Colony Collapse and the Consequences of Bee Disease: Market Adaptation to Environmental Change

Randal R. Rucker, Walter N. Thurman, Michael Burgett

Abstract: The most extensive markets for pollination services in the world are those for honey bee pollination in the United States. They play important roles in coordinating agricultural producers and migratory beekeepers, who both produce honey and provide pollination for crops. Recent trends in bee disease—including the still poorly understood colony collapse disorder, or CCD—can usefully be viewed in the context of how markets respond to environmental change. We analyze economic indicators of input and output markets related to managed honey bee operations, looking for effects from CCD. We find strong evidence of adaptation in these markets and remarkably little to suggest dramatic and widespread economic effects from CCD.

JEL Codes: Q11, Q15, Q54, Q57

Keywords: pollinator health, pollination markets, colony collapse disorder, honey bees, market adaptation

ENVIRONMENTAL CHANGE OCCURS ON A VARIETY of time scales. Earthquakes and tornadoes wreak havoc in minutes and leave paths of destruction that take years to repair. Hurricanes occur over days, leaving comparable mayhem. Invasive species migrate into new ecological niches over years or decades, gradually changing the produc-

Randal R. Rucker is at Montana State University. Walter N. Thurman (corresponding author) is at North Carolina State University (wally_thurman@ncsu.edu). Michael Burgett is at Oregon State University. We gratefully acknowledge helpful comments from Mark Anderson, Gary Brester, Peyton Ferrier, Nick Parker, Wendy Stock, David Tarpy, and Jon Yoder, as well as from participants at seminars at Clemson, Montana State, North Carolina State, and Washington State Universities, the Property and Environment Research Center (PERC), and the Universities of Georgia and Wisconsin. For able research assistance we thank Fritz Baird, James Banovetz, Vanessa Elizondo, Anja Gruber, Bryan Leonard, Mike Tarrant, Amanda Vogstad, Chris Watson, and Paul Watson. Rucker acknowledges support from the Montana State Agricultural Experiment Station and also from a Lone Mountain Fellowship at PERC. Thurman acknowledges the support

Received February 10, 2016; Accepted October 16, 2018; Published online July 8, 2019.

JAERE, volume 6, number 5. 2333-5955/2019/0605-00XX$10.00 http://dx.doi.org/10.1086/704360

tive opportunities of landscapes. Climate change evolves over decades and centuries. A fundamental challenge in assessing the effects of environmental change arises when the change is gradual and hard to measure. Climate change is a case in point, where the difficulty of identifying the effect of a slow-moving system is compounded by the noisiness of the signal—weather—that represents unobservable climate. Further—good for humans but problematic for econometricians—humans and economies adapt continuously in response to gradual change, confounding the raw effects of environmental change with the effects mediated by adaptation.[1]

In this article, we study economic adaptation to changes in the health of pollinators, important contributors to the biological and economic environment. While some change in the pollinator environment is continuous, we argue that discrete, measurable, and significant changes to the overwinter survivability of European honey bees (*Apis mellifera*) occurred in North America in 2006. Known as colony collapse disorder (or CCD), this phenomenon constitutes a natural experiment, which we use to examine the consequences of changes in pollinator health—some of which occur more gradually than CCD—to assess the ability of pollination service and related markets to adapt.

We contribute to an economic understanding of an important and high-profile interaction between the environment and agriculture. More broadly, we contribute to the literature on agricultural adaptation to environmental change, of which climate change is a leading example.[2]

In the next section, we provide brief introductions to honey bee biology and the managed pollinator industry in the United States. We discuss the available evidence on winter honey bee mortality from 2006 to the present and describe the distinctive symptoms of CCD and the current state of knowledge regarding its causes. In following sections, we present an economic model of the beekeeping industry and the results of our empirical examination of primary and secondary data from disparate sources that might be expected to react to the advent of CCD. We analyze annual estimates of both colony numbers and honey production at the aggregate (US) and state levels. We also examine the prices

of the North Carolina Agricultural Research Service. We also acknowledge support from USDA Cooperative Agreement no. 58-3000-4-0027.

1. See, e.g., Deschenes and Greenstone (2011) on the relationship between cold and heat and mortality, and Barreca et al. (2016) on heat and mortality and the ways that technology and innovation condition these relationships. Also see Hsiang and Narita (2012), who find evidence of adaptation to tropical cyclone risk in countries that experience higher risk levels.

2. The extant literature on agricultural adaptation to climate change focuses almost exclusively on the relationship between crop yields and weather and how that relationship adapts to more permanent changes in weather. See Kurukulasuriya and Mendelsohn (2008) and Olmstead and Rhode (2011) for examples and Auffhammer and Schlenker (2014) for a review. A separate connection here is that some have attributed pollinator declines to climate change. See National Research Council (2007), Potts et al. (2010), and Kerr et al. (2015).

of two important inputs to beekeeping—queens and packaged bees—that might be expected to rise as the industry adjusts to higher mortality rates. Finally, we investigate pollination fees paid by farmers using annual survey data from the Pacific Northwest and California and estimate the impacts of CCD on beekeeper income and consumer prices.

While the tone of much discussion of pollinators and their health is bleak, our results give cause for considerable optimism, at least for the economically dominant honey bee. We find that CCD has had measurable impacts in only one economically important segment of the industry: pollination fees for almonds. As a whole, the impacts are small relative to our priors. Moreover, and in stark contrast to perceptions formed from surveying media sources as well as a substantial body of academic literature, we find that CCD has not had measurable effects on honey production, input prices, or even numbers of bee colonies. We attribute these findings to a factor largely overlooked in the scientific and popular literature on pollinator decline: the ability of well-functioning markets to adapt quickly to environmental shocks and to mitigate their potential negative impacts.[3] Our finding that pollination markets adapted so quickly and effectively to a sudden large adverse environmental change also engenders confidence that, where well-functioning markets are present, effective adaptation to much slower developing changes in climate is likely to occur.

1. BEES, BEEKEEPING, AND BEE DISEASE

Bees are livestock managed for economic returns. And just as cattle diseases preoccupy ranchers, diseases and other threats to bee colonies have been important to beekeepers for at least a century.[4] Broader public concern over honey bee health is much more recent and largely is coincident with the appearance and labeling of colony collapse disorder in 2006, described below.

Examples of attention to pollinator health from the scientific community include the National Research Council (2007), Aizen et al. (2008), Gallai et al. (2009), and Ratnieks and Carreck (2010). From the popular press, an early alarm was sounded by Pollan (2007), and press accounts of dwindling pollinators have grown steadily

3. The limited economic literature on beekeeping can be cast broadly as a debate over the extent and efficacy of pollination markets. Notable economists J. E. Meade (1952) and Francis Bator (1958) used the example of honey bees and orchards to illustrate market failure due to two-way positive externalities. In 1973, Steven Cheung published a study of Washington beekeepers in which he pointed out that beekeepers and orchard owners contract with each other and that pollination fees and apiary rentals reflected social marginal values. More recent research has analyzed pollination markets and migratory commercial beekeepers, who often transport their colonies thousands of miles annually. See Muth et al. (2003), Rucker et al. (2012), Champetier et al. (2015), and Ferrier et al. (2018).

4. For example, the June 1928 issue of the *American Bee Journal* featured four articles on its cover, the first two of which were titled "Bee Diseases and Their Eradication" and "May Disease."

since that time.[5] An early governmental response came in 2007 from then Secretary of Agriculture Mike Johanns, who warned that "if left unchecked, CCD has the potential to cause a $15 billion direct loss of crop production and $75 billion in indirect losses."[6] A later governmental response came in 2014 when President Obama established a multiagency Pollinator Health Task Force, charged with developing a strategy for reversing pollinator losses (White House 2014.)

1.1. Commercial Beekeeping

The pollinator most amenable to management is the economically dominant European honey bee (*Apis mellifera*). Honey bees collect nectar and pollen from flowering plants. In the process of moving from bloom to bloom, bees pick up pollen grains (which contain male gametes or sperm) on their bodies and transfer them to the pistils (the female reproductive organs) of other flowers. This process enables plant reproduction.[7] Worker bees are attracted to the blossoms primarily by nectar, which is carried back to the hive. There, the nectar is transformed into honey for later consumption (or extraction by beekeepers), and gathered pollen is stored for future use as a source of protein for the hive. The honey bee is polylectic—a floral generalist—foraging on almost anything that blooms.

A typical full-strength colony of honey bees consists of a single queen and 25,000–40,000 worker bees. The queen usually lives for about 2 years and lays all the eggs in the hive. As the queen becomes less productive, the beekeeper replaces her with a newly fertilized queen. Assuming the new queen is accepted by the colony and begins laying fertilized eggs immediately, the hive will remain healthy and productive. All the worker bees are sterile females, half-sisters with life spans of about 6 weeks in the summer. The colony also contains a small number of males, or drones, whose sole function is to mate with fledgling queens from other colonies.

5. Pollinator decline in the literature refers to two different issues: declines in managed honey bees and declines in unmanaged insects such as wild bumblebees and monarch butterflies (and other pollinating insects, birds, and mammals). The present paper addresses managed bees. Concern over wild pollinators stems from their role in pollinating commercial crops, as well as their influence on wildlife habitat and food and the production of ecosystem services such as clean water. See Kleijn et al. (2015) for a discussion of the agricultural benefits from wild pollinators. A lack of data on population levels precludes analysis of wild pollinator health issues comparable to our analysis below.

6. See Stipp (2007). The source of the multiplier of five that inflates $15 billion to $75 billion was not identified. Secretary Johann's $15 billion figure is a commonly cited estimate of the value of pollination services from a study by Morse and Calderone (2000). Muth and Thurman (1995) criticize these estimates and suggest that from a standard economic perspective, they are too high by at least an order of magnitude.

7. Honey bees are but one of thousands of animal species that pollinate about 90% of flowering plants, with the remaining 10% reproducing through pollination by wind and water.

In the United States, beekeeping is an industry with \$600–\$700 million in annual sales in recent years, not large compared with other segments of agriculture.[8] For comparison, the annual value of the US corn crop in recent years has been between \$50 billion and \$80 billion. But bee pollination is critical to the production of a wide variety of economically important crops. Bee colonies are moved into almond and apple and other fruit tree orchards at blossom time to pollinate and enable fruit and nut production. They play similar roles in pollinating commercial crops of blueberries, cranberries, melons, cucumbers, and other fruits and vegetables.

Modern commercial beekeeping in the United States is highly migratory. Hives are moved by truck from crop to crop for pollination in the spring and, later in the year, to bee pasture for honey production. In addition to strategically moving their bees at the right times and places, beekeepers manipulate and manage the biological capital stock in their hives. The rearing of new bees is critical, as is providing them with proper nutrition and veterinary care. A key environmental backdrop to this process—and a constant concern to beekeepers—is the presence of bee disease, parasites, and toxins.

Honey bees have long suffered from a variety of diseases and other biological threats. Underwood and vanEngelsdorp (2007) document 23 episodes of major colony losses between 1868 and 2003. The most recent major predecessors to CCD are two species of mite parasites (*Varroa destructor* and *Acarapis woodi*—or tracheal mites), which first appeared in North America in the mid- to late-1980s. *Varroa* mites are ectoparasites that attach themselves to bees and feed on their blood.[9] Tracheal mites are endoparasites that attack bees' breathing tubes. Diseases that currently affect honey bees include the following: American foulbrood, a bacterial infection that attacks bee larvae and pupae; nosema, a fungus that invades the intestinal tracts of adult bees; and chalkbrood, a fungus that infests the guts of honey bee larvae.[10] It is notable that, over time, commercial beekeepers have developed methods to combat each of these bee diseases. That said, such methods are costly,[11] and bee diseases and parasites have periodically devastated nonmanaged feral colonies.

1.2. Colony Collapse Disorder

In October 2006 David Hackenberg, a Pennsylvania beekeeper, took almost 3,000 honey bee colonies to Florida for the winter. In mid-November, he discovered

8. In 2016, farm-gate revenues from honey were \$336 million and pollination income was \$338 million (USDA NASS 2017). The USDA's 2017 Honey report also indicates that beekeepers had revenues from other sources equal to about \$149 million, but an unknown portion of those revenues is from beekeeper-to-beekeeper sales of queens and packages.

9. Nordhaus (2011, chap. 3) recounts the spread of the *Varroa* mite and ongoing efforts to control it.

10. See Morse and Flottum (1997) for additional discussion of bee disease.

11. In their analysis of pollination fees, Rucker et al. (2012) find that pollination fees increased following the advent of the *Varroa* mite by roughly the costs of treating *Varroa*.

that two-thirds were practically empty—no adult worker bees and no dead bees in or near the hives. That winter other beekeepers reported similar high rates of colony mortality and the same unusual symptoms. The phenomenon was dubbed colony collapse disorder. In addition to the absence of both worker bees and dead bees in or near the hive, colonies with CCD contained brood (developing young), the queen, and food stores (honey and bee pollen). Although pests such as wax moths and small hive beetles typically invade empty hives and consume any remaining food stores, they did not occupy CCD-infested colonies.

Over the eight winters from 2006/2007 through 2013/2014, surveys indicate that the average annual losses for responding beekeepers were 29.6%.[12] While these loss rates are striking, it is important to realize that some bees and bee colonies die every winter, whether CCD is present or not. Burgett et al. (2009) estimate that normal annual winter mortality rates for commercial beekeepers in the Pacific Northwest were about 14% prior to the appearance of CCD; 14% of colonies that were healthy going into winter did not survive to spring.[13] Thus, colony replacement has long been a standard part of beekeeping.

Research into the causes of CCD began in the winter of 2006–7 with regulators and bee scientists concluding that bees from CCD colonies were infected with a broad range of known pathogens, as well as with pathogens not reported before in the United States.[14] Since these initial efforts, a number of investigations into the causes of CCD have been undertaken. Early speculation was that cell phone signals may have caused honey bees to lose their bearings and fail to return to their hives. Alternative explanations with more longevity include CCD being a new disease (possibly brought in by foreign bees), a response to malnutrition as a result of drought or habitat loss, or as a result of exposure to stress (possibly induced by traveling increasingly long distances for pollination), toxins, and pesticides (in particular a class of insecticides, called neonicotinoids that has seen increased use in recent years).[15] It has also been noted that there have been several instances of "disappearing diseases" in past decades with symptoms similar to CCD,

12. The highest national mortality rate during this span was 36% in the winter of 2006/2007, while the lowest was 22.5% in 2011/2012. See vanEngelsdorp et al. (2007, 2008, 2010, 2011, 2012, 2014), Spleen et al. (2013), and Steinhauer et al. (2014).

13. Similarly, Pernal (2008) estimates that before CCD, normal winter mortality was 15%, and van Englesdorp et al. (2007) report that during the winter of 2006/2007, beekeepers experiencing normal losses had an average mortality rate of 15.9%. In the mid- to late-1980s, colony losses for North American beekeepers were elevated following the arrival of *Varroa* and tracheal mites. Prior to that time, good beekeepers were able to keep their winter losses below 10%. After the arrival of the mites, between 1989 and 1998 the average annual estimated colony loss for commercial beekeepers was 22.6% (Burgett 1998).

14. See Columbia University (2007) as well as, e.g., Maori et al. (2007) and vanEnglesdorp et al. (2009).

15. See Mussen (2007) for an early review of the then-current state of knowledge and Bromenshenk et al. (2010) and Cornman et al. (2012) for later overviews.

whose causes have never been determined.[16] A current theme from the bee research community is that CCD is multifactorial and, as such, cannot be explained by a single causal agent.

1.3. Methods of Adapting

Two methods are commonly employed by beekeepers to maintain and rebuild hive numbers. Understanding these methods is critical to understanding how the industry responds to bee disease. The first method used to replace hives involves a beekeeper splitting a healthy, full-strength hive, typically into two parts. Known in the industry as "making increase," the method has been used for decades. The process requires the beekeeper to move a portion of the brood and adult bees, typically less than 50%, from a healthy hive to a new hive. The new hives are known as nuclei colonies (or nucs, or splits). For a nuc to be viable, a fertilized queen is required. Newly mated queens are often purchased from specialized commercial queen breeders, who in aggregate produce hundreds of thousands of queens annually for sale. Most commercial beekeepers produce nucs from their own base of healthy colonies, although on occasion beekeepers will purchase nucs from other beekeepers.

The parent hive used for the split has a near-uniform age distribution, from egg to mature foraging worker bee. Thus, the original hive can continually replace its cadre of pollinators and is often strong enough to pollinate crops shortly after the split. The new hive will not be strong enough to pollinate crops for about 6 weeks due to the time it takes newly produced brood to mature. In California, beekeepers typically make increase for the season in March, after almond pollination is complete. In Oregon and Washington, beekeepers typically make increase in April. In addition, commercial beekeepers anticipate winter colony losses and regularly produce nucs in mid- to late-summer for the purpose of maintaining total colony numbers for next year's pollination season.

The second method used to build or replenish hive numbers is to buy packaged bees—roughly 12,000 worker bees and a fertilized queen—typically sold by the same companies that sell queens. An empty hive stocked with a package of bees might be productive immediately. Soon, however, production will decline due to the time lag between the placement of the package of workers in the hive and the time that a new generation of worker bees is hatched and matured to the point of leaving the hive to collect nectar, pollen, and water. If the new queen begins laying fertilized eggs immediately, it will take 21–25 days before worker bees hatch. If a hive in Oregon or Washington is stocked with packaged bees in mid-April, the hive probably will not produce surplus honey until the following year.[17]

16. See, e.g., Shimanuki (1997) and Underwood and vanEngelsdorp (2007).

17. Regarding the relative use of these two replacement processes, over 3 years of a post-CCD survey of Pacific Northwest beekeepers, 80% of replacement colonies were obtained through making increase (or creating splits/nucs). See Burgett at al. (2009), Caron et al.

The "making increase" or "splitting" approach has the potential to allow for complete replacement of dead colonies within 6 weeks for mortality rates of up to 50%. Replacing a dead colony using this approach is relatively inexpensive because the purchase of new hives or boxes for the colonies is not necessary. At the aggregate level, given that mortality rates are not constant across beekeepers, it may take longer than 6 weeks to completely replace lost colonies with the making-increase approach. If an unfortunate beekeeper suffers, say, a 70% mortality rate, it will likely take him double the time indicated above to return to his pre-winter colony numbers.

2. AN EMPIRICAL ASSESSMENT OF CCD'S ECONOMIC IMPACTS

We assess the impacts of CCD on consumers, farmers, and beekeepers by focusing on four economic indicators. We first examine the impacts of CCD on honey bee colony numbers at both aggregate US and state levels. Numbers of bee colonies are not exogenous reflections of bee disease. Rather, they reflect disease along with the strategies beekeepers employ in response, moderated by the equilibrium changes in input and output prices that result. Our other three economic indicators are output levels (honey) and input and output prices. For input prices, we analyze prices for queen bees and packages of bees. For output prices, we analyze fees for pollination services.

2.1. Structural and Reduced Form Models of the Commercial Beekeeping Industry

We provide context for our empirics with a model of profit-maximizing commercial beekeepers and then develop structural and reduced form models of the interconnected markets that underlie the data. Beekeeping firms are assumed to maximize profits by choosing the inputs required to produce two outputs—honey and pollination services—which for simplicity, are assumed to have separable production functions:[18]

$$q_H = q_H(c, x_T) \quad \text{and} \quad q_P = q_P(c, x_T), \tag{1}$$

where q_H and q_P are quantities of honey and pollination services, c is the number of colonies, and x_T is transportation services, critical inputs for the mobile, migratory industry.

Colonies are intermediate inputs that beekeepers produce by combining purchased queens (x_Q) with other colony inputs, x_c, (e.g., labor, the physical Langstroth hive, and medication). The presence of diseases (D) like CCD negatively affects colony production. The production function for colonies is therefore $c = c(x_Q, x_c, D)$.

(2010), and Caron and Sagili (2011). No systematic information is available regarding replacement methods used by beekeepers outside the PNW.

18. A more detailed derivation of the model is available in app. I (apps. I–IX are available online). That model allows for jointness of the production functions for pollination services and honey. The reduced form specifications developed in the text are not affected by this feature of the production functions, so we suppress it.

A beekeeper's optimization problem is to:

$$\max_{\{x_Q, x_c, x_T\}} \pi_B = p_H \cdot q_H[c(\cdot), x_T)] + p_P \cdot q_P[c(\cdot), x_T)] - w_Q \cdot x_Q - w_c \cdot x_c - w_T \cdot x_T, \quad (2)$$

where $c(\cdot) = c(x_Q, x_c, D)$. The solution to this problem yields the optimal choices of x_Q, x_c, and x_T, where each is a function of output and input prices and disease level $(p_H, p_P, w_Q, w_c, w_T, D)$. The optimal number of colonies for beekeeper i to produce is $c_i^* = c_i(x_Q^*, x_c^*, D) = c_i^*(p_H, p_P, w_Q, w_c, w_T, D)$. Aggregating to the industry level, the observed number of colonies is $C = \Sigma_i c_i^*(p_H, p_P, w_Q, w_c, w_T, D) = C^*(p_H, p_P, w_Q, w_c, w_T, D)$, where the summation is over all beekeepers in the area under consideration.

Firm-level supply functions for honey and pollination services are found by substituting the optimal input choices into (1). The aggregate supply of honey is the summation of the individual supply functions, $S_H = \Sigma_i q_{Hi}^*(p_H, p_P, w_Q, w_c, w_T, D)$. In our reduced-form estimation below, we assume the prices of honey, transportation, and colony inputs to be fixed.

In the market for pollination services, the aggregate supply is the summation of the individual supply functions, $S_P = \Sigma_i q_{pi}^*(p_H, p_P, w_Q, w_c, w_T, D)$. Demanders of pollination services are the farmers who produce crops that benefit from pollination. Rucker et al. (2012) provide a theoretical and empirical analysis of pollination markets. Based on their findings, we conclude that the empirical factor of primary relevance to the demand side for pollination services is the number of almond acres and specify the demand for pollination services aggregated across farmers producing crops that benefit from pollination as $D_P = D_P(p_P, \text{ almond acres})$.[19]

Turning to the market for the input queens, the aggregate demand and supply are

$$D_Q = \sum\nolimits_k x_{Qk}{}^* \left(p_H, p_P, w_Q, w_c, w_T, D\right), \quad (3)$$

$$S_Q = \sum\nolimits_m x_{Qm}{}^* \left(p_H, p_P, w_Q, w_c, w_T\right), \quad (4)$$

where k and m are indexes representing beekeepers and queen suppliers.[20]

19. Approximately two-thirds of the US commercial honey bee population is employed in the California almond orchards every February and March. See app. I, n. 8, for a detailed discussion of why we treat almond acres as exogenous. Briefly, (1) pollination fees are a small proportion of almond production costs (roughly 3% by our calculations), and (2) there is a time lag of several years between the decision to plant more almond acres and the time those additional acres yield almonds.

20. Profit-maximizing beekeepers can be either (or both) demanders and suppliers of queens, depending on their individual comparative advantages. While CCD and other diseases are important influences on demand for packages and queens, the biology of queen production limits the impacts of this factor on the supply of queens. During the spring and summer, a typical productive queen may lay 1,500 eggs per day (Oliver 2016), all of which can become queens. (See Laidlaw [1992] for a discussion of queen production.) As a result, even if such beekeepers

Empirically exogenous variables in this system of supply and demand equations include the price of honey (predetermined by world trade in honey), the price of diesel, the number of almond acres, and a binary variable to distinguish time periods when CCD is active. The possible impacts of other time-varying factors are represented with trend variables, denoted below by $f(t)$. These variables are put on the right-hand sides of empirical reduced forms to explain the endogenous responses of aggregate colonies and honey production, the price of queens and packages, and the prices of pollination services. The five reduced forms that we estimate can be written as:

$$Y_i = f\left(P_{\text{Honey}}, P_{\text{diesel}}, \text{almond acres, CCD}, f(t)\right),$$

where $Y_i = \{Q_{\text{Colonies}}, Q_{\text{Honey}}, P_{\text{Queens}}, P_{\text{Packages}}, P_{\text{Pollination}}\}$.

The reduced forms capture the channels of influence of CCD on beekeeping industry quantities and prices. Assuming that CCD has important impacts on the operations of beekeepers, the comparative static predictions can be summarized as follows. CCD increases colony production costs (because more splits are required to maintain a given number of colonies) and therefore causes the equilibrium number of colonies to fall. This reduction in colony numbers reduces the supplies of both pollination services and honey, thereby causing the market price of pollination services to rise and the market-clearing quantity of honey produced to fall. CCD also increases beekeepers' demand for queens and packages. Insofar as the supply of queens is less than perfectly elastic, the increase in demand will result in an increase in the price of queens. In the market for packages of bees, CCD not only increases the demand for packages but may also decrease the supply of packages, both of which will cause the price of packages to increase.

We turn next to empirical tests of these predictions. Subject to minor model differences necessitated by inherent differences in the data available for the four outcome measures, the structure and sequence of the models we estimate are parallel. We discuss the models in some detail for colony numbers and then provide more abbreviated discussions for the other measures.

2.2. The Effects of CCD on Colony Numbers

The average rate of winter mortality for managed honey bees over 2007–14 was 29.6%, roughly double the normal rates prior to the appearance of CCD. Mortality represents an outflow from the population of colonies, while the splitting and re-queening of hives is an inflow. The net result is the change in colony numbers, which we analyze at na-

suffer substantial losses from CCD or *Varroa*, they still have the ability to produce large quantities of queens for sale. Accordingly, we do not include D—the indicator of bee disease—in the queen supply equation. The specifications of the demand and supply of packaged bees are the same as for queens with the exception that the supply of packages is affected by CCD.

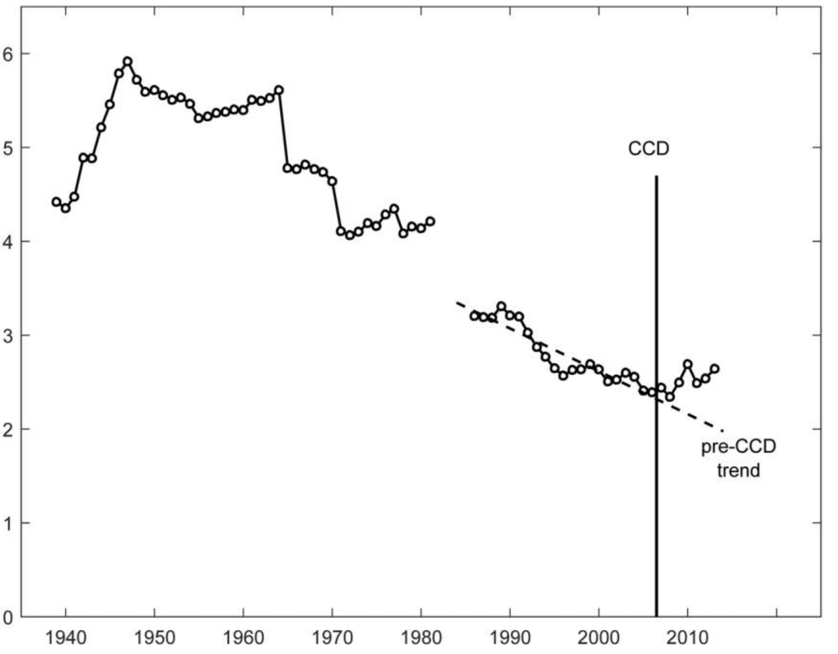

Figure 1. US bee numbers: 1939–2013 (millions of colonies)

tional and state levels. Our source of colonies data is the USDA annual survey of beekeepers.[21] Data from the survey are available at both the national and the state levels. The national data are plotted in figure 1.

The most obvious feature of the data in figure 1 is their substantial decline since the mid-twentieth century.[22] The USDA did not conduct its annual survey from 1982 to 1985, and in 1986 changed its data collection procedures, implying that comparisons between the pre- and post-1985 periods should be made with caution.[23] However, visual inspection of the figure does not reveal a notable decrease in US colony numbers

21. A second potential source of information is the US Census of Agriculture, which also counts bee colonies, but is less suitable for our purposes because it is only conducted every 5 years. See app. II for a brief discussion and comparison of the two data sources.

22. We are aware of no systematic economic analysis of the causes of this decline, and such an investigation is beyond the scope of the present paper.

23. Estimates prior to 1982 included colony counts from all beekeepers, whereas post-1985 estimates included colony counts only from beekeepers who maintained at least five colonies. Muth et al. (2003, 497–98) determine the one-time reduction in estimated colony numbers from this change in methodology to be 863,000 colonies with a standard error of 195,000 colonies.

in the years since 2007. In fact, there have been more colonies in every year but one since CCD appeared than there were in either 2005 or 2006.[24]

We report the results of a more formal statistical analysis in table 1, limiting our analysis to the period since 1986, following the span during which the annual USDA surveys were not conducted and after which the survey methodology was altered. We also limit our statistical analysis to the 39 states for which complete data series are available for the period 1986–2013.

The top section of table 1 reports means for three different pre- and post-CCD periods, and the differences between those means. The three time periods include data from three different pre-CCD time spans of successively narrowing scope: 1986–2006, 1990–2006, and 2000–2006. The longest pre-CCD period (1986–2006) is relevant to the extent that conditions are constant over time. The shorter intervals provide robustness checks by focusing on periods less susceptible to distortions from ancillary trends. The post-CCD period is always 2007–13. As can be seen, for the longest period comparison, the average number of colonies in the post-CCD years is 256,000 less than during the pre-CCD years. Consistent with the observation that colony numbers have trended downward over time, this difference is less for the 1990–2006 period. For the shortest period (2000–2013) the difference is a positive 7,000 colonies, displaying no evidence of fewer colonies in the post-CCD period.

In the other portions of table 1, we report results from several statistical specifications. The fullest version of the specifications we examine is

Aggregate colonies (full specification):

$$y_t = \alpha + \varphi \mathrm{CCD}_t + X_t'\beta + \theta t + \delta \mathrm{CCD}_t \cdot t + \varepsilon_t, \quad (5)$$

$$t = 1, \ldots, T \ \ (\mathrm{CCD}_t = 1 \text{ for } t > 2006),$$

where colony numbers is the dependent variable, CCD is the binary variable that we assign a value of one after CCD appeared, X_t is the vector of three shifter variables from the reduced-form model, and t is a time trend. Model 1 includes only the CCD variable on the right-hand side, and we report estimated coefficients from three regressions (corresponding to the three pre-CCD time periods). The OLS-estimated coefficients on the CCD variable in these regressions simply reflect the differences in average colony numbers between the pre- and post-CCD years. The coefficients labeled "GLS" come from a

24. Appendix IX, fig. A1, plots colony numbers for the five states with the most colonies, ranked by the average number of colonies over 2009–13 (apps. I–IX are available online). As with total US numbers, a visual examination of the plots in this figure reveals no systematic or dramatic reductions in colony numbers after 2006. Although colony numbers in both California and Florida have fallen over time, colony numbers in Florida were about 30% greater in 2013 than in 2006, there is no obvious acceleration in the decline rate for California, and colony numbers in North Dakota increased by 37% between 2006 and 2013.

Table 1. Effects of CCD on Aggregate US Colony Numbers

	1986–2013					1990–2013					2000–2013				
	Colony Averages over Subperiods														
Post-CCD	2007–2013	2,484				2007–2013	2,484				2007–2013	2,484			
Pre-CCD	1986–2006	2,740				1990–2006	2,645				2000–2006	2,477			
Change		−256					−161					7			
	Colony Regressions, Model 1: CCD Dummy Only														
	CCD Effect	*t*-Ratio				CCD Effect	*t*-Ratio				CCD Effect	*t*-Ratio			
OLS	−256	−2.26				−161	−1.73				7	.12			
GLS	−30	−.28				−61	−.56				10	.15			
	Colony Regressions, Model 2: CCD and Reduced-Form Shifters														
	CCD Effect	*t*-Ratio				CCD Effect	*t*-Ratio				CCD Effect	*t*-Ratio			
OLS	387	1.79				270	1.43				−61	−.58			
GLS	45	.38				65	.49				−87	−.98			
	Colony Regressions, Model 3: CCD, Shifters, Trends before and after 2007														
	Trend Before	*t*-Ratio	Trend After	*t*-Ratio	*t*-Ratio for Diff	Trend Before	*t*-Ratio	Trend After	*t*-Ratio	*t*-Ratio for Diff	Trend Before	*t*-Ratio	Trend After	*t*-Ratio	*t*-Ratio for Diff
OLS	−60	−6.47	−19	−.56	1.44	−93	−5.31	−92	−2.05	.05	27	.68	104.3	1.52	2.03
GLS	−51	−4.40	5	.12	1.57	−88	−4.78	−80	−1.69	.25	43	1.10	116.6	1.78	2.25

Note. Dependent variable, aggregate colonies, measures in thousands. GLS models specify AR1 disturbances.

generalized least squares procedure that models the regression disturbances as AR1 processes.[25] The GLS coefficients on the CCD variable in the regressions for the first two periods are negative, but considerably smaller than in the OLS regressions and not statistically significant. For the third period, the coefficient on the CCD variable is actually positive (but not significantly so). None of the three pre- and post-comparisons show evidence of a decline in national colony numbers.

As suggested in the reduced-form model developed above, several factors besides CCD may affect colony numbers. In model 2, we include the three "shifter" (X_t) variables from the reduced form equation (almond acres, honey price, and diesel price) to control for their effects. The empirical measure we use for almond acres is the number of bearing acres in California (where all US almonds are produced) in year *t*. For diesel and honey prices, we use annual real national average measures. As can be seen, there are no instances in any of the three time periods for either the OLS or GLS models in which the estimated coefficient on the CCD variable is negative and statistically significant.

We next consider the possibility of changes in time trends.[26] Figure 1 makes clear the preexisting downward trend in US colony numbers prior to 2007. The CCD-induced increased mortality rate after 2006, insofar as it reduced colony numbers, should manifest itself as a more negatively sloped trend line during this period. To account for both shifters and trends we estimate model 3 as the full specification in (5). It allows for the trend in colony numbers to differ before and after 2007 and allows for a discontinuous shift in the height of the trend line in 2007. The results displayed for model 3 in table 1 provide no evidence of a significantly more negative trend following the appearance of CCD. In fact, all OLS and GLS point estimates indicate that colony numbers either declined more slowly post-CCD or increased at a more rapid rate. The difference in pre- and post-CCD trends is statistically significant only for the 2000–2013 series, where a small positive 2000–2006 trend becomes more positive in the 2007–13 period.[27]

---

25. To limit clutter in this table and others below, we do not report the estimated AR coefficients. Broadly, these coefficients are positive and statistically significant. For the same reason, in regressions to come we do not report the estimated coefficients on the shifter variables (almond acres, diesel prices, and honey prices).

26. The four outcome variables we study comprise two measures of quantities—colony numbers and honey production—and two prices—package (and queen) prices and pollination fees. Visual examination of the quantity variables suggests that they followed preexisting trends at the time CCD appeared, while, if anything, the prices are subject only to level changes. This fact leads us to incorporate time trends by estimating changes in the trends in 2007 for the two quantity measures, but only changes in levels for the two price measures.

27. To reduce clutter in table 1, we do not report the estimated coefficients on the CCD indicator variables. These coefficients indicate that there was no significant drop in the height of the trend line in 2007. We also estimated models that include the trend line and exclude the

The consistent result from table 1 is that aggregate US data provide no indication that CCD resulted in a decline in colonies or an acceleration in the rate at which they declined. To investigate the possibility that the aggregate numbers mask CCD impacts in individual states, we estimate regression specifications analogous to those in table 1 for all 39 individual states for which colony numbers are reported in recent years.[28]

Table 2 reports the state-level results, employing a GLS estimator with an AR1 model for the disturbance and standard errors that are corrected for contemporaneous correlations across states. The estimated coefficient on CCD is allowed to differ by state, and the AR1 coefficient is constant across states. The fullest specification of the panel model is

$$\text{Colonies panel (full specification):}$$
$$y_{it} = \alpha_i + \varphi_i \text{CCD}_t + X_t'\beta_i + \theta_i t + \delta_i \text{CCD}_t \cdot t + \varepsilon_{it}. \tag{6}$$

Model 1 in table 2 is a panel specification of its aggregate counterpart in table 1 with the CCD indicator as the only explanatory variable. The first row of results for model 1 shows that 31 of the 39 states experienced declines in average colony numbers between the longest pre-CCD period (1986–2006) and the post-CCD period (2007–13). Twelve of those declines were statistically significant. Eight states saw increased colony numbers between the two periods, with two of those increases being statistically significant. The sum of the 39 state-level effects (the estimated aggregate effect) is about −123 (thousands). The estimated CCD effect in the corresponding aggregate specification in table 1 is −256, which is well within two standard errors of −123, implying that the two tables come to consistent conclusions. From the other two rows under model 1 of table 2, it can be seen that as the pre-CCD period is shortened, the number of states in which the average colony count was lower in the post-CCD years falls, and there is an equal offsetting increase in the number of states where colony count rises. The number of states with significant differences (either positive or negative), however, is not greatly affected. The sum of the estimated state-level CCD effects becomes less negative and is even positive in the third row of results.[29]

---

three shifter variables and obtained substantively identical results—no evidence that CCD caused either a downward level shift in 2007 or an accelerated rate of decline in colony numbers.

28. The 11 states dropped from the analysis are AL, CT, DE, MD, MA, NV, NH, NM, OK, RI, and SC. The remaining 39 states accounted for 98.75% of total colonies in 2013.

29. A natural suggestion for modifying eq. (6), following the program evaluation literature, is to replace the covariates and/or time trends with year dummy variables. In many contexts this allows a more flexible nonparametric treatment of incidental time effects. In the analysis of the panels treated in the current paper, however, estimating year fixed effects in this way is problematic—both because of problems of perfect multicollinearity and the logical inability to identify CCD effects in such a model. See app. III for a discussion of the issues that arise.

Table 2. Effects of CCD on Colony Numbers: Panel Results from 39 States

Subperiod	State Counts of CCD Effects: Negative	Sig. Neg.	Positive	Sig. Pos.	Sum across States	SE of Sum				
	Model 1: State-Specific CCD Effects with State Fixed Effects									
1986–2013	31	12	8	2	−122.9	111.2				
1990–2013	29	12	10	2	−89.9	106.0				
2000–2013	24	11	15	5	11.2	73.0				
	Model 2: State-Specific CCD Effects with State Fixed Effects and State-Specific Shifter Effects									
1986–2013	8	1	31	1	187.7	161.0				
1990–2013	12	1	27	3	176.6	157.8				
2000–2013	30	1	9	1	−59.5	90.5				
	Model 3: CCD, State-Specific Trends Pre- and Post-CCD, and Shifters									
	Pre-CCD Trends by State				Post-CCD Trends by State				Trends Sig. Dif Post-CCD	
	Sig. Neg.	Sig. Pos.	Sum across States	SE of Sum	Sig. Neg.	Sig. Pos.	Sum across States	SE of Sum	Lower	Higher
1986–2013	25	5	−59.1	8.9	14	11	−16.9	32.9	10	13
1990–2013	30	1	−93.3	16.2	20	4	−91.5	41.3	11	8
2000–2013	3	5	39.1	32.7	2	8	112.6	55.2	3	16

Note. Sample comprises the 39 states with complete colony series over 1986–2013. Colonies are measured in thousands. All estimates are GLS specifying a first-order autoregressive error structure; standard error of sums of coefficients are calculated assuming contemporaneous correlation across states. Coefficients on shifter variables vary by state. Tests of significance are one sided and carried out at the 5% level.

As with the analysis of aggregate US colony numbers, we next control for the possible impacts of the three shifter variables from the reduced-form model. Model 2 of table 2 is the panel analogue of its table 1 counterpart. Our empirical measures of the three variables are the same as for the analysis of national colony numbers. Each of the three shifter variables has the same values across states in any given year, and we allow the estimated coefficients on these variables to vary across states. The take-away message from the regressions for the three model 2 time periods is that after controlling for the impacts of the shifter variables, only one of the 39 estimated CCD coefficients is negative and statistically significant for each time period. In addition, the sums of the state-level CCD coefficients are not large relative to the sums of the standard errors of those coefficients.

Model 3 in table 2, which is the full specification in equation (6), adds a linear trend variable to the model 2 specification and interacts it with the CCD dummy indicator, with trend and interactive coefficients varying across states. The results indicate that for all three pre-CCD periods, the sum (across states) of the post-CCD trends is less negative (or more positive) than the sum of the pre-CCD trends. The results also show that for the first two time periods, the number of states with significantly lower time trends in the post-CCD years is roughly equal to the number with significantly higher time trends (10 vs. 13 and 11 vs. 8). For the third time span, the number of states with significantly higher time trends after the appearance of CCD is much greater than the number of states with significantly lower trends (16 vs. 3).[30]

To summarize, the empirical results suggest that although colony numbers have declined over time, when we control for other factors that affect colony numbers, there is no evidence of an increase in the rate of decline since the onset of CCD, either at the aggregate level or across individual states. Given that an average of almost one-third of the honey bee colonies in the United States have died each winter since the onset of CCD, how can this be? Our favored interpretation, which we elaborate on in another section, rests on the fact that beekeepers have always lost hives during the winter. Sustainable beekeeping requires them to replace dead and weak colonies using the methods described in section 1.3. Since the onset of CCD, beekeepers have had to replace more hives to maintain colony numbers, and the results in this section suggest that they have succeeded in doing that.

---

30. To conclude that CCD (a potential negative supply shift) has not reduced colony counts one must rule out the possible colony-increasing effects of an outward demand shift that coincided with the onset of CCD. From that perspective, it is noteworthy that models 2 and 3 in both tables 1 and 2 control for the dramatic demand-increasing effects of the steady increase in almond acres over our sample (from about 400,000 acres in 1986 to over 800,000 acres in 2013). The estimates from models 2 and 3 in both tables indicate no supply-reducing effect from CCD, even controlling for the effects of almond acres, diesel price, and honey price. We are grateful to a referee for focusing our attention on this issue.

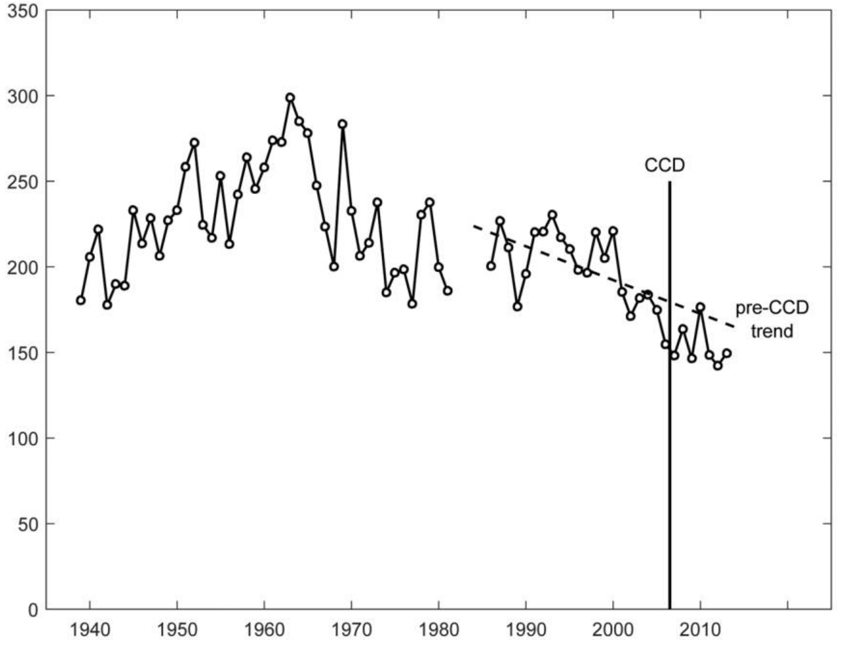

Figure 2. US honey production: 1939–2013 (millions of pounds)

2.3. The Effects of CCD on Honey Production

Colonies, the subject of the previous section, are inputs in beekeeping. Here we examine data for honey—one of the primary outputs of the beekeeping industry—for evidence of CCD.[31] As with colony numbers, data on honey production are available at both the national and state levels. The national data are plotted in figure 2, where honey production displays a sporadic upward trend until (roughly) the mid-1960s, after which production has trended downward with substantial year-to-year variation.[32] As with colony numbers, comparisons between the pre- and post-1985 periods should be made with caution due to changes in collection procedures in 1986. In the figure, a vertical line be-

31. USDA's annual survey of beekeepers asks them to report the total pounds of honey harvested from their colonies in each state where they maintained colonies for all or part of the year. Possible biases in colony numbers from the surveys are discussed in app. II. We see no comparable sources of potential bias related to the questions that ask beekeepers about their honey production.

32. We attribute much of the year-to-year variation in honey production to weather-induced variation in per-colony yields. One noteworthy recent change in US honey markets is the growing importance of imported honey. In recent years, the quantity of honey imported has substantially exceeded the production of domestic honey. See Daberkow at al. (2009) for a discussion of US honey markets.

tween 2006 and 2007 indicates when CCD might have first influenced honey production. Visual inspection of the figure reveals no dramatic decrease. The dotted line indicates the estimated trend line based on production over the 1986–2006 period. As can be seen, in all but one year since 2007, actual production has been less than the extension of the trend line, but the shortfalls are not dramatic. Moreover, it is notable that there has not been a significantly negative trend since 2006.[33]

Because colonies and honey are measured at the same state level, the empirical specifications are identical to equations (5) and (6). Detailed results from analysis of the honey production data are reported in appendix IV but can be summarized here simply. Although US honey production has declined over time, we find no statistical evidence of a downward shift in production or of an accelerated rate of decline since the appearance of CCD, either in aggregate US production or in individual states.

2.4. The Effects of CCD on Queen Bee and Package Prices

Concluding that bee populations and honey production have not responded dramatically, if at all, does not imply that there have been no effects of CCD. Our third set of empirics looks specifically at an important factor market for evidence of such response.

As discussed above, two common methods for replacing lost colonies are by making splits and by purchasing packaged bees. Splitting colonies requires newly fertilized queens, often purchased from specialized queen breeders. Alternatively, packages of worker bees, which also come with fertilized queens, can be used to start a colony from scratch. By all accounts, CCD has resulted in an increase in winter mortality of colonies, which causes an increase in the demand for queens and packages. This increase in demand should cause an increase in the prices of queens and packages to the extent that the supply of queens and packages is less than perfectly elastic. Relevant to the supply elasticity question is the discussion in Laidlaw (1992), which suggests that queens can be reared in large numbers quickly: from egg to fertilized queen in less than a month. Moreover, any of the fertilized eggs has the potential to become a queen if it is fed sufficient amounts of royal jelly by its broodmates. While the very shortest-run supply of queens is fixed, queen producers can substantially expand production at what would seem to be near constant marginal cost with a month's lead time.

There is no published analysis of the determinants of queen and packaged bee prices, and there are no previously assembled data series on either quantities or prices of queen and packaged bees. Therefore we construct a data series on prices for packages and

33. Appendix IX, fig. A2, displays honey production for the top five honey-producing states, ranked by average honey production over the period 2009–13. As with total US honey production, a visual examination of the plots in this figure reveals no dramatic reductions in honey production after 2006.

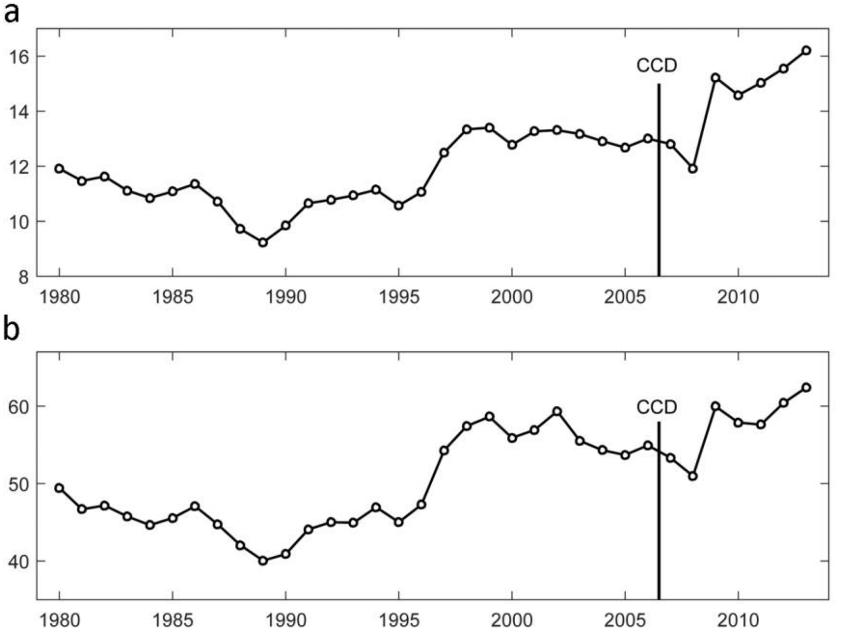

Figure 3. Real queen (*a*) and package (*b*) bee prices. Both queen and package prices are averages (across five sellers) for quantities of 100 or more. Prices are in 2013 dollars.

queen bees from advertisements in March issues of the *American Bee Journal,* which has been published continuously since 1861.[34]

Figure 3 displays the queen and package prices averaged across a consistent core of five sellers from 1980 to 2013. The two price series shown are for purchases of 100 (or more) queens and packages of bees. Both of these series suggest a modest upward trend in real (2013 dollar) prices. Simple estimated trend lines suggest that queen prices have increased by about \$0.14 per year (with a *t*-statistic of 7.34) and that package prices have increased by about \$0.52 per year (with a *t*-statistic of 7.49). Both of these annual rates of increase are about 1% of the mean prices for the respective series. Regarding the possible impacts of CCD, both package and queen prices have increased since 2006, but it is notable that the increase did not occur until 2009, a full 2 years after the onset of CCD.

34. From the *American Bee Journal* masthead: "The American Bee Journal was established in 1861 . . . and . . . has the honor of being the oldest English language beekeeping publication in the world." Spring is when beekeepers typically make increase (which often employs purchased queens) or replenish depleted hives with packaged bees—hence our decision to collect information on queen and package prices from March issues of the *American Bee Journal.* A typical March issue contains advertisements from dozens of sellers, and an online list of sellers in 2011 counted 146 sellers. To construct a consistent time series we focus on price quotes from a core of five long-lived sellers. Our data collection procedure is described further in app. V.

Both package and queen prices then fell in 2010 and have increased at modest rates since then. This pattern of prices, from the outset, is not consistent with CCD having major sustained impacts on input markets for honey bees.[35]

Our statistical approach here differs somewhat from those we use for colony numbers and honey production. Package and queen prices, unlike colonies and honey, are not trending in any obvious way that might have changed with CCD. Therefore, when incorporating time we put autonomous linear trends in the price regressions and test for level shifts in prices that might have resulted from CCD. Results for queen prices are presented in table 3. The top section of the table shows the differences in average queen prices between the three pre-CCD periods of varying duration and the post-CCD period. The difference in averages is a \$2.83 increase for the longest pre-CCD period comparison, with the increase falling to \$1.45 as the pre-CCD period is shortened. The middle section of table 3 reports two regression model results, where the dependent variable is the average queen price across the five sellers in a year. The fullest specification of the models we estimate is

Queen price averages (full specification):

$$y_t = \alpha + \theta \mathrm{CCD}_t + X_t'\beta + \delta t + \varepsilon_t. \tag{7}$$

The first specification (model 1) is a simple regression of the average annual queen price on an intercept and the CCD dummy. The estimated OLS coefficients on the CCD dummy variable (all three of which are significantly greater than zero) reflect the differences in means from the top portion of the table. In the GLS estimates of model 1, both the CCD coefficients and their significance are considerably smaller. In model 2, we estimate the full version of (7) with the three shifter variables from our reduced-form model, as well as a linear trend variable. We find that the CCD coefficient is no longer positive and significant—in fact, the point estimates of the CCD effect on prices are all negative.[36]

The bottom section of table 3 reports results from a panel analysis of the annual time series of queen prices charged by the five sellers. The fullest specification of that

35. The prices we analyze are posted and advertised, not transaction prices charged to long-term customers. For this reason, we see no structural reason to expect prices to respond sluggishly. Appendix IX, fig. A3, displays the prices of the five individual sellers in our analysis, which generally move together. Pairwise correlation coefficients for the queen prices all exceed 0.69, and for package prices, all but one of the correlation coefficients exceed 0.64. In recent years, the plots of the package and queen prices of each of the sellers look quite similar, with each being slightly higher in 2013 than in 2006. Neither of these figures provides visual evidence of minaciously large increases in either queen or package prices for any of the sellers since the appearance of CCD.

36. Qualitatively identical results regarding the impacts of CCD are obtained for models with only the shifter variables and only the trend variable.

Table 3. Effects of CCD on Queen Bee Prices:

	Queen Price Averages over Subperiods					
	1980–2013		1990–2013		2000–2013	
Post-CCD	2007–2013	14.47	2007–2013	14.47	2007–2013	14.47
Pre-CCD	1980–2006	11.64	1990–2006	12.08	2000–2006	13.02
Difference		$2.83		$2.39		$1.45
Regression Analysis of Time Series of Average Queen Price across Five Sellers						
	1980–2013 (n = 34)		1990–2013 (n = 24)		2000–2013 (n = 14)	
	CCD Effect	*t*-Ratio	CCD Effect	*t*-Ratio	CCD Effect	*t*-Ratio
	Model 1: Regressions of Price on Intercept and CCD Dummy					
OLS	$2.82	5.13	$2.38	4.01	$1.44	2.46
GLS	$1.23	1.65	$1.58	1.92	$1.16	1.50
	Model 2: Controlling for Linear Effects of Time and Shifters					
OLS	–$.48	–.52	–$.75	–1.36	–$1.38	–2.75
GLS	–$.43	–.55	–$.71	–1.35	–$1.52	–3.26
Panel Analysis of Time Series of Queen Prices from Five Sellers						
	1980–2013 (n = 157)		1990–2013 (n = 117)		2000–2013 (n = 68)	
	CCD Effect	*t*-Ratio	CCD Effect	*t*-Ratio	CCD Effect	*t*-Ratio
	Model 1: Regressions of Price on CCD Dummy with Fixed Seller Effects					
OLS	$2.80	9.63	$2.36	7.56	$1.44	4.07
GLS	$1.74	2.50	$1.53	2.41	$.87	1.43
	Model 2: Fixed Seller Effects and Controlling for Covariates					
OLS	–$.46	–.90	–$.75	–1.58	–$1.38	–2.22
GLS	–$.28	–.53	–$.37	–.90	–$.41	–1.11

Note. GLS estimates model the regression disturbance with contemporaneous correlation across sellers and a time series AR1 component. Advertised prices for queen bees in quantities of 100 or greater, in 2013 real prices, taken from March issues of the *American Bee Journal*.

model is shown in (8) and the estimation results are very similar to those for the analysis of average queen prices.

$$\text{Queen price panel data (full specification):} \qquad y_{it} = \alpha_i + \theta \text{CCD}_t + X_t'\beta + \delta t + \varepsilon_{it}. \tag{8}$$

In model 1, the CCD effects in the OLS specification are positive and significant, but the effects are smaller and less significant in the GLS specification. In model 2 for the panel data, we add the shifters and a time trend and find the CCD effect to no longer be significant. Moreover, all CCD coefficient estimates are negative. In appendix IV, we analyze package bee prices in models parallel to the analysis of queen prices in table 3. The results are substantively identical to those for queen prices.

Prices of packaged bees and queens reflect the cost and scarcity of these inputs into beekeeping. If CCD-induced increases in winter mortality have had significant impacts on beekeeping, then one would expect to observe not only decreases in colony numbers (which we do not find) but also changes in the prices of inputs used to adapt. Increased winter mortality results in increases in the demand for packaged bees and queens as beekeepers replace greater numbers of lost colonies resulting from CCD. The results in this section suggest that there is no evidence that this increased demand has resulted in increased queen or packaged bee prices. We infer that the supply (even in the short run) of queens and packaged bees is sufficiently elastic that any increases in demand associated with CCD have not resulted in measurable increases in prices.

2.5. The Effects of CCD on Pollination Fees

In this final empirical section, we study the price of pollination services.[37] Our empirical strategy is to analyze panel data on fees by crop for two distinct groups of beekeepers responding to two similar surveys. The most comprehensive data on fees come from a survey that Michael Burgett (and in recent years, his successor Ramesh Sagili) has administered from Oregon State University since 1987. Every year Oregon and Washington (Pacific Northwest, PNW) beekeepers are asked to report the fees they received for pollinating crops. This survey has often garnered responses from beekeepers responsible for 60%–70% of bees used for commercial pollination from the region. The second data source is a similar beekeeper survey administered by the California State Beekeepers Association, modeled after the PNW survey but conducted only since 1996.

A broad sense of the time paths of PNW fees can be gained from figure 4, which displays the annual averages for almond fees and for an average of four other crops (pears, cherries, apples, and blueberries), chosen because of their complete history over the 1987–2013 frame. Because almond fees are by far the largest source of pollination revenues, and because these fees have behaved differently from fees for other crops in recent years, we treat them separately. Notable in figure 4 is the dramatic increase in almond pollination fees that occurred after 2004—behavior not seen for other surveyed crops. Average reported almond fees rose from $65 to $104 between 2004 and 2005, and increased again to close to $150 in inflation-adjusted terms for the years after 2005. It is tempting to attribute the fee increases to CCD, and it may indeed be

37. The jointness of supply of pollination services and honey has implications for the equilibrium pricing of pollination services. See Rucker et al. (2012), who develop and econometrically analyze a model of pollination fees.

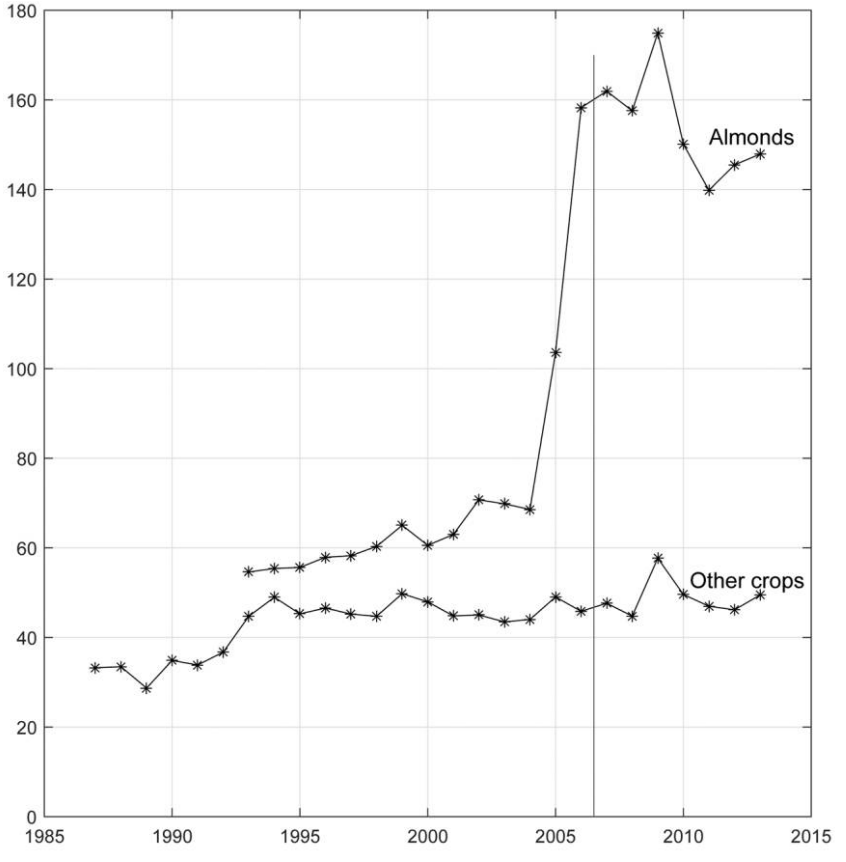

Figure 4. Real Pacific Northwest fees (1987–2013)

partly to blame, but the timing is not right. The first reported instance of CCD was in the fall of 2006, which could only have affected fees beginning in spring 2007. But as figure 4 shows, almond fees rose earlier, in 2005 and 2006.

Data on California pollination fees for almonds and other crops are displayed in figure 5. The California survey has a shorter history than the PNW survey and covers a somewhat different set of crops. In figure 5, we plot fees for almonds and average fees for seven crops pollinated after almond pollination is completed. These plots of California fees look very similar to the PNW fees, with substantial increases in almond fees in 2004 and 2005 that have persisted to the present, but very little change in the other fees. Whereas the only crop pollinated by PNW beekeepers in February is almonds, California beekeepers provide services for two other "early" crops of relatively minor importance—plums and early cherries. Because these two crops compete directly with almonds for pollination services, the time path of their pollination fees is expected to look similar to

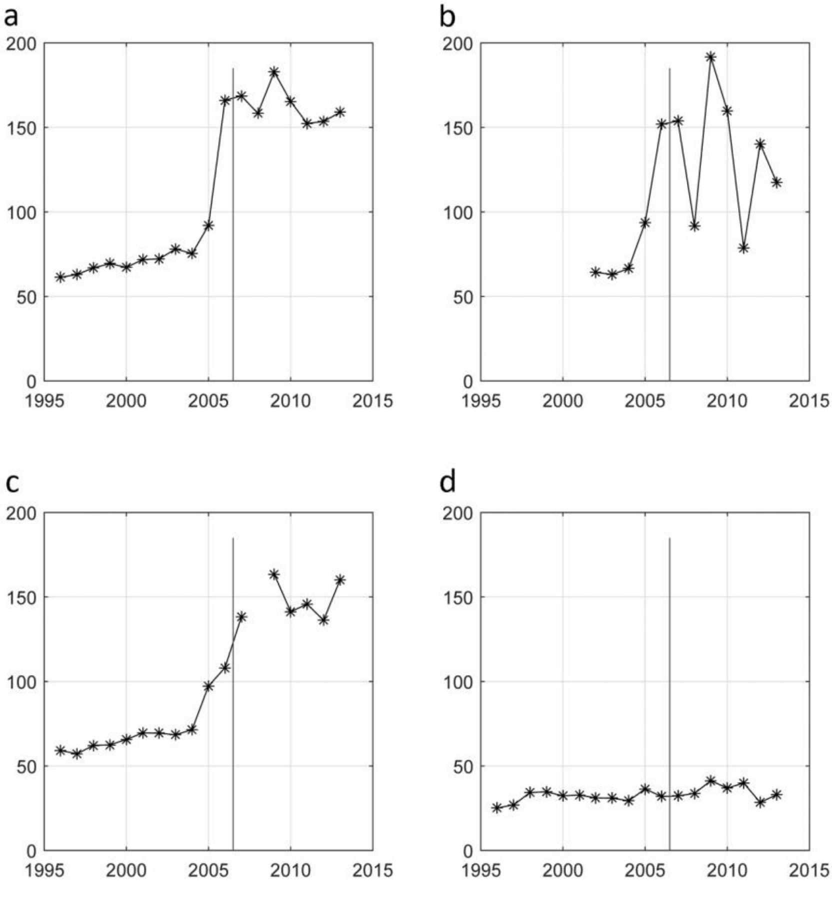

Figure 5. Real California fees (1996–2013). *a*, Almonds. *b*, Early cherries. *c*, Plums. *d*, Average of other crops.

that of almond fees. Figure A5 confirms this expectation. It can be seen that plum fees increased in 2004 and 2005 in a manner similar to those for almonds and then leveled off. Early cherry fees also increased in 2004 and 2005 but then varied substantially after 2007, though the average of the 2007–13 fees is significantly higher than the average of fees in the years preceding 2005.

Statistical analysis of the PNW and California pollination fees is presented in tables 4 and 5. The shorter sample periods for pollination fees (in particular, for California, where data are not available until 1996) necessitate a slightly different empirical approach. For PNW fees, we split the data into two, rather than three, periods: a longer 1987–2013 sample and a shorter 2000–2013 sample. For California, we do

Table 4. Effects of CCD on Pollination Fees: A Pacific Northwest Panel of 11 Crops (1987–2013)

	Fee Averages over Subperiods					
	1987–2013			2000–2013		
	Years	Almonds	Other Crops	Years	Almonds	Other Crops
Post-CCD	2007–13	$153.97	$47.93	2007–13	$153.97	$47.93
Pre-CCD	1987–2006	$72.55	$38.54	2000–2006	$84.93	$44.30
Difference		$81.42	$9.39		$69.03	$3.63

	Regression Analysis			
	1987–2013 (n = 276)		2000–2013 (n = 147)	
	CCD Effect	t-Ratio	CCD Effect	t-Ratio
	Model 1: Regressions of Price on CCD Dummies with Crop Fixed Effects			
Almonds	$75.84	13.77	$64.64	25.72
Other crops	$6.17	2.73	$1.64	1.38
	Model 2: Fixed Effects and Controlling for Linear Effects of Time and Shifters*			
Almonds	$48.76	5.49	$45.84	4.16
Other crops	$.30	.10	–$.16	–.06

Note. Pollination fees are real in 2013 dollars. Estimates are GLS specifying a regression disturbance with contemporaneous correlation across sellers and a time series AR1 component. Estimates are GLS specifying a regression disturbance with contemporaneous correlation across sellers and a time series AR1 component. Pollination fees for apples, almonds, blueberries, cherries (not early), cranberries, crimson clover, cucumbers, pears, radishes, red clover, and squash.

* Separate time trends estimated for almonds and other crops; common shifter effects estimated for all crops.

not split the pre-CCD period, instead focusing our analysis on the full 1996–2013 span for which we have data.[38]

Table 4 reports the estimated impacts of CCD on PNW pollination fees. The top panel indicates that average almond fees received by PNW beekeepers after 2006 are substantially higher than the pre-2007 average. For non-almond PNW crops, the post-2006 average is also higher, but the difference is much smaller than for almonds, both in dollar and percentage terms. The lower panel of table 4 displays the results

38. The PNW and California panels are nearly balanced but contain holes due to survey nonresponse. From the PNW surveys, a total potential number of observations of 11 crops × 27 years = 297 reduces to 276 usable observations. For California, from a potential maximum of 10 crops × 18 years = 180, we have 173 usable observations.

Table 5. Effects of CCD on Pollination Fees: A California Panel of 10 Crops (1996–2013)

	Fee Averages over Subperiods				
		Early Crops			
	Years	Almonds	Plums	Cherries	Other Crops
Post-CCD	2007–13	162.87	147.47	133.40	35.09
Pre-CCD	1996–2006	80.31	71.93	87.87	31.47
Difference		\$82.56	\$75.54	\$45.53	\$3.62

	Regression Analysis				
	Model 1: Regressions of Price on CCD Dummies with Crop Fixed Effects				
	Early Crops Separate (n = 173)			Early Crops Merged (n = 173)	
	CCD Effect	t-Ratio		CCD Effect	t-Ratio
Early crops:					
Almonds	\$76.04	8.53	Early	\$66.24	13.16
Plums	\$69.78	13.30	Other	\$3.32	3.74
Cherries	\$41.61	3.05			
Other	\$3.42	3.85			
	H_o: Early crop effects are identical (p = .001)				
	Model 2: Fixed Effects and Controlling for Linear Effects of Time and Shifters*				
Early crops:					
Almonds	\$47.82	5.67	Early	\$37.24	5.19
Plums	\$39.83	5.74	Other	\$.35	.12
Cherries	\$16.14	1.25			
Other	\$2.92	.99			
	H_o: Early crop effects are identical (p = .001)				

Note. Pollination fees are real in 2013 dollars. Estimates are GLS specifying a regression disturbance with contemporaneous correlation across sellers and a time series AR1 component. Pollination fees for apples, almonds, avocados, early cherries, melons, plums, prunes, sunflowers, vegetable seed, and alfalfa seed.

* Separate time trends estimated for early crops (almonds, plums, cherries) and other crops; common shifter effects estimated for all crops.

from two regression models for pollination fees. The full specification of the regression model is

Pollination fee panel data (full specification):

$$y_{it} = \alpha_i + \varphi_A d_i^A \mathrm{CCD}_t + \varphi_{\mathrm{NA}}(1 - d_i^A)\mathrm{CCD}_t + \delta_A d_i^A \cdot t + \delta_{\mathrm{NA}}(1 - d_i^A) \cdot t + X_t'\beta + \varepsilon_{it}. \tag{9}$$

$i = 1, \ldots, 11$ (crops), $t = 1, \ldots T$, $d_i^{\mathrm{A}} = 1$ for almond observations.

Model 1 is a GLS regression that includes crop fixed effects and two binary CCD variables (one for almonds and one for all other PNW crops).[39] The estimated CCD impact for almond fees is in the \$65–\$75 range and is highly significant for both time periods. Consistent with figure 4, the CCD impact on other crops is much smaller and, for the shorter pre-CCD period, is not statistically different from zero at standard significance levels. Model 2 is a GLS regression that modifies (9) by including the three shifter variables, as well as linear time trends that differ for almonds and nonalmond crops to account for possible preexisting trends. The CCD effect on almond fees is between \$45 and \$50 and is statistically different from zero for both sample periods. The estimated CCD effect for other crop fees is small and not significantly different from zero for either sample period.

Table 5 presents estimates from a parallel analysis of California pollination fees. The top panel indicates that fees for almonds increased substantially. Further, fees for plums and early cherries move with almond fees and are considerably higher following the appearance of CCD. Fees for other (later) crops also increase after 2006, but by a relatively small amount. The bottom panel of table 5 displays results from several GLS regression specifications. Beyond examining a single sample period for the shorter time series of California fees, the California specifications posit separate CCD effects for plums and early cherries. The first column of both models suggests that the estimated impact of CCD is large and significant for almonds and plums, with a somewhat smaller impact for early cherries that is not significant in model 2. The estimated impact of CCD on pollination fees for all other crops is relatively small in both models, and in model 2, when we control for the three shifter variables and linear trends, the estimated CCD impact is not statistically different from zero.

The conclusions we draw regarding the effects of CCD on pollination fees are as follows. For both the PNW and California, the estimated effects of CCD on almond fees are substantial. Using the model 2 estimates, which account for possible effects of time trends and shifter variables, we estimate that almond fees in the PNW and California increased by slightly less than \$50. Plum fees in California increased by \$40.[40]

The timing of the increase in early-crop pollination fees (see figs. 4, 5) raises the question of whether there were forces at work earlier than the 2006 discovery of CCD, despite what we view as clear evidence that CCD is a distinct phenomenon, unrecognized prior to 2007. (No such suspicions of a pre-2006 effect are raised, however, from the colony number, honey production, or package and queen price data.) Contemporary accounts from the spring of 2005 describe high winter mortality rates, a reduced supply of bees to pollinate almonds, and a resulting increase in almond pollination fees.

39. To reduce clutter in tables 4 and 5, we do not present OLS results.

40. A discussion of these estimates of the impacts of CCD on pollination fees with the smaller CCD impacts estimated found by Rucker et al. (2012) is contained in app. VI.

However, from the limited descriptions from that time, the symptoms of dead colonies were not consistent with mortality due to CCD.[41]

If one views all pollinator health problems at the time as reflecting CCD, then a reasonable specification that maintains the spirit of our analysis would include only a 0–1 dummy variable for the post-2004 years (and no post-2006 dummy). The estimates from such a model indicate that the increase in almond pollination fees following 2004 was about $70, which might be interpreted as an impact of declining pollinator health from all sources after that time.[42]

3. EVALUATING THE IMPACTS OF CCD ON CONSUMERS AND BEEKEEPERS

Despite finding limited measurable response to CCD in key economic indicators, there remain channels of influence consistent with the data. In this section, we briefly discuss our back-of-the envelope estimates of the impacts of CCD on consumer prices and on beekeeper costs and revenues. These estimates are developed and discussed in detail in appendix VIII.

---

41. Industry observers and participants attributed the reduced supply of bees in the spring of 2005 to (1) a growing resistance of *Varroa* to the treatments being used by beekeepers and (2) scarcity of late summer and fall forage in 2004, leading to reduced brood rearing and increased winter mortality. See fourth-generation commercial beekeeper John Miller's description of his dying hives in Nordhaus (2011, 76), also Mussen (2005, 2006) and Nordhaus (2011, 74–82).

A recent theme from a few experts studying pollinator health problems has been that, although CCD was an important factor in winter mortality rates in the mid- to late-2000s, its impacts have since subsided, and in more recent years CCD has been replaced by other growing pollinator health problems. If this perspective is correct, our economic impact estimates are still relevant but are more appropriately interpreted as the impacts of CCD plus other sources of increased colony mortality in recent years.

42. There are other possible impacts of CCD operating through pollination markets, which we mention here. In particular, almond yields, and yields of other crops, could fall because of bees having reduced vitality early in the pollination season. Appendix VII.A provides graphs and brief discussions of time series of almond prices and per-acre yields of almonds, apples, cherries, and pears. As with the factors examined rigorously in this section, there is no evidence of CCD having substantial adverse impacts in almond markets or on PNW tree fruit yields. Appendix VII.B discusses an alternative approach that offers a robustness check and alternative identification strategy based on limited data on state variation in mortality rates attributable to CCD. Results from this approach provide qualitatively similar conclusions regarding the economic impacts of CCD. As we discuss in the appendix, however, the data we were able to obtain for this test have shortcomings, and so we focus on the discrete CCD effects in the text.

3.1. Effects on Consumers

To develop an estimate of the impacts of CCD on the consumer price of almonds, we use our estimates of the impacts of CCD on almond pollination fees along with information on almond yields and prices, combined with a zero-profit assumption for almond producers to determine that the farm-gate cost share of pollination fees in almond production is roughly 3.1%. Similar downstream calculations suggest that (1) the cost share of pollination services in the retail price of a can of almonds is about 1.8% and (2) the CCD-induced increase in pollination fees increased the retail price of a $7-per-pound can of Smokehouse Almonds by approximately 1.2% or 8.4¢.[43] In the aggregate, we estimate that the farm-gate costs of almond production have increased by about $120 million, which translates into impacts of about $0.124 per person in the United States.

3.2. Effects on Beekeepers

The negative impacts of CCD on beekeepers arise from increased colony mortality. As indicated in section 2.3, the primary method used by PNW beekeepers to replace dead colonies is to "split" healthy colonies, which requires beekeeper time and the purchase price of a newly fertilized queen. We estimate this cost to be about $23 per colony, based on queen prices at the end of the data we use for our empirical analysis (see app. VIII). Our empirical analysis above suggests, however, that beekeepers also benefited from CCD because its onset resulted in increased almond pollination fees. Assuming that the onset of CCD resulted in an increase in the annual mortality rate of 15% concomitant with an increase in almond pollination fees of $60 per colony, our back-of-the-envelope estimates suggest that the average PNW beekeeper actually gained from the appearance of CCD, even in a scenario where he is assumed not to anticipate increased winter mortality rates.

4. CONCLUSIONS

Colony collapse disorder has been portrayed as an environmental disaster decimating honey bee populations in the United States and elsewhere. While challenges to honey bee health and the difficulties faced by commercial beekeepers are considerable, our analysis of colony numbers, input prices, honey production, and pollination fees provides slim evidence against a null hypothesis that CCD has had no economic impact. This null hypothesis cannot be rejected for colony numbers, package and queen prices, and honey production. For crops other than almonds and early cherries and plums in California, we similarly find no evidence of an increase in pollination fees following the advent of CCD. For almonds, the fee increase attributable to CCD is nontrivial from the perspective of almond growers and beekeepers but translates into a small increase in prices paid by consumers.

---

43. For reasons discussed in app. VIII, our estimated impacts of CCD on other consumer prices are not substantively different from $0.00.

Extending our conclusions to other situations of adaptation to environmental change requires an appreciation of the importance of institutions and technology. For CCD, the key institutions are well-functioning markets for the services of managed pollinators and for beekeeping inputs such as queens. Acting within these markets, US beekeepers have adjusted quickly to a sudden and large environmental shock. Concern over the issue of pollinator health, however, is not limited to the United States. The extent and sophistication of markets that enable adaptation in other countries is unclear; this and previous analyses have all focused on the United States. In contexts other than pollination markets, our results suggest that there is reason for optimism about the ability to adapt to environmental change (e.g., climate change) in settings where there are well-functioning markets.

Finally, there is the separate issue of wild pollinators. (See, e.g., National Research Council 2007; Potts et al. 2010; Kerr et al. 2015.) Managed pollinators, mainly honey bees (but also greenhouse bumblebees, alfalfa leafcutter bees, and a handful of others) are strategically manipulated by beekeepers. But much pollination is done by unmanaged insects (wild bumblebees, flies, and wasps, for example), birds, and mammals. What sort of adaptation might we expect, for example, in response to decreasing biodiversity as native pollinators lose habitat to human development and agriculture? On the one hand, as wild pollinator populations decrease, the demand for managed pollination services by agricultural producers will increase. Where markets for managed pollinators exist, our findings suggest the potential for quick responses by beekeepers to limit negative impacts on the agricultural sector. Such adjustments serve to accommodate the interests of producers and consumers of food. They do not serve to protect wild pollinator species themselves or accommodate the interests of those who seek to preserve them.

Where markets do not exist, an increased demand for managed pollination services may provide the impetus for new markets to develop. The pace and scope of market development for managed and unmanaged pollinators will depend on transaction costs related to such factors as farm sizes and transportation infrastructure. Such transaction costs may be quite high for wild pollinators, which do not conveniently organize themselves into large-scale manageable communities like those of the European honey bee.

REFERENCES

Aizen, M. A., L. A. Garibaldi, S. A. Cunningham, and A. M. Klein. 2008. Long-term global trends in crop yield and production reveal no current pollination shortage but increasing pollinator dependency. *Current Biology* 18:1572–75. doi:10.1016/j.cub.2008.08.066.

Auffhammer, Maximilian, and Wolfram Schlenker. 2014. Empirical studies on agricultural impacts and adaptation. *Energy Economics* 46:555–61.

Barreca, Alan, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S. Shapiro. 2016. Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the twentieth century. *Journal of Political Economy* 124 (1): 105–59.

Bator, Francis M. 1958. The anatomy of market failure. *Quarterly Journal of Economics* 72:351–64.

Bromenshenk, J. J., et al. 2010. Iridovirus and microsporidian linked to honey bee colony decline. *PloS ONE* 5 (10). http://www.plosone.org/article/info:doi/10.1371/journal.pone.0013181 (accessed February 10, 2011).

Burgett, Michael. 1998. PNW colony mortality. *USDA National Honey Market News*, no. 9.

Burgett, Michael, Randal Rucker, and Walter Thurman. 2009. Honey bee colony mortality in the Pacific Northwest (USA). *American Bee Journal* 149 (6): 573–75.

Caron, Dewey, Michael Burgett, Randal Rucker, and Walter Thurman. 2010. Honey bee colony mortality in the Pacific Northwest: Winter 2008/2009. *American Bee Journal* 150 (March): 265–69.

Caron, Dewey, and Ramesh Sagili. 2011. Honey bee colony mortality in the Pacific Northwest: Winter 2009/2010. *American Bee Journal* 151 (1): 73–76.

Champetier, Antoine, Daniel A. Sumner, and James E. Wilen. 2015. The bioeconomics of honey bees and pollination. *Environmental and Resource Economics* 60 (1): 143–64.

Cheung, Steven N. S. 1973. The fable of the bees: An economic investigation. *Journal of Law and Economics* 16:11–33.

Columbia University, Mailman School of Public Health. 2007. Virus implicated in colony collapse disorder in bees. *ScienceDaily*. www.sciencedaily.com/releases/2007/09/070906140803.htm (accessed August 15, 2015).

Cornman, R. S., et al. 2012. Pathogen webs in collapsing honey bee colonies. *PLoS ONE* 7 (8): e43562. doi:10.1371/journal.pone.0043562.

Daberkow, Stan, Randal Rucker, Walter Thurman, and Michael Burgett. 2009. U.S. honey markets: Recent changes and historical perspective. *American Bee Journal* 149 (December): 1125–29.

Deschenes, Olivier, and Michael Greenstone. 2011. Climate change, mortality, and adaptation: Evidence from annual fluctuations in weather in the U.S. *American Economic Journal: Applied Economics* 3 (October): 152–85.

Ferrier, Peyton M., Randal R. Rucker, Walter N. Thurman, and Michael Burgett. 2018. Economic effects and responses to changes in honey bee health. Economic research report 246, US Department of Agriculture, Economic Research Service, Washington, DC.

Gallai, N., J.-M. Salles, J. Settele, and B. E. Vaissière. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics* 68:810–21.

Hsiang, Solomon, and Daiju Narita. 2012. Adaptation to cyclone risk: Evidence from the global cross-section. *Climate Change Economics* 3 (2): 1250011.

Kerr, Jeremy T., et al. 2015. Climate change impacts on bumblebees converge across continents. *Science* 349 (July 10): 177–80. http://www.sciencemag.org/content/349/6244/177.abstract.

Kleijn, David, et al. 2015. Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. *Nature Communications* 6 (June), article 7414. doi:10.1038/ncomms8414.

Kurukulasuriya, Pradeep, and Robert Mendelsohn. 2008. Crop switching as a strategy for adapting to climate change. *African Journal of Agricultural and Resource Economics* 1 (2): 105–25.

Laidlaw, Harry. 1992. Queen rearing. In *The hive and the honey bee*, ed. Joe Graham, chap. 8. Hamilton, IL: Dadant & Sons.

Maori, E., S. Lavi, R. Mozes-Koch, Y. Gantman, Y. Peretz, Orit Edelbaum, Edna Tanne, and Ilan Sela. 2007. Isolation and characterization of Israeli acute paralysis virus, a dicistrovirus affecting honey bees in Israel. *Journal of General Virology* 88:3428–38. http://vir.sgmjournals.org/cgi/reprint/88/12/3428.

Meade, J. E. 1952. External economies and diseconomies in a competitive situation. *Economic Journal* 5:54–67.

Morse, Roger A., and Nicholas W. Calderone. 2000. The value of honey bees as pollinators of U.S. crops in 2000. *Bee Culture* 128 (March): 15.

Morse, R. A., and K. Flottum. 1997. *Honey bee pests, predators, and diseases*. Medina, OH: A. I. Root.

Mussen, Eric. 2007. BSI: The case of the disappearing bees. Public lecture, University of California, Davis, October 17. Summary article (accessed January 27, 2015) and video of lecture available at http://169.237.77.3/news/dssericmussen.html.

———. 2005. Almonds and honey bees. *Apiculture Newsletter* (March/April). University of California, Davis, Department of Entomology and Nematology, University of California. http://entomology.ucdavis.edu/Faculty/Eric_C_Mussen/Apiculture_Newsletter (accessed Sept. 8, 2017).

———. 2006. Chaotic almond pollination. *Apiculture Newsletter* (January/February). University of California, Davis, Department of Entomology and Nematology, University of California. http://entomology.ucdavis.edu/Faculty/Eric_C_Mussen/Apiculture_Newsletter (accessed September 8, 2017).

Muth, Mary, Randal Rucker, Walter Thurman, and Ching-Ta Chuang. 2003. The fable of the bees revisited: Causes and consequences of the U.S. honey program. *Journal of Law and Economics* 46:479–516.

Muth, Mary K., and Walter N. Thurman. 1995. Why support the price of honey? *Choices* (2nd quarter): 13–17.

National Research Council. 2007. *Status of pollinators in North America*. Washington, DC: National Academies Press.

Nordhaus, Hannah. 2011. *The beekeeper's lament: How one man and half a billion honey bees help feed America*. New York: HarperCollins.

Oliver, Randy. 2016. Understanding colony buildup and decline, part 13d: The impact of parasites. *American Bee Journal* 156 (10): 1113–17.

Olmstead, Alan L., and Paul W. Rhode. 2011. Adapting North American wheat production to climatic challenges: 1839–2009. *Proceedings of the National Academy of Sciences* 108 (2): 480–85.

Pernal, S. F. 2008. CAPA statement on honey bee losses in Canada (spring 2008): Final revision. Canadian Association of Professional Apiculturists.

Pollan, Michael. 2007. Our decrepit food factories. *New York Times*, December 16.

Potts, Simon G., et al. 2010. Global pollinator declines: Trends, impacts and drivers. *Trends in Ecology and Evolution* 25 (6): 345–53.

Ratnieks, Francis L., and Norman L. Carreck. 2010. Clarity on honey bee collapse. *Science* 327 (8): 152–53.

Rucker, R., W. Thurman, and M. Burgett. 2012. Honey bee pollination markets and the internalization of reciprocal benefits. *American Journal of Agricultural Economics* 94:956–77.

Shimanuki, H. 1997. Synonymy in bee diseases. In *Honey bee pests, predators, and diseases*, ed. R. A. Morse and K. Flottum, 534–37. Medina, OH: A. I. Root.

Spleen, A. M., et al., for the Bee Informed Partnership. 2013. A national survey of managed honey bee 2011–12 winter colony losses in the United States: Results from the Bee Informed Partnership. *Journal of Apicultural Research* 52 (2): 44–53.

Steinhauer, Nathalie A., et al. 2014. A national survey of managed honey bee 2012–13 annual colony losses in the United States: Results from the Bee Informed Partnership. *Journal of Apicultural Research* 53 (1): 1–18.

Stipp, David. 2007. As bees go missing a $9.3B crisis lurks. *Fortune*, August 28, 2:55 p.m. EDT. http://money.cnn.com/magazines/fortune/fortune_archive/2007/09/03/100202647/index.htm (accessed June 8, 2008).

Underwood, Robyn M., and Dennis vanEngelsdorp. 2007. Colony collapse disorder: Have we seen this before? *Bee Culture* 135 (7): 12–15.

USDA NASS (US Department of Agriculture, National Agricultural Statistics Service). 2017. Honey. Annual report (March 23). US Department of Agriculture, Washington, DC.

vanEngelsdorp, D., et al. 2009. Colony collapse disorder: A descriptive study. *PLoS ONE* 4 (8): e6481. http://www.plosone.org/article/info:doi/10.1371/journal.pone.0006481 (accessed February 10, 2011).

vanEngelsdorp, D. et al. 2011. A survey of managed honey bee colony losses in the USA, fall 2009 to winter 2010. *Journal of Apicultural Research* 50 (1): 1–10.

vanEngelsdorp, D., et al. 2012. A national survey of managed honey bee 2010–11 colony losses in the USA: Results from the Bee Informed Partnership, *Journal of Apicultural Research* 51 (1): 115–24.

vanEngelsdorp, D., et al., for the Bee Informed Partnership. 2014. Preliminary results: Honey bee colony losses in the United States, 2013–2014. http://beeinformed.org/2014/05/colony-loss-2013-2014/ (accessed August 11, 2014).

vanEngelsdorp, D., J. Hayes, and J. Pettis. 2008. A survey of honey bee colony losses in the U.S., fall 2007 to spring 2008. *PLoS ONE* 3 (12): e4071. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2606032.

vanEngelsdorp D., J. Hayes, R. M. Underwood, and J. Pettis. 2010. A survey of honey bee colony losses in the United States, fall 2008 to spring 2009. *Journal of Apicultural Research* 49 (1): 7–14.

vanEngelsdorp, D., R. Underwood, D. Caron, and J. Hayes. 2007. An estimate of managed colony losses in the winter of 2006–07: A report commissioned by the Apiary Inspectors of America. *American Bee Journal* 147:599–603.

White House, Office of the Press Secretary. 2014. Presidential memorandum: Creating a federal strategy to promote the health of honey bees and other pollinators, June 20. https://www.whitehouse.gov/the-press-office/2014/06/20/presidential-memorandum-creating-federal-strategy-promote-health-honey-b (accessed January 16, 2015).