farm production per acre.[32] Among the 16 crops considered, only almonds had the farm-level cost share of pollination services exceeding 5 percent. Cranberries, plums, and pumpkins had the next highest shares, with rates between 2 and 3 percent.

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[30] The price elasticity of demand is the percentage change in quantity demanded divided by the percentage change in price.

[31] Almond retail prices are obtained directly from the Walmart website.

[32] This calculation assumes that total costs are equal to total revenues, so can be thought of as the cost share in a competitive equilibrium.

Table 9

Price, colonies used, acreage farmed, percent of acres pollinated, and cost share—NASS data

Crop	1. Harvested acres (thousands)	2. Total value of farm production (thousand dollars)	3. Value of farm production per acre (1/2) (dollars)	4. Pounds produced (million pounds, fresh equivalent)	5. Farm revenue per pound produced[6] (2/4) (dollars)	6. Pollination fees paid per paid pollinated acre (dollars)	7. Pollination's share of farm costs: acres paying pollination fees (6/3) (percent)	8. Share of all farm acres paying pollination service fees (percent)	9. Retail price per pound (dollars)	10. Farm costs as a share of retail food costs[6] (5/9) (dollars)	11. Pollination's share of retail food value: farms renting colonies (10*7) (percent)	12. Pollination's share of retail food value: all farms (11*8) (percent)
Alfalfa	16,885.0	8,729,134	NA	NA	NA	80.20	NA	0.2	NA	NA	NA	0.0
Almond[5]	920.0	5,325,000	5,983	1,900	2.80	313.00	5.23	100.0	7.98	35.1	1.1	1.1
Apple	315.9	3,394,185	10,745	10,004	0.34	37.20	0.35	67.2	1.57	21.6	0.1	0.1
Avocado	59.3	295,797	4,990	448	0.66	74.20	1.49	14.5	2.24	29.5	0.4	0.1
Blueberry[1]	89.8	584,150	6,504	560	1.04	154.14	1.71	91.7	4.73	22.1	0.7	0.7
Cantaloupe[4]	54.0	207,498	3,843	1,377	0.15	46.30	0.91	52.9	0.54	27.9	0.3	0.1
Cherry[1, 5]	89.8	703,228	7,828	677	1.04	74.95	0.89	100.0	3.59	28.9	0.3	0.3
Clover[3]	NA	NA	NA	NA	NA	38.80	NA	NA	NA	NA	NA	NA
Cranberry	40.9	267,527	6,541	856	0.31	158.46	2.42	87.4	4.79	6.5	0.2	0.1
Cucumber[4]	118.7	345,670	2,912	1,769	0.20	42.64	0.92	50.7	1.30	15.0	0.1	0.1
Honeydew[4]	11.0	67,584	6,144	352	0.19	45.80	0.77	64.0	0.80	24.0	0.2	0.1
Kiwi	4.0	30,893	7,723	47	0.65	86.80	1.12	61.3	2.04	31.9	0.4	0.2
Pear	48.9	500,416	10,225	1,641	0.30	56.00	0.55	56.8	1.46	20.9	0.1	0.1
Plum[1]	434.7	331,197	762	870	0.38	117.00	2.29	20.1	1.83	20.8	0.5	0.1
Pumpkin	43.2	90,214	2,206	754	0.12	51.53	2.34	43.0	1.35	8.9	0.2	0.1
Raspberry	20.3	580,924	28,589	262	2.21	127.55	0.45	48.2	6.98	31.6	0.1	0.1
Squash	38.7	174,259	4,504	602	0.29	50.51	1.12	55.8	1.64	17.7	0.2	0.1
Sunflower[2]	1,510.0	559,257	NA	NA	NA	53.30	NA	1.4	NA	NA	NA	0.2
Watermelon[4]	118.5	579,011	4,886	4,020	0.14	60.94	1.46	62.3	0.33	43.7	0.5	0.3
Other crops	NA	NA	NA	NA	NA	126.35	NA	NA	NA	NA	NA	NA

Notes: NA = not available. 1. Total acreage and sales for blueberries includes cultivated varieties only. Cherries includes sweet varieties only. 2. Pollination services are used for seed production in alfalfa and sunflower only, which makes the total pollinated acreage of these crops far less than that for all planted acreage. Since seed prices are likely to be far higher than that of the underlying crop produced, we do not report farm prices and treat the crops themselves as final products. Since all fields are eventually replanted, the retail price shares are calculated as the crop's total expenditures on pollination services divided by the crop's value. 3. Clover is primarily planted for livestock forage and as a cover crop. No USDA data record its planted acreage or value in terms of those uses or as seed. 4. Honeydew, canteloupe, watermelon, and cucumbers use 2016 production figures. 5. Almonds and cherries report acres having paid for pollination services (column 1) being higher than harvested acres (table 6, column 5). We attribute this data anomaly to differences in the collection of these separate datasets and report the percentage of all farm acres paying pollination service fees (column 8) as 100.0 percent. 6. In calculating the farm's costs as a share of retail food costs, we assume that a farm's revenue equals its costs of production. In other words, we assume that the farm's economic profit is zero as is consistent with competitive markets in long-run equilibrium.

Sources: USDA, Economic Research Service using farm production data from USDA, National Agricultural Statistics Service (NASS) (2015) for noncitrus fruits and nuts and vegetables and from Walmart (2016) for almonds; NASS, Cost of Polination Report (2015); data on paid pollinated acres (table 6, column 5) divided by harvested acres (table 8, column 1) to derive the share of all farm acres paying pollination service fees; and data on retail prices from IRI (2013) for most crops and Walmart (2016) for almonds.

The share of all farm acres for which owners paid for pollination services in 2015 varies considerably across crops, from 100 percent for almonds and cherries to 15 percent for avocados. The farm revenue per pound produced is calculated by dividing the total value of farm production by the fresh equivalent number of pounds produced. The farm share of retail food costs is simply the farm revenue per pound divided by the retail price per pound. This share ranges from 7 percent for cranberries to 44 percent for watermelons.

Table 9 also displays two alternative estimates of pollination's share of the retail price of food (see columns 11 and 12). With either value, the pollination share of the retail price of food is small; almonds had the highest share of 1.1 percent. An implication of these estimates is that even if pollination fees increase substantially, the impact on retail food prices will be small.

Table 10

Pollinator cost shares for selected crops—Extension budgets data

Crop	1. Stocking density (colonies per acre)	2. Pollination Fee (dollars per colony)	3. Total colony rental cost (dollars)	4. Total farm costs per acre (dollars)	5. Pollination's share of farm costs (percent)	6. Farm share of retail food costs[3] (percent)	7. Pollination's share of retail costs (5*6) (percent)
Almonds	2.5	50	125	1,426	8.77	35.1	3.08
	2.5	100	250	3,509	7.12	35.1	2.50
	2.5	112	280	3,526	7.94	35.1	2.79
	2.5	112	280	3,327	8.42	35.1	2.95
	2.5	150	375	3,288	11.4	35.1	4.00
Apples	NA	NA	45	21,486	0.21	21.6	0.05
	NA	NA	45	22,102	0.20	21.6	0.04
	2	50	100	7,986	1.25	21.6	0.27
	1	25	25	2,586	0.97	21.6	0.21
Apples, organic[1]	2	45	90	11,407	0.79	16.1	0.13
Blackberries	2	50	100	23,049	0.43	12.9	0.06
Blueberries	2	165	330	30,243	1.09	22.1	0.24
	3	50	150	12,208	1.23	22.1	0.27
	2	45	90	6,426	1.40	22.1	0.31
	NA	NA	200	1,362	14.69	22.1	3.25
	NA	NA	400	1,865	21.45	22.1	4.74
Cantaloupe	1	50	50	4,554	1.10	32.3	0.35
	1.5	22	33	1,802	1.83	32.3	0.59
	1	75	75	4,577	1.64	32.3	0.53
	1.5	22	33	1,848	1.79	32.3	0.58
Cherries	NA	NA	45	11,824	0.38	28.9	0.11
	2	140	280	6,036	4.64	28.9	1.34
	2	44	88	10,290	0.86	28.9	0.25
Clover, seed	2	40	80	907	8.82	NA	NA
Honeydew	1	75	75	4,893	1.53	24.0	0.37
Muskmelons[2]	1	75	75	4,771	1.57	28.2	0.44
Pears	NA	NA	100	9,684	1.03	20.9	0.22

Table 10

Pollinator cost shares for selected crops—Extension budgets data - *continued*

Crop	1. Stocking density (colonies per acre)	2. Pollination Fee (dollars per colony)	3. Total colony rental cost (dollars)	4. Total farm costs per acre (dollars)	5. Pollination's share of farm costs (percent)	6. Farm share of retail food costs[3] (percent)	7. Pollination's share of retail costs (5*6) (percent)
Plums	1 to 2	NA	150	8,025	1.87	20.8	0.39%
Raspberries	2	30	60	47,296	0.13	31.6	0.04
Watermelons	NA	NA	4	3,978	0.10	43.7	0.04
	NA	NA	30	4,979	0.60	43.7	0.26
	1	75	75	2,515	2.98	43.7	1.30
	1	75	75	925	8.10	43.7	3.54
	1	75	75	2,514	2.98	43.7	1.30
	1	75	75	3,265	2.30	43.7	1.00
	1	75	75	3,730	2.01	43.7	0.88
	1	85	85	1,244	6.83	43.7	2.99
	1	85	85	3,660	2.32	43.7	1.01
Cucumbers	NA	NA	30	6,044	0.50	18.1	0.09
	2	22	44	448	9.83	18.1	1.78
	0.5	50	25	2,068	1.21	18.1	0.22
	1	75	75	4,565	1.64	18.1	0.30
	1	75	75	6,168	1.22	18.1	0.22
Squash, summer	1	75	75	6,778	1.11	15.8	0.17
Squash, winter	1	75	75	3,276	2.29	15.8	0.36
Pumpkin	1	75	75	1,743	4.30	8.9	0.38

Notes: NA = not available. 1. Retail prices for organics apples are estimated to be approximately 34 percent higher than those of conventional apples by Carlson and Jaenecke (2016) so we use the farm share of retail prices for conventional apples (21.6 percent) multiplied by 1/1.34 as the farm share of retail prices for organic apples. 2. Muskmelons include cantaloupe and honey dew. The farm share of retail costs for muskmelons (28.8 percent) is the simple average of the farm share of retail costs for canteloupe and honey dew (32.3 and 25.3 percent). 3. See table 9, column 10.

Source: USDA, Economic Research Service using sources listed in appendix table 1.

Tables 10 and 11 display pollination's share of farm costs using different methods and data. **Table 10** compiles the cost of production for each crop based on production business plans developed by various regional agricultural extension offices. In the process of developing these plans, cooperative extension agents interviewed local farmers and developed comprehensive detailed summaries of the various costs of producing a crop at the farm level using different technologies. These plans provide local farmers with various price and yield thresholds that allow the farmers to assess the crop's profitability in production. These plans are often specific to a particular crop variety.[33]

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[33] Different varieties can vary substantially in their pollination requirements. For blueberries, for example, recommended stocking densities per acre are 0.5 colonies for Rancocas, June, and Rubel; 1.0 for Weymouth, Bluette, Blueray, Pembarton, and Darrow; 1.5 for Bluecrop; 2.0 for Stanley, Concrod, Berkely, Coville, and Elliot; and 2.5 for Jersey and Earliblue (Pritts, 1992).

The estimates in **table 11** were developed based on PNW and California pollination fee data, stocking ratios, farm revenue and prices, and retail prices. Acreage yields and wholesale crop prices were multiplied to calculate a crop's revenue per acre. The pollination share of farm costs was derived by dividing the cost of pollinating an acre of farmland by farm revenue per acre, employing the common assumption that costs and revenue are equal in competitive markets in long-run equilibrium. The farm's share of the retail food cost is the crop price divided by the retail price per pound. The product of that value and pollination's share of food costs is pollination's share of retail food costs.

Table 11

Pollinator cost shares for selected crops—CA and PNW survey data

Regional source of data	Crop	1. Stocking density (colonies per acre)	2. Pollination fee (dollars per colony)	3. Farm revenue per acre[1] (percent)	4. Pollination's share of farm costs ((1*2)/3) (percent)	5. Farm's costs as a share of retail food cost[1] (percent)	6. Pollination's share of retail food costs (4*5) (percent)
Surveys of beekeepers based in the Pacific Northwest States	Almonds	2.00	180.00	5,604	6.42	57.08	3.67
	Apples	1.34	47.90	9,055	0.71	31.64	0.22
	Sweet cherries	1.54	47.78	4,953	1.49	21.15	0.31
	Pears	1.40	49.48	6,969	1.00	19.90	0.20
	Blueberries	2.07	42.57	8,987	0.98	27.82	0.27
	Cucumbers	0.98	69.07	N/A	N/A	N/A	N/A
	Cranberries	1.59	59.26	4,349	2.17	11.70	0.25
	Pumpkins and squash	0.86	46.67	3,526	1.14	8.90	0.10
	Red clover seed	1.30	32.26	778	5.39	N/A	N/A
	Crimson clover seed	1.07	12.97	775	1.79	N/A	N/A
	Radish Seed	1.60	41.22	898	7.34	N/A	N/A
Survery of beekeepers based in California	Almonds	2.00	150.00	5,604	5.35	57.08	3.06
	Plums	1.50	142.51	3,509	6.09	15.82	0.96
	Early cherries	1.33	120.49	8,316	1.93	42.98	0.83
	Apples	1.28	38.37	4,849	1.02	21.97	0.22
	Avocadoes	3.17	34.54	9,263	1.18	51.56	0.61
	Melons, cantaloupe	2.07	31.44	4,582	1.42	28.52	0.40
	Melons, honeydew	1.00	31.44	4,369	0.72	22.88	0.16
	Prunes	1.03	17.89	3,257	0.56	18.53	0.10
	Sunflowers	1.88	30.99	306	18.96	N/A	N/A
	Vegetable seed	4.14	36.55	N/A	N/A	N/A	N/A
	Alfalfa seed	4.89	47.42	N/A	N/A	N/A	N/A

Note: NA = not available. 1. In calculating the farm's costs as a share of retail food costs, we assume that a farm's revenue equals its costs of production. In other words, we assume that the farm's economic profit is zero as is consistent with competitive markets in long-run equilibrium.

Source: USDA, Economic Research Service (ERS) using Rucker et al. (2012) for data on stocking density—for almonds, the value is set to 2.0; Sagili and Caron (2016) and California State Beekeepers Association (2016) for survey data on average pollination service fees from 2010 to 2013; USDA, National Agricultural Statistics Service (NASS) (2013) for revenue per acre, which is yield per acre times the crop price; and USDA, ERS (2013) and USDA, NASS (2013) for farm costs as a share of food cost, which is retail price per pound divided by crop price.

While **table 9** uses nationally representative NASS data to measure the cost of pollination per acre, **tables 10 and 11** use regional data from, respectively, State cooperative extension services and State-level surveys of beekeepers (who may themselves travel out of State to provide pollination services or make honey in the course of the year). Both datasets used to create **tables 9 and 11** assume that a farm's revenue equals its costs or, in other words, the farm's economic profit is zero, an assumption consistent with competitive markets in long-run equilibrium. We further assume that total beekeeper pollination service revenue is equal to total farm payments for pollination services.[34] In addition to omitting certain crops covered in **table 9**, the cost of pollination services in these data reflect the production method and regional timing of a crop's bloom, which directly affects the pollination services fee paid (most acutely when the crop's bloom coincides with the almond bloom), and the stocking density.

While **tables 9 and 11** use 2015 pollination services fee estimates, **table 10** uses estimates ranging from 2008 to 2014.[35] Despite these differences, for most crops considered, pollination costs account for less than 5 percent of production costs at the farm level. In **table 10**, pollination fee cost shares at the farm level exceed 5 percent for 11 of the 45 crop budgets displayed, or 5 of the 18 crops considered (almonds, blueberries, clover seed, watermelons, and cucumbers). In **table 11**, pollination fee cost shares exceed 5 percent for 5 of the 16 crops listed (almonds, red clover seed, radish seed, plums, sunflowers).

The pollination service's share of farm-level costs is highest for almonds (5.2 percent) based on the cost of pollination data **(table 9)**; almonds (11.4 percent) and Maine blueberries (14.7 and 21.5 percent) using the extension data **(table 10)**; and radish seed production (7.3 percent) and almonds (6.4 percent) in the data collected from the PNW and California surveys **(table 11)**. (For more information on pollination fees for almonds, see box "Almond Pollination Fees Explained.")

A conclusion to be drawn from **tables 9-11** is that because the farm-level cost share of pollination services is relatively small for most crops, if there are widespread increases in future pollination fees, wholesale buyers are unlikely to curtail their purchases from farmers substantially, even if farmers pass on all or most of the higher fees.[36] If the cost share is 2 percent, a doubling of the price of pollination service fees may only cause a farm's costs to increase by 2 percent at most. The impact on retail prices will be smaller still.

Almond Pollination Fees Explained

Pollination service fees for almonds are far higher than fees for most other crops. The summary figures in **table 6** for pollination costs for almonds and crops excluding almonds show that almond producers pay three times more per colony than the average of other crops ($165.0/$54.8 = 3.0) and about four times more per acre for pollination services ($313.0/$76.5 = 4.09). There are at least five reasons why almond pollination fees are so much higher than other pollination fees. First, because of the large number of planted acres and relatively high stocking density for

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[34] Farm payments may exceed beekeeper receipts if broker-intermediaries retain a portion of pollination service fees. Our understanding is that the use of such "bee broker" services is limited to almond pollination.

[35] Crop production acreage and values are from 2012 and retail food prices are from 2013. If these values changed dramatically between 2012 and 2015, our analysis will reflect that limitation.

[36] The effect of pollination service fee changes on farm costs may be higher in local areas where its share of costs is higher than the national-level figures reported in table 8.

almonds, almond producers use more paid honey bee pollination services than all other crop producers combined. The almond share of pollinated acres is 52.8 percent, the share of colonies used is 60.5 percent, and the share of pollination service fees paid is 82.2 percent. Moreover, almond acreage is extremely geographically concentrated in the central valley of California so that bloom for nearly all almond acres is simultaneous. To meet this very high demand, almond producers must offer high fees to induce beekeepers to cover the high transportation and housing costs associated with moving their colonies cross country, an activity that may induce higher colony mortality (Simone-Finstrom, 2016; Goodrich, 2017).

Second, little or no honey is obtained from almond pollination. When the value of the honey produced during crop pollination is low, beekeepers demand a higher pollination service fee (Cheung, 1973; Rucker et al., 2012).

Third, almonds bloom in February, before all other crops requiring pollination services. At this time of year, bee colonies are still in a winter torpor and are staged in warm areas with few available blooms for the bees to become active prior to their placement in almond orchards. If loss rates are particularly high for a specific beekeeper, they will have had little ability to rebuild hives weakened or lost over winter. Around April, colonies are capable of being split and excess colonies are frequently sold or exported.

Fourth, almonds trees have a pollinator dependence ratio of 1, which suggests that farmers have few options in terms of substituting to alternative inputs. Moreover, almond groves represent a 20- to 25-year investment, only becoming fully productive after 3 to 4 years (Boriss and Brunke, 2005). Unlike some crops, almond farmers cannot easily switch production to other crops within the course of a year or two if input costs rise, nor can they curtail colony placements without substantial yield loss. For this reason, Rucker et al. (2012) show stocking densities are unresponsive to price.

Box table

Almond acreage and trees per acre

Year	Trees per acre	Acreage (thousands)
1986	84.5	416
1990	88.4	411
1995	93.7	418
2000	99.0	510
2005	104.0	590
2010	108.0	770
2015	114.0	920
2016	116.0	940

Source: USDA, Economic Research Service using California Almond Objective Report (2017).

Fifth, some almond producers pay premiums for higher quality colonies. Based on beekeeper surveys, Goodrich and Goodhue (2016) document that beekeepers operating under performance contracts that provide premiums for high colony strength receive pollination fees 5.7 percent higher than contracts without these incentives, and that 20 percent of surveyed beekeepers servicing the almond bloom operate under these contracts. It is unclear to what extent such contracts have become more common since the steep rise in almond pollination fees began in 2004 (see **figure 2**). Relatedly, as shown in **box table,** the average number of almond trees per acre has steadily risen from its 1986 level along with acreage. The increase in trees per acre, which may have encouraged almond producers to either increase stocking densities or demand greater colony strength from beekeepers, likely increases almond's demand growth independent of its concurrent expansion of acreage.

Availability of Substitute Inputs and Outputs

The availability of substitute inputs for pollination services also affects how much farmers will curtail colony rentals in response to price increases. If substitution is relatively easy, farmers will reduce colony rentals in response to increases in pollination fees, and beekeepers will have difficulty passing on a high portion of the increased costs to farmers. Substitution away from honey bee colony rentals might include switching from honey bee colony rentals to the use of alternative pollinators. For example, leafcutter bees are currently used for a portion of alfalfa seed pollination and some berry pollination with bumblebees, and their use may be feasible with apple and cherry pollination by *non-Apis* genera bees should managed honey bees become prohibitively expensive (Bosch et al., 2006, Vicens and Bosch, 2000). For some crops and localities, wild pollinators may provide sufficient pollination services to allow farmers to reduce colony rentals without substantial reductions in outputs, such as with blueberries in Michigan (Isaacs and Kirk, 2010).

Honey bee dependency ratios range from 0.0 to 1.0.[37] For almonds and lemons, the bee dependency ratio is 1.0, indicating that, in the complete absence of managed honey bees, yields for currently planted varieties of these crops would fall by 100 percent and no output would be produced. For strawberries and pumpkins, the dependency ratio is 0.10, indicating that these yields would fall by only 10 percent if all managed honey bees disappeared. In general, a higher bee dependency ratio suggests that farmers will be less able to substitute other methods of pollination for honey bees and that farmers growing honey bee-dependent crops will likely be less responsive to increases (or decreases) in the price of pollination services when making their colony rental decisions.

Besides foregoing colony rentals or lowering stocking densities in response to higher colony rental costs, farmers of some crops can also substitute away from colony rentals by adopting plant breeds and cultivars that are less reliant on honey bees for pollination. For example, a recently introduced almond variety requires 0.5 colonies per acre rather than the currently recommended 2.0 colonies (Harvey, 2012; Sagoff, 2011; Souza, 2013).

Despite the possibility of input substitution, no evidence indicates that farmers are reducing stocking densities. Rucker et al. (2012) find that stocking densities are not significantly affected by crop prices, honey price, acres planted, the appearance of Varroa in the early 1990s, or CCD in the mid-2000s. They do find that stocking densities differ significantly among crops but attribute the negligible response of stocking density to both the input's small cost share and the tendency of agronomically recommended stocking densities to not be conditioned on economic variables.

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[37] Biologists sometimes present the separate metric of insect dependency that refers to the extent that a crop's pollination is dependent on the large biological phylum of insects generally. Across crops, bee and insect dependency ratios are closely correlated.

Demand Response and Pollination's Shares of Costs at the Farm and Retail Food Levels

Insofar as food processors and consumers have the ability to substitute relatively easily away from a particular wholesale food item, they may be responsive to changes in those items' prices and availability. One possible option for such substitution would be to use more labor in processing or handling to reduce waste in the use of the food item, thereby allowing processors or consumers to purchase less of the item (Gardner, 1975). For example, fewer apples might be damaged in handling (and as a result, fewer might be purchased initially) if more workers are added to the facilities where apples are washed, packaged, and stored. Most observers think that currently unexploited substitution opportunities are limited. Wohlgenant (1989) finds that a 10-percent increase in the price of farm-level vegetables causes food processors to increase their purchases of other inputs relative to wholesale vegetables by 5.4 percent, holding constant the level of production. While this suggests some potential for substitution, demand for farm-level food inputs at the retail level is still largely unresponsive to price changes (i.e., it is inelastic).

Aside from avoiding waste, in another option, in response to increases in the price of pollination services that increase the price of pollinator-dependent food, food processors and retail consumers may choose to substitute to less pollinator-dependent foods. A large volume of empirical studies has generally found, however, that consumer purchases of fruits and vegetables are unresponsive to changes in price (see Andreyeva et al., 2012, for a brief overview). Dong and Lin (2009) find that a 10-percent retail price increase would cause low-income households to decrease their consumption of fruits by 2.1 to 5.2 percent and vegetables by 2.1 to 4.9 percent. Similarly, Dong and Leibtag (2010) find that a 10-percent increase in retail price would generally cause households to decrease their consumption of fruits by 6.2 percent and vegetables by 5.7 percent. These relatively inelastic responses suggest that, if the price of pollinator-dependent food increases, although substitution away from such food is possible, consumer responses will be limited.

Given the substitution possibilities discussed here, if pollination fees increase substantially in the future, how will retail food prices be affected? Because pollination services are an input to wholesale food production and wholesale food is an input to retail food production, a parallel structure exists in their analysis. A smaller farm-level cost share of pollination services makes farmers less responsive to changes in pollination fees. Similarly, a smaller cost share of wholesale food in the production of retail food makes retail food producers less responsive to changes in the prices of wholesale food. The farmer's unresponsiveness to potential increases in pollination service fees enables beekeepers to pass along higher beekeeping management costs to farmers. Similarly, the retail food producers' general unresponsiveness to wholesale food price increases enables wholesale producers to pass along higher costs of pollination services to retailers. In short, the same mechanisms that mitigate much of the impact of higher management costs on beekeepers also mitigate the impact of higher wholesale food production costs on food producers.

A large body of economic literature considers how changes in various components of the costs of producing retail foods affect the price of those foods. **Tables 9-11** provide three independently calculated crop-specific shares of farm-level costs attributable to pollination services. Those tables also provide estimates of pollination's crop-specific shares of retail prices. **Tables 9** and **10** report (identical) estimates of the farm's share of retail food costs, which are obtained by dividing estimates of the retail price of food per pound (USDA-ERS, 2016) by the farm revenue per fresh-equivalent pound (USDA-NASS, 2016b).[38] For bee-pollinated crops, these figures range from 6.5 percent for cranberries to 37.2 percent for watermelons, with the average share being 22.1 percent.[39] **Table 11** draws its estimates of the farm share of retail costs from regional data and, with the exception of almonds, avocadoes, and early cherries, the estimates fall in the same range as those in **tables 9 and 10**.

Tables 9-11 each present an estimate of pollination's share of retail food value (under the implicit assumption that all farms pay pollination fees), which is calculated by multiplying pollination's share of farm costs for farms paying pollination fees by the farm's share of retail cost. In **table 9**, this value is 0.54 percent on average across the crops shown, with almonds having the highest pollination share of retail food costs at 1.1 percent. **Tables 9 and 10** generally have higher estimates of this value, with shares ranging as high as 6.59 percent for Maine blueberries in **table 10** and 3.67 percent for almonds in **table 11**. Because the estimates displayed in **tables 10 and 11** are not based on nationally representative data, the estimates of pollination's share of farm revenue may be specific to a particular regional variety or production technology.[40] For this reason, no average pollination shares of retail food costs are reported for these tables.

Nearly all almond acres are pollinated. For avocados, on the other hand, only 14 percent of total acreage is pollinated (see **table 8**). For crops like avocados, the pollination shares of retail costs in **tables 10 and 11** and also those in the penultimate column of the table are biased upward for aggregate purposes. The last column of **table 10** presents pollination's share of retail costs for all acres by multiplying the retail share of paid pollinated acres by the share of farms paying pollination fees. The primary conclusion from the discussion in this section is that the small share of pollination service's costs in both farm and retail food costs greatly dampens the proportionate effect of any changes in the price of pollination services on both crop and retail prices.

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[38] Sunflowers and alfalfa are assumed to be final goods, even though they are typically used in the production of vegetable oil and cattle feed, respectively. Cost shares are not calculated for these crops because few seeds are sold at the retail level.

[39] This average is weighted by the crop's value of farm production.

[40] The regional timing of a crop bloom can have a large effect on pollination fees. For example, in the Cost of Pollination Survey data, the rental cost per colony for cherries is $67.6 in the California region but only $27.0 in the Northern Great Plains region.

Conclusion

Despite the elevation in honey bee colony loss rates since 2006, there is little evidence of disruption to agricultural crop or retail food markets in terms of rising prices or decreasing availability. This study provides background detail on the biology of beekeeping to describe how beekeepers respond to pollinator health challenges and the methods they use to replace lost colonies. While the number of U.S. bee colonies fell steadily between 1946 and 1996, it has remained roughly constant since that time despite the onset of CCD in the winter of 2006-07 and increasing concern over pollinator health issues since then.

Pollination revenues have increased over time and now equal or exceed revenues from honey production for many large commercial beekeepers. A primary driver of this increase in pollination revenues has been the expansion of almond acreage in California. More than most crops, almonds require pollination by honey bees at high stocking densities at a time of the year when healthy, active honey bee colonies are most scarce. In recent years, inflation-adjusted almond pollination fees have more than doubled. To the extent that pollination fees for crops that do not compete with almonds for pollination services have increased at all, the increases have been far more modest.[41] High pollination fees for almonds have induced commercial beekeepers to load their honey bees on flatbeds and trek to California from as far away as Florida and North Carolina. In recent years, 60 to 70 percent of all commercial honey bee colonies in the United States have been transported to California in February for the almond bloom.

This study's discussion of the market for pollination services identifies three reasons why the effect of higher winter loss rates on food markets has been largely muted. First, experienced commercial beekeepers have a robust ability to replace (split) colonies to recover from winter colony losses. As a result, despite the dramatic increases in winter mortality rates in the mid-2000s, colony numbers have remained roughly constant, with the most recently released colony numbers for 2016 being the largest in more than two decades. Second, and closely related, pollination markets result in changes in relative pollination fees among crops that provide incentives for beekeepers to move their tiny livestock to the fields where they have the highest value. At the same time, increases in pollination fees for a particular crop provide motivation over the longer run to develop alternative pollinator sources and self-pollinating crop varieties. Third, pollination fees for most fruits and vegetables are a very small percentage of costs, at both the farm and retail levels. Even for almonds, whose pollination fees have risen substantially and whose fees account for a high share of costs relative to most pollinated produce, the increase in prices paid by consumers is minor (Rucker et al., 2016).

Appropriate here is the adage: "High prices are the solution to their own problem." An unexpected increase in honey bee colony winter mortality rates in the mid-2000s resulted in an increase in pollination service fees, in particular for almonds. Although higher costs of managing honey bees are certainly undesirable, increased pollination fees provide direct offsetting benefits and also serve to provide beekeepers with the incentive to replace their lost colonies and to direct colonies to their highest valued uses, in the process minimizing downstream effects on food markets in the short run. In the long run, insofar as increased pollination fees result in higher wholesale prices, food retailers will be motivated to search out substitutes for pollinated food items. The lack of major changes in

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[41] Rucker et al. (2016) find that, with the exception of almonds and two relatively minor crops that also bloom in California during late February and March, pollination fees for other crops grown in California and the Pacific Northwest have not increased significantly since the winter of 2006/07 when CCD first caught the attention of the media.

most economic indicators in the years since CCD appeared suggests that adjustments in beekeeping, farming, wholesale production, and consumption have been made quickly and effectively. Direct evidence suggests that most of the adjustment has occurred at the level of the beekeeper, with less adjustment at downstream levels in the production and marketing chain.

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Appendix

Appendix table 1

Sources for table 10 pollinator cost shares for selected crops—Extension budgets data

Crop	Data sources
Almonds	Connell et al. (2012), Mark W. Freeman (2008), Richard P. Buchner (2001), Roger A. Duncan (2011a), Roger A. Duncan (2011b)
Apples	Gallardo and Galinato (2012a, 2012b), West et al. (2012a, 2012b)
Apples, organic (1)	Galinato et al. (2012)
Blackberries	Bolda et al. (2008)
Blueberries	Fonsah et al. (2011b, 2012c), Jimenez et al. (2009), Julian et al. (2011)
Cantaloupe	Fonsah et al. (2011a), Texas Cooperative Extension Service (2012a, 2013b)
Cherries	Black et al. (2012), Galinato et al. (2009), Grant et al. (2011), West et al. (2012d)
Clover, seed	Eleveld et al. (2010)
Honeydew	Texas Cooperative Extension Service (2012c)
Muskmelons (2)	University of Kentucky (2013)
Pears	West et al. (2012c)
Plums	Day et al. (2009)
Raspberries	University of California (2014)
Watermelons	Texas Cooperative Extension Service (2012d, 2013a, 2013c)
Cucumbers	Texas Cooperative Extension Service (2012b)
Squash, summer	
Squash, winter	University of Kentucky (2013)
Pumpkin	