NC STATE UNIVERSITY

Center for Environmental and Resource Economic Policy
College of Agriculture and Life Sciences
https://cenrep.ncsu.edu

Colony Collapse and the Economic Consequences of Bee Disease:

Adaptation to Environmental Change

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

Center for Environmental and Resource Economic Policy
Working Paper Series: No. 16-018
January 2016

COLONY COLLAPSE AND THE ECONOMIC CONSEQUENCES OF BEE DISEASE:

ADAPTATION TO ENVIRONMENTAL CHANGE*

January 16, 2016

Randal R. Rucker
Montana State University

Walter N. Thurman
North Carolina State University

Michael Burgett
Oregon State University

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 the behavior of 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.

I. Introduction

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 productive 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. We use the natural experiment 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 input markets to adapt.

We contribute to an economic understanding of an important and high-profile interaction

---

[1] See, for example, Deschenes and Greenstone (2011) on the relationship between cold and heat and mortality, and Barreca *et al.* (2015) 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, and Portnykh (2015), who finds that Russians who live in northern and cold climates are better adapted to cold and suffer lower mortality from low temperatures.

between the environment and agriculture. More broadly, we contribute to the literature on agricultural adaptation to environmental change, of which climate change and its attendant biological changes 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 the results of an empirical examination of the impacts of CCD, based on primary and secondary data from disparate sources that might be expected to react to the advent of CCD. We analyze annual estimates of colony numbers at the aggregate (U.S.) and state levels to determine the extent to which managed honey bee populations have been affected by CCD. We similarly analyze aggregate and state-level honey production. We then examine the prices 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 use our results to estimate the impacts of CCD on beekeeper income and consumer prices.

While the tone of much discussion of pollinators borders on the bleak, our results give cause for considerable optimism, at least for the economically dominant honey bee. We find that CCD has had

[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 (2008 and 2011) for examples and Aufhammer and Schlenker (2014) for a recent review. A separate connection here is that some have attributed pollinator declines to climate change. See National Research Council (2007), Potts *et al*. (2010), Kerr *at al*. (2015).

measurable impacts in only one segment of the industry: pollination fees for almonds.[3] These impacts are small relative to our priors (and also presumably those of the literature we cite below). 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 impacts on honey production, input prices, or even numbers of bee colonies. We attribute these findings to a factor that is largely overlooked in the scientific and popular literature on pollinator decline: the ability of well-functioning markets to adapt quickly to mitigate the potential negative impacts of adverse shocks.[4]

II. Bees, Beekeeping, and Bee Disease

Bees are livestock managed for economic returns. And just as cattle disease preoccupies ranchers, diseases and other threats to healthy bee colonies have been important to beekeepers for at least a century.[5] 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 in detail below.

Examples of attention to pollinator health from the scientific community include the National

---

[3] We also find significant impacts of CCD on pollination fees for two other California crops—early cherries and plums—whose values are small relative to almonds.

[4] The limited economic literature on beekeeping can be cast broadly as a debate over the extent and efficacy of such markets. Notable economists such as J.E. Meade (1952) and Francis Bator (1958) used the example of honey bees and orchards to illustrate market failure associated with a two-way positive externality. In 1973, Steven Cheung published a study of Washington farmers and beekeepers in which he argued that contracting between beekeepers and orchard owners was sufficiently well developed that fees paid for pollinating and apiary rental reflected social marginal values. More recently, a small number of other studies have documented and analyzed the theoretical and empirical regularities of pollination markets and the activities of migratory commercial beekeepers who often transport their colonies thousands of miles annually. See Muth *et al.* (2003) Rucker, Thurman, and Burgett (2012), and Champetier, Sumner, and Wilen (2015).

[5] For example, the June 1928 issue of the *American Bee Journal* featured four articles on its cover. The first two of these were titled “Bee Diseases and Their Eradication” and “May Disease.”

Research Council (2007), Gallai *et al.* (2009), Aizen *et al.* (2008) 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 since that time.[6] 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."[7] A later governmental response to bee disease came in 2014 when President Obama established a multi-agency Pollinator Health Task Force, charged with developing a strategy for reversing pollinator losses.[8]

II.A. Commercial Beekeeping

The bee that is 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

---

[6] Pollinator decline in the literature refers to two different issues: declines in managed honey bees and declines in unmanaged, wild pollinators such as wild bumblebees and monarch butterflies, as well as a variety of other insects, birds, and mammals. The present paper addresses issues of managed bees. Concern over wild pollinators stems from their role in pollinating commercial crops, as well as their influence on wildlife habitat and food sources 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.

[7] 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 the most commonly cited estimate of the value of pollination services. It comes from a study by Morse and Calderone (2000), which updates an earlier estimate of $9 billion from Robinson *et al.* (1989). A recent study pegged the world-wide value of pollination at $217 billion (ScienceDaily, 2008). Muth and Thurman (1995) criticize the logic underlying these estimates and suggest that from a standard economics perspective, they are too high by at least an order of magnitude.

[8] The task force's membership is remarkably broad. It is co-chaired by the Secretary of Agriculture and the Administrator of the Environmental Protection Agency. Other members include representatives from the Departments of State, Defense, Interior, Housing and Urban Development, Transportation, Energy, and Education, as well as representatives from the Council on Environmental Quality, the Domestic Policy Council, the General Services Administration, the National Science Foundation, the National Security Council Staff, the Office of Management and Budget, the office of Science and Technology Policy, and "such executive departments, agencies and offices as the Co-chairs may designate" (White House 2014, p. 3). The President's budget request for 2016 includes $83 million "targeted to address pollinator health, including Colony Collapse Disorder" (White House 2015, p. 13).

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.[9] 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 just about anything that blooms.

A typical full strength colony of honey bees consists of a single queen and 25,000 to 40,000 worker bees. The queen usually lives for about two years and lays all the eggs in the hive. All the worker bees are sterile females, half-sisters with life spans of about six weeks. The colony also contains a small number of males, or drones, whose sole function is to mate with fledgling queens from other colonies.

In the United States, beekeeping is an industry with $600 to $700 million in annual sales in recent years, not large compared with other segments of agriculture.[10] For comparison, the annual value of the U.S. corn crop over the last five years has been between $50 and $80 billion. But bee pollination is a critical input in 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. Bee hives are moved

---

[9] Honey bees are but one of thousands of animal species that pollinate about 90 percent of flowering plants. The remaining 10 percent reproduce through abiotic pollination, most of which is accomplished by wind, with the remainder pollinated via water.

[10] In 2013, farm-gate revenues from honey were $317 million (USDA NASS Honey 2014). Assuming annual pollination revenues of $150 per colony for each of the 2.64 million bee colonies reported by the U.S. Department of Agriculture in 2013, U.S. beekeeper revenues from this source were $396 million.

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 nearly 20 episodes of major colony losses since the late 1860s. 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.[11] 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.[12] It is notable that, over time, commercial beekeepers have developed methods to combat each of these bee diseases. That said, such methods are costly, and bee diseases and parasites have devastated non-managed feral colonies.[13]

II.B 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 that two-thirds were practically

---

[11] Nordhaus (2011, Chapter 3) recounts the spread of the *Varroa* mite and ongoing efforts to control it.

[12] See Morse and Flottum (1997) for additional discussion of bee diseases.

[13] In their analysis of pollination fees, Rucker, Thurman, and Burgett (2012) find that pollination fees increased following the advent of the *Varroa* mite and that the estimated increase in fees was roughly equal to the costs of treating *Varroa*.

empty—no adult worker bees and no dead bees were in or near the hives. That winter other beekeepers reported similar experiences with 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 such pests 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 the beekeepers who responded to the surveys were 29.6 percent.[14] While these loss rates are notable, 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 percent prior to the appearance of CCD; 14 percent of colonies that were healthy going into winter did not survive to spring.[15] Thus, colony replacement at some level is a standard part of beekeeping.

Research into the causes of CCD began in the winter of 2006-2007. Regulators and bee

---

[14] The highest national mortality rate during this span was 36 percent in the winter of 2006/2007 , while the lowest was 22.5 percent in 2011/2012. See vanEngelsdorp *et al.* 2007, 2008, 2010, 2011, 2012, and 2014, Spleen *et al.* (2013) and Steinhauer *et al.* (2014) for discussions of the methodology used for each of the annual national surveys, which were initially conducted by the Apiary Inspectors of America in cooperation with the U.S. Department of Agriculture and since the 2010/2011 survey by the Bee Informed Partnership.

[15] Similarly, Pernal (2008) estimates that prior to CCD, normal winter mortality was 15 percent, and vanEnglesdorp *et al.* (2007) reported 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 severely elevated following the arrival of the two important species of honey bee mite parasites mentioned above (*Acarapis woodi* and *Varroa destructor*). Prior to that time good beekeepers were able to keep their average winter losses below 10 percent. After the arrival of the mites, for the ten year period from 1989 to 1998 the average annual colony loss for commercial beekeepers was found to be 22.6 percent (Burgett 1998).

scientists working from samples of CCD-afflicted bees concluded 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. Further analysis suggested that one in particular (Israeli Acute Paralysis Virus or IAPV) was strongly associated with CCD.[16] Some researchers speculated that the immune systems of the bees had collapsed, which led to the increase in parasite and pathogen load, while others blamed the increased disease directly as the cause of collapse.

Since these initial efforts, a number of investigations into the causes of CCD have been carried out. Early speculation was that cell phone signals may have caused honey bees to lose their bearings and fail to return to their hives.[17] 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 for pollination), toxins, and pesticides (in particular a class of insecticides, called neonicotinoids that have seen increased use in recent years).[18] It has also been pointed out that there have been several instances of "disappearing diseases" in past decades with symptoms similar to CCD and whose causes have never been determined.[19] The current dominant theme from the bee research community is that CCD is multi-

---

[16] See Columbia University (2007). It is notable that this relationship was not found in subsequent studies. See, for example, Maori *et al.* (2007), vanEnglesdorp *et al.* (2009), Bromenshenk *et al.* (2010) and Cornman *et al.* (2012).

[17] Scientists seem to have fairly quickly dismissed cell phones as a serious culprit in the disappearance of bees. As recently as May 2011, however, research was published supporting the notion that man-made electromagnetic fields (in particular, those generated by cell phones) cause bees to become disoriented and may be one factor contributing to the disappearance of bees around the world. See Favre (2011).

[18] 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 more recent overviews.

[19] See Shimanuki (1997), Underwood and vanEngelsdorp (2007), and Wilson and Menapace (1979).

factorial and, as such, cannot be explained by a single causal agent.[20]

II.C. Methods of Adapting

Three methods are commonly employed by beekeepers to maintain and rebuild hive numbers. Understanding these methods is critical to understanding how the beekeeping industry responds to bee disease. The three methods are discussed below, along with what is known about the relative frequency with which each is used.

The first method used to replace weak hives or hives lost over the winter 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 many years. The process requires the beekeeper to move a portion of the brood and adult bees, typically less than 50 percent, 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 for this purpose are often purchased from specialized commercial queen breeders, who produce hundreds of thousands of queens annually for sale.[21] Sometimes beekeepers do not provide the nucs with newly mated queens, but instead allow bees to produce their own queens from the eggs and/or young larvae that provisioned the unit. In this instance they are referred to as "egg" nucs. Most commercial beekeepers produce nucs from their own base of healthy colonies, although on occasion beekeepers will purchase nucs from other beekeepers.

The original hive used for the split has a near-uniform age distribution, from egg to mature

[20] A recent study by Cornman *et al.* (2012) conducted a retrospective analysis of colonies from across the United States, some with CCD and others without. They found that (1) pathogen identities differed across the United States, (2) there was a greater abundance and incidence of pathogens in CCD colonies, and (3) pathogen loads were highly covariant in CCD hives, but not in control hives. These results suggest that complex interactions of pathogens may be important components of bee disease in general, and CCD in particular.

[21] The average price of a fertilized queen bee (purchased 100 at a time) was about $18 in 2014. Queen prices are discussed in more detail below.

foraging worker bee. Thus, the original hive can continually replace its cadre of pollinators, and the hive is often strong enough to pollinate crops shortly after the split. The new hive will not be sufficiently strong to pollinate crops for about six weeks, 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, where winters last longer than in California, 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. A number of companies sell packaged bees for this purpose, typically the same companies that sell queens. In 2014, the average price of a three pound package of bees, which includes roughly 12,000 worker bees and a fertilized queen, was $70.[22] If an empty hive is stocked with a package of bees it might be productive immediately. Soon, however, there will be a drop-off in production 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. Even if the new queen begins laying fertilized eggs immediately upon her placement in the empty hive, 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.

The third method, which is used to maintain hive vigor (rather than increase the number of hives), is to replace the queen. A fertilized queen typically lays eggs for about two seasons. As the old queen becomes less productive, a beekeeper will replace her with a new fertilized queen. Assuming the new queen is accepted and begins laying fertilized eggs immediately, the hive will

[22] The average price is the price in 2014 for purchases of 100 three pound packages from the five sellers whose prices we analyze below.

remain strong, healthy, and productive. Insofar as the productivity of the old queen had diminished prior to replacement, the productivity of the new hive will increase with the addition of the new queen.[23]

The three replacement and enhancement processes are used to different extents by different beekeepers. Over three years of a post-CCD survey of Pacific Northwest beekeepers, 80 percent of replacement colonies were obtained through making increase (or creating splits/nucs). About 10 percent of the colonies replaced were nucs purchased from other beekeepers and 2 percent were mature colonies obtained from other beekeepers. Survey respondents reported using packaged bees for about 8 percent of their replacements. Because no systematic information is available regarding replacement methods used by beekeepers outside the PNW, it is not known whether splits are the predominant method used elsewhere in the United States.[24]

For any given beekeeper, the “making increase” or “splitting” approach has the potential to allow for complete replacement of dead colonies within six weeks for mortality rates of up to 50 percent. Replacing a dead colony using this approach is relatively inexpensive as the purchase of new hives or boxes for the hives is not necessary. The total amount of time required of an experienced commercial beekeeper to split a healthy colony is about 20 minutes, and newly fertilized queens can be purchased through the mail for $15-20 per queen. At the aggregate level, given that mortality rates are not constant across beekeepers, it may take longer than six weeks to completely replace lost colonies

[23] For experienced beekeepers, the expected acceptance rate of new queens is reported to be between 80 and 95 percent. Beekeepers often prefer to replace the old queen with a purchased new queen (rather than letting the colony replace the queen on its own) because it allows them to better control the genetic makeup of the colony.

[24] See Burgett at al. (2009), Caron et al. (2010), and Caron and Sagili (2011).

with the making-increase approach. If an unfortunate beekeeper suffers, say, a 70 percent mortality rate, it will likely take him double the time indicated above to return to his pre-winter colony numbers.[25]

III. Economic Indicators of CCD and its Economic Impact

We address the issue of how CCD has affected consumers, farmers, and beekeepers, focusing on four economic indicators. We first turn to bee populations and examine the impacts of CCD on colony numbers at both the aggregate U.S. level and at the state level. 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 from disease and beekeepers' responses. Accordingly, our second, third, and fourth economic indicators are output levels, and input and output prices. For output levels, we examine honey production. For input prices, we analyze prices for queen bees and packages of worker bees, inputs into producing hives of healthy bees. For output prices, we look at fees for pollination services, which should reflect any increase in the costs beekeepers face as a result of exposure to CCD.[26]

III.A. The Effects of CCD on Colony Numbers

The average rate of winter mortality for managed honey bees over 2007-2014 has been 29.6 percent.[27] Although honey bees have always suffered winter mortality from a number of causes, recent

---

[25] Industry participants and observers indicate that colonies are sometimes split 3:1 (and even 4:1 under some circumstances), meaning three healthy hives are created from one by dividing the healthy hive's population between the healthy hive and two dead ones to create three hives with a single split. We have no information on the extent to which this practice is employed, but it could conceivably allow a beekeeper to replace winter mortality losses of up to 67 percent in a single split.

[26] We also discuss the possible impacts of CCD on several other economic indicators in Appendix I.

[27] This number represents the simple average of the eight years of mortality rates estimated by vanEnglesdorp *et al.* (2007, 2008, 2010, 2011, 2012, and 2014), Spleen *et al.* (2013) and Steinhauer *et al.* (2014).

mortality rates are substantially higher than normal. A reasonable assessment derived from beekeeper surveys is that since the appearance of CCD, mortality rates have roughly doubled.[28] Mortality represents an outflow from the population of bees, while the splitting and re-queening of hives and the creation of new colonies represents an inflow. The net result is the change in colony numbers, which we analyze at the national and state levels.

There are two sources for estimates of honey bee colony numbers, both generated by the USDA. Estimates from these two sources are displayed in figure 1. The first results from responses to questions asked in the U.S. Census of Agriculture, which is conducted every five years. The numbers in this series are interesting for a variety of reasons, but are not of much use for our purposes because of the five year lag between them. It is noteworthy, however, that there was a substantial increase in the estimated number of managed colonies in the 2007 and 2012 censuses relative to the 2002 census.[29] This change is inconsistent with CCD causing reductions in colony numbers.

The second source of data, and the focus of our analysis, derives from annual surveys of beekeepers. Data from these surveys are generally available back to 1939 at both the national and the state levels. The national data are plotted in figure 1 and labeled "USDA Honey Report." As the name suggests, the primary purpose of USDA's annual survey is to obtain estimates of the number of colonies used to produce honey. Beekeepers participating in the survey are asked to list the states in which they had colonies during the year just completed, and then to indicate from how many colonies they harvested honey (and how much honey they harvested) in each of those states.[30]

[28] Burgett *et al.* (2009), Pernal (2008), and vanEngelsdorp *et al.* (2007) all report pre-CCD or "normal" mortality rates as being about 15 percent.

[29] According to this source, the number of colonies in the United States rose from 2.35 million to 3.28 million, an increase of 40 percent.

[30] This approach can yield inaccurate estimates of the number of managed honey bee colonies for two reasons. First, insofar as beekeepers have bee colonies that are not used for honey production (e.g., they are used solely to provide pollination services), then the numbers reported by the USDA will

The most obvious feature of the Honey Report estimates of colony numbers in figure 1 is their substantial decline since the mid-20th century.[31] The fact that the USDA did not conduct its annual survey from 1982-1985, combined with a change in 1986 in the data collection procedures used by the USDA, suggests that comparisons between the pre- and post-1985 periods should be made with caution.[32] Visual inspection of the figure does not reveal a notable decrease in U.S. colony numbers 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.

Figure 2 displays colony numbers from the Honey Report for the top five colony number states, ranked by the average number of colonies over the five year period 2009-2013. As with total U.S.

---

underestimate the actual number of managed colonies. Second, to the extent that individual beekeepers use hives to produce honey in more than one state, those hives will be counted more than once, and the numbers reported by the USDA will overestimate the actual number of managed colonies.

We are aware of no research that assesses the magnitude of these two sources of bias. Champetier *et al.* (2010) suggest, however, that the USDA annual colony estimates are misleading, particularly in recent years. Their argument is that recent increases in almond pollination fees have dramatically increased both pollination revenues per hive and the fraction of per hive revenues obtained from pollination relative to honey, thereby inducing beekeepers to focus more on pollination services. Insofar as there is an increase in the number of hives that are used for pollination only, the USDA numbers will overstate any possible recent reductions in colony numbers. Note that in the Census of Agriculture survey, beekeepers are asked simply how many colonies they owned on December 31 of the year prior to the Census, thereby avoiding the double-counting problem inherent in the annual USDA surveys. Pollination revenues are not, however, considered to be revenues from agricultural products in the North American Industry Classification System, so colonies from which only pollination revenues are generated are not counted in the Census.

Assuming the argument of Champetier *et al.* is correct, what are its implications for our analysis below? An increase in the number of hives that are not being used to produce honey will cause the recent USDA (and Census) estimates of colony numbers to be biased downward. This phenomenon will make colony numbers appear to fall in recent years more than they have actually fallen, which could overstate losses due to recent events, including CCD.

[31] 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.

[32] Estimates prior to 1982 included colony counts from all beekeepers, whereas estimates for years after 1985 included colony counts only from those beekeepers that maintained at least five colonies. Muth *et al.* (2003, pp. 497-498) determine the one-time reduction in estimated colony numbers from this change in survey methodology to be 863,000 colonies with a standard error of 195,000 colonies.

colony 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 percent greater in 2013 than in 2006, and there is no obvious acceleration in the decline rate for California.

We turn now to a more formal statistical analysis of the possible impacts of CCD. We limit this portion of our analysis to the period since 1986, which follows the four year period 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.[33] Table 1 displays results from our analysis of the impacts of CCD on national colony numbers. In the top section of the table, we report the means for three different pre- and post-CCD periods, as well as the differences between those means. The three different time periods include data from three different pre-CCD time spans of successively narrowing scope:1986-2006, 1990-2006, and 2000-2006. The longer pre-CCD period (1986-2006) is relevant to the extent that conditions are constant over time. The shorter intervals provide robustness checks by focusing the measurement of pre-CCD colony numbers on periods least susceptible to distortions from ancillary trends.

For the longest time period, 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 are declining over time, this difference is less for the 1990-2006 period. For the shortest period (2000-2013) the difference is actually positive (albeit small).

In model 1 of table 1, we report estimated coefficients from three OLS regressions (corresponding to the three pre-CCD time periods) with colony numbers as the dependent variable and

[33] Figure 1 displays the aggregate numbers reported in the USDA's annual surveys. In that series, data are not available for every year for some states, typically because the number of colonies is small. The USDA tables indicate that the data for these states are "not published separately to avoid disclosing data for individual operations" (USDA, Honey, 2014, p. 2).

a zero-one CCD variable (which we assign a value of one for 2007-2013 and zero for the pre-CCD years) as the sole right hand side variable.

$$\text{Table1, Model 1: Colonies}_t = \alpha + \varphi \text{CCD}_t + \varepsilon_t, \quad t = 1, \ldots, t_o, t_0+1, \ldots, T.$$

$$\text{CCD}_t = 1 \text{ for } t > t_o \ (t_o \text{ corresponds to } 2006).$$

As can be seen from the table, the estimated coefficients on the CCD variable in these regressions are the differences in the average colony numbers between the respective pre-CCD years and the CCD years. The estimated coefficients reported in the second row of results in model 1 of table 1 are GLS estimates that model the regression disturbances as AR1 processes.[34] The estimated 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 estimated coefficient on the CCD variable is actually positive (but not significantly so).

It is clear from figure 1 that there was a pre-existing downward trend in U.S. colony numbers prior to 2007, a feature of the data not accounted for by the model 1 regressions. Figure 1 displays the pre-existing trend estimated using data from 1986 - 2006.[35] The figure extends the line beyond 2006 to indicate what colony numbers would have been had the pre-existing trend persisted. The CCD-induced increased mortality rate after 2006, insofar as it reduced colony numbers, would manifest itself as a more negatively sloped trend line during this period. The regressions in model 2 of table 1 account for this temporal pattern by including a calibrated linear trend variable.

$$\text{Table 1, Model 2: Colonies}_t = \alpha + \beta t + \delta \text{CCD}_t(t - t_o) + \varepsilon_t.$$

This approach constrains the pre- and post-CCD trend lines to intersect in 2006. We test the null

[34] To limit clutter in this table and others below, we do not report the estimated coefficients for the AR(1) term. In general, these coefficients are positive and statistically significant.

[35] The pre-CCD trend line in the figure has a statistically significant slope coefficient that suggests colony numbers fell by about 46,000 per year over the period 1986-2000.

hypothesis that the trend difference between the pre- and post-CCD periods is zero against the alternative that the difference is negative and significant.[36]

The Model 2 results are reported with both OLS and GLS estimators. For the longer 1986-2013 period, for example, the OLS results indicate that there is a statistically significant downward trend of 43,000 colonies per year for the years 1986-2006. For the post-CCD period (2007-2013), instead of a more negative trend, there is a statistically significant *upward* trend in colony numbers of 41,000 colonies annually. Similar results are obtained for the two shorter pre-CCD time periods and also when GLS estimators are employed. In all instances, we find (1) a statistically significant downward trend in colony numbers in the pre-CCD years, (2) a statistically significant upward trend in the post-CCD years, and (3) a significant difference between the estimated trend coefficients in the two sub-periods—with the sign and significance of the difference being strongly inconsistent with CCD causing accelerated reductions in colony numbers.

The regression specification just discussed is sparse. Arguably the most important factor affecting colony numbers in recent years is the increasing demand for pollination services resulting from increased almond acreage in California. In model 3 of table 1, we report estimates from specifications that include both linear trend variables (with slopes allowed to differ before and after the appearance of CCD) and annual almond acreage.[37] As can be seen, although the estimated coefficients

[36] The fact that the extension of the pre-CCD trend line in figure 1 lies below actual colony numbers in all post-CCD years suggests that the null will not be rejected in this test for the national numbers. The results of analogous tests at the state level, which are discussed below, are not all as apparent *a priori*.

[37] To limit clutter in table 1, we do not report the estimated coefficients for the almond acres variable. Results for these coefficients are available on request. Our prediction is that an increase in almond acreage increases the demand for high-paying pollination services, which in turn induces beekeepers to increase their colony numbers. Despite the fact that almond acres and our trend variable are very highly correlated (a correlation coefficient of 0.93 for the period 1986-2013), the estimated coefficients on almond acres are generally positive and significant. The exception to this (as might be expected) is that the estimated almond acreage coefficients are not precisely estimated in regressions with the shortest pre-CCD period.

on the trend variables are affected by the inclusion of the almond acres variable, the previousl finding is not altered—there is no evidence that CCD caused a dramatic acceleration in the rate of colony number decline.[38]

The consistent result from table 1 is that aggregate U.S. data provide no indication that CCD has resulted in a sharp acceleration in the rate at which colony numbers are declining. To investigate the possibility that the aggregate numbers mask CCD impacts in individual states, we examine the plots (see figure 2) of colony numbers in the five states with the most colonies in recent years, and then estimate regression specifications analogous to those in table 1 for all 39 individual states for which colony numbers are reported in recent years.[39] Visual examination of figure 2 suggests it is unlikely that the aggregate U.S. data are masking important negative state level CCD impacts, at least for the states with the most colonies. Table 2 reports results from the state level statistical tests. The estimator employed in the regressions summarized in this table is GLS with an AR(1) model for the disturbance and standard errors that are corrected for contemporaneous correlations across states. Estimated regression coefficients on the right hand side variables are allowed to differ by state, and the

[38] Apart from providing no strong evidence that CCD has caused an acceleration in the decline in colony numbers, how informative are our estimates of the change in trends since CCD appeared? A 95% confidence interval for the pre- and post-CCD difference in trends constructed from, e.g., the first set of OLS estimates in model 2 is (55, 113). Even the lower end of this interval suggests a decrease in the rate of decline in colony numbers (in fact, the trend would change from -43,000 per year to +12,000 per year). Similar results hold for all of the other five specifications estimated in model 2 and also for the final set of results for model 3. The results in table 1 that are the closest to being consistent with a negative view of the impacts of CCD are the OLS estimates for the middle set of results in model 3. The 95% confidence interval for the difference in trends there is (-39, 69). At the bottom end of this interval, the decline in colony numbers would increase from -79,000 colonies per year (during the pre-CCD period) to -108,000 (= -79,000 - 39,000). This change represents about 1.6 percent of the current stock of bees. Even in this set of results, however, there is an equal likelihood that the annual rate of decline in colony numbers would fall from 79,000 to 10,000 (= -79,000 + 69,000).

[39] In 2013, colony numbers in the five states in figure 2 comprised 55 percent of total U.S. colony numbers. The eleven states we drop from this portion of our analysis are Alaska, Connecticut, Delaware, Maryland, Massachusetts, Nevada, New Hampshire, New Mexico, Oklahoma, Rhode Island, and South Carolina.

AR(1) coefficient is constant across states.

Under model 1, we summarize results from a panel regression in which each of the 39 states in our data has a different intercept and CCD coefficient.

$$\text{Table 2, Model 1: } \text{Colonies}_{it} = \alpha_i + \varphi_i \text{CCD}_t + \varepsilon_{it}, \quad i = 1, \ldots, 39; \; t = 1, \ldots, T.$$

From the first line under Model we see 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- 2013). 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 -123,000. The estimated CCD effect in the corresponding specification in model 1 of table 1 is -256,000, which is well within two standard errors of -123,000, suggesting 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 in which the colony count rises. The number of states with significant differences (either positive or negative), however, is not greatly altered. The sum of the estimated state-level CCD effects also falls.

As with the analysis of aggregate U.S. colony numbers, these simple regression specifications do not account for pre-existing trends. Model 2 of table 2 presents summary information from panel regressions with linear trends that are allowed to be different for each state before and after the onset of CCD.

$$\text{Table 2, Model 2: } \text{Colonies}_{it} = \alpha_i + \beta_i t + \delta_i \text{CCD}_t (t - t_o) + \varepsilon_{it}.$$

Across the three pre-CCD periods, we see (1) more states had negative and significant trends in colony numbers than had positive and significant trends in the pre-CCD periods; (2) that relationship is reversed in the post-CCD period–that is, more states have positive and significant trends than have negative and significant trends; and (3) the sums across states of both pre- and post-CCD trends in table 2 are very close to the corresponding values from the aggregate GLS regression results in model 2 of table 1.

Of primary interest for our analysis, the final two columns of the model 2 results indicate that, for the two longest pre-CCD periods there were only two states in which the trends in colony numbers were significantly lower after the appearance of CCD. In contrast, for those two pre-CCD periods, there were 20 and 19 states in which the trends in colony numbers were significantly *greater* in the post-CCD period. For the shortest pre-CCD period, there were 11 such states. Another perspective on the impacts of CCD is provided by comparing the sum (across states) of the trend coefficients for the pre- and post-CCD periods. For all three of the regressions summarized in model 2, the sum of the post-CCD trend coefficients is *greater than* the sum of the pre-CCD trend coefficients. Moreover, the differences between the sums for the pre- and post-CCD periods are considerably greater than two standard errors of either the pre- or post-CCD sums.

Model 3 of table 2 shows results from regression specifications that include as covariates both time trends and almond acres. As can be seen, for all three pre-CCD periods, the sum (across states) of the post-CCD trends is again greater than the sum of the pre-CCD trends. Referring to the final two columns in model 3, although there is an increase in the number of states in which the estimated trends in colony numbers are significantly less in the post-CCD period, there still is a considerable number of states where the opposite relationship holds.

To summarize, empirical results suggest that although colony numbers have declined over time, the rate of decline has not dramatically increased, or increased at all, since the onset of CCD, either at the aggregate level or in individual states. Given that an average of almost one-third of the honey bee colonies in the United States have died in each of the eight winters since the onset of CCD, how can this be? Our favored interpretation 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 III above. Since the onset of CCD, beekeepers have had to replace more hives to maintain their colony numbers, and the results in this section suggest they have done that.

III.B. The Effects of CCD on Honey Production

Colonies, the subject of the previous section, are inputs in the production of honey and pollination services. Here we examine data for one of the primary outputs of the beekeeping industry—honey—to look for evidence of CCD.

The USDA's annual survey of beekeepers reports not only estimates of colony numbers, but also estimates of honey production. Each year, the survey asks beekeepers 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.[40] As with colony numbers, data from the surveys on honey production are generally available back to 1939 at both the national and individual state levels. The national data are plotted in figure 3.

The plot of the Honey Report (survey) estimates of honey production in figure 3 indicates a sporadic upward trend in honey production until (roughly) the mid-1960s, after which honey production has trended downward with substantial year-to-year variation.[41] The fact (mentioned above) that the USDA did not conduct its annual survey from 1982-1985, combined with a change in 1986 in the data collection procedures used by the USDA, suggests (as it did with colony numbers) that

[40] Possible biases in colony numbers were discussed above (see footnote #30 supra). We see no comparable sources of potential bias related to the questions that ask beekeepers about their honey production.

[41] 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 U.S. 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 past and recent conditions in U.S. honey markets.

comparisons between the pre- and post-1985 periods should be made with caution. In the figure, a vertical line is drawn between 2006 and 2007 to indicate when CCD might have first influenced honey production. Visual inspection of the figure does not reveal a dramatic decrease in U.S. honey production in the years since 2007. The dotted line indicates the estimated trend line based on production over the 1980-2006 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.

Figure 4 displays honey production from the Honey Report for the top five honey producing states, ranked by average honey production over the five year period 2009-2013. As with total U.S. honey production, a visual examination of the plots in this figure reveals no dramatic reductions in honey production after 2006.

Our statistical analysis of the possible impacts of CCD are reported in tables 3 and 4, in specifications analogous to those for colony numbers. The top portion of table 3 supports the visual impression from figure 3 that average honey production is lower in the post-CCD years than in the pre-CCD years. Both the OLS and GLS specifications in model 1 indicate that these differences are statistically significant. Model 2 accounts for the pre-existing trend evident in figure 1 by employing the same "kinked" trend line specification as we use for the analysis of colony numbers. As evidenced by the t-ratios for the difference in trend lines, there is no evidence of an increase in the rate of decline in honey production following the appearance of CCD.[42]

[42] Apart from providing no strong evidence for CCD, how informative are the estimated changes in trends since CCD appeared? The results in models 2 and 3 that provide the largest negative impact of CCD on the trend in honey production are those with the CCD period from 1986 - 2006. Noting that the differences in trend for these results are not significantly different from zero, a 95 percent confidence interval for the pre- and post-CCD difference in trend from the OLS estimates is [-6.75, 1.75]. The lower end of the interval represents 3.8 percent of 2014 honey production. A strong prior that CCD must be causing reductions in honey production, then, allows at most (at the 95 percent level of confidence) an effect of -3.8 percent.

Pollination of California almonds in the early spring has become increasingly important in recent years. Marketable honey is not produced when a beekeeper provides this service, and the travel associated with pollinating in California is stressful to bees. It is possible, therefore, that honey production has fallen with the growth in almond production, and that in our efforts to measure the impacts of CCD, it may be important to account for this fact. In model 3, where we add almond acres as a control variable, the trends in the post-CCD period are actually more positive/less negative than in the pre-CCD period in all six specifications, but not significantly so.

In table 4, we report the results from state-level panel regressions with the same structure as the state panels for colony numbers in table 2. The estimator is GLS with an AR(1) model for the disturbance and with standard errors that are corrected for contemporaneous correlations across states. Estimated regression coefficients on the right hand side variables are allowed to differ by state, but the AR(1) coefficient is constant across states. In model 1, we summarize results from a panel regression in which each of the 39 states in our data has a different intercept and CCD coefficient. From the first line, 35 of the 39 states experienced declines in average honey production between the longest pre-CCD period (1986-2006) and the post-CCD period (2007- 2013). Twenty-eight of those declines are statistically significant. Four states saw increased honey production between the two periods, with two of those increases being statistically significant. The sum of the 39 state-level effects is about -43 million pounds. The estimated CCD effect in the corresponding GLS specification in model 1 of table 3 has a similar value of -38 million. From the other two rows in model 1 of table 4, it can be seen that as the pre-CCD period is shortened, the number of states in which average honey production was lower in the post-CCD years stays about the same. The number of states with significant negative differences does fall (from 28 to 21) for the shortest pre-CCD period. The sum of the estimated state-level CCD effects also becomes substantially less negative for that period.

To account for possible pre-existing trends, model 2 in table 4 presents summary information from panel regressions with linear trends allowed to be different for each state before and after the onset of CCD. Across the three pre-CCD periods and the single post-CCD period, (1) more states had negative and significant trends in honey production than had positive and significant trends in both the pre-and post-CCD periods, and (2) the sums across states of both pre- and post-CCD trends in table 4 are very close to the corresponding values from the aggregate regressions in table 3.

Of primary interest for our analysis, the final two columns of the model 2 results indicate that, in comparison with the three pre-CCD periods of varying duration, trends in production post-CCD are significantly more positive than they are pre-CCD in a number of states. The number of states for which this is true is always at least as great as the number of states in which post-CCD trends are significantly more negative. This is evidence, on net, of increased not decreased honey production since CCD.

Another perspective on the honey impacts of CCD is provided by comparing the sum (across states) of the trend coefficients for the pre- and post-CCD periods. For the results with the longest pre-CCD period, the sum across states is more negative for the post-CCD period, but the difference is only about one standard error of the sum. With the shorter 1990-2006 pre-CCD period, the sums are essentially the same, and for the shortest pre-CCD period, the sum is significantly less negative in the post-CCD period than in the pre-CCD period. As one draws a tighter focus on the pre- and post-CCD comparison, the measured effect of CCD is positive, not negative.

Model 3 of table 4 shows results from regression specifications that include both time trends and almond acres. As can be seen, for all three pre-CCD periods, the sum (across states) of the post-CCD trends is greater than the sum of the pre-CCD trends. Referring to the last two columns in model 3, we see again that there tend to be at least as many states where there are significant increases in estimated trends in honey production as there are states with significant decreases in these trends.

The analysis presented in this section suggests that although U.S. honey production has declined over time, the rate of decline has at least not dramatically increased since the onset of CCD, either at the aggregate level or in individual states.

III.C. The Effects of CCD on Queen Bee and Package Prices

Concluding that bee populations and honey production have not changed dramatically, if at all, does not imply that there have not been other market responses to CCD. Our third empirical exercise 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.[43]

The mechanism behind a potential impact of CCD on package and queen prices is straightforward. Splitting colonies requires newly fertilized queens, which often are purchased from specialized queen breeders. Alternatively, packages of worker bees, which also come with newly 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 is expected to 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 mated queen in less than a month. Moreover, any of the fertilized eggs laid by a queen has the potential to become a queen if it is fed sufficient amounts of royal jelly. While the very shortest-run supply of queens is fixed, queen producers can substantially

[43] In our survey of Pacific Northwest beekeepers, we found that most replacement colonies come from splits and that considerably fewer colonies are replaced by purchases of packages.

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 packaged and queen bees from advertisements in the monthly *American Bee Journal* (*ABJ*), which has been published continuously since 1861.[44] A description of the procedure we use to construct this data series follows.

Because spring is a typical time of year when beekeepers make increase (which often employs purchased queens) or to replenish depleted hives with packaged bees, we collected information on advertisements for queen and package prices in March issues of the *ABJ*. We constructed a list of all sellers who advertised in March issues by selecting roughly one year per decade going back to the 1960s. From this list, we identified eight sellers who advertised in the *ABJ* for an extended period of time.[45] We then examined each March issue from 1964 to 2010 and recorded the package and queen bee prices for each of the eight sellers who advertised in the issue.

This procedure was complicated by a number of considerations, one being that sellers often offer quantity discounts.[46] To account for the discounts we constructed a data set that includes—for

[44] The *ABJ* describes itself on its masthead as follows: "The American Bee Journal was established in 1861 by Samuel Wagner and has been published continuously since that time, except for a brief period during the Civil War. The Journal has the honor of being the oldest English language beekeeping publication in the world. ... Readership is concentrated among hobby and commercial beekeepers, bee supply dealers, queen breeders, package-bee shippers, honey packers, and entomologists."

[45] The sellers we identified were Drew Apiaries, Hardeman Apiaries, Walter T. Kelley Co., Russell Apiaries, Wilbanks Apiaries, York Bee Co. (now H&R Apiaries), Spell Bee Co. (now Gardner Apiaries), and Jerry Schumans Apiaries.

[46] The quantity breaks vary across sellers. For example, one seller in the March 2007 *ABJ* had no quantity discounts, another had only two price categories—one for quantities of 1-9, and another for quantities of 10 or more. Another seller had four price categories, and price breaks are at different quantities for different sellers.

each seller and year—the prices the seller charged for queens and packages in quantities of 1, 5, 25, 50 and 100.

The focus of our inquiry is to assess the impacts of CCD on package and queen prices. Three of the eight sellers whose price data we collected stopped advertising their prices in the *ABJ* in recent years. For two of the three sellers, price data were obtained for only one year since the appearance of CCD. For the third seller we found only two years of price data. Accordingly, we drop these sellers and conduct the analysis presented below using data from the remaining five sellers.[47]

Figure 5 displays the queen and package price averages across the remaining five sellers from 1980 to 2013. The two price series shown are for purchases of 100 (or more) queens and packages of bees.[48] 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 percent of the mean prices for the respective series.[49] 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 two years after the onset of CCD. Both

---

[47] Where possible, we also obtained pricing data from package and queen producers' websites if prices were not advertised in the *ABJ*. The sellers we drop are Walter T. Kelley Co., Russell Apiaries, and Jerry Schumans Apiaries. For the five sellers included in our empirical analysis, with one exception we have prices for all of them for both packages and queens for all seven years from 2007 through 2013. The exception is that for one of the sellers, we do not have package prices for 2011.

[48] Plots of the price series for the other quantities on which we collected prices (1, 5, 25, and 50) look substantively the same as the plot for quantity = 100, differing by fixed-over-time differentials. The simple pairwise correlations between the average prices for different quantities of packages all exceed 0.99. For queens the corresponding pairwise correlations all exceed 0.96.

[49] It is noteworthy that the trends in both of the package and queen price series are not uniform throughout the data. For example, in the package price series, there is little indication of an upward trend from 1980 - 1995 or from 1999 - 2013. Most of the upward movement in package prices took place between 1995 and 1999. Because of this feature of the package and queen price series, in what follows we analyze models of level shifts instead of trend shifts.

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

Figure 6 displays the prices of the five individual sellers in our analysis. As can be seen, for the most part, prices of the individual sellers tend to move together. Simple pairwise correlation coefficients for the queen prices of the five sellers 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 prices of each of the sellers looks quite similar, with each of them being slightly higher in 2013 than in 2006. The plots of the queen prices look similar, except that the overall increase in prices since 2006 appears to be somewhat greater than for the package prices relative to their historic levels. 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.

We now conduct a more formal statistical analysis of the possible impacts of CCD on queen and package prices. Results for queen prices are presented in table 5. The top section of the table shows the differences in average queen prices between the three pre-CCD periods of varying scope and the post-CCD period. The difference in these averages is seen to be a $2.83 increase for the longest pre-CCD period comparison, with the difference falling as the scope of the pre-CCD period is shortened. The middle section of table 5 reports two regression model results that we use to estimate the impacts of CCD on average (for the five sellers in our sample) queen prices. Whereas the biology of honey bee populations suggested that the impacts of CCD might be manifested by a kink in the trend rate of change in colony numbers and honey production, the impact of CCD on package and queen markets is better thought of as inducing an increase in demand for these inputs. Accordingly, we use a standard regression discontinuity framework for our analysis of package and queen prices where we test for a discontinuity with the appearance of CCD. The first specification (model 1) is a simple regression of the average annual queen price on an intercept and the 0-1 CCD dummy. As can be seen, the estimated OLS coefficients on the CCD dummy variable in these regressions are equal to the differences in means from the top portion of the table. All three of the estimated coefficients on the CCD dummy are significantly greater than zero. The second specification in model 1 uses a GLS estimator to model the regression disturbance as an AR(1) process. When this property of the disturbance is accounted for, both the values of the CCD coefficients and their significance are considerably smaller.

As with colony numbers and honey production, there is a pre-existing (upward) trend in queen prices, and the specifications in model 1 do not control for its impacts. We account for this trend, as well as for the increase in almond acres over time, in model 2.[50]

$$\text{Table 5, Model 2: Queen price}_{it} = \alpha_i + \varphi \, CCD_t + \beta t + \theta \, \text{Almond acres}_t + \varepsilon_{it}, \quad i = 1, \ldots, 5;\; t = 1, \ldots, T.$$

Neither the OLS nor GLS results indicate a significant CCD-induced increase in queen prices and the shortest comparison period, 2000-2013, reveals significant declines in prices.[51]

The bottom section of table 5 reports the analysis of the panel of annual queen prices charged by the five sellers in our analysis are presented. The results are very similar to those for the analysis of average queen prices in the middle section of the table. 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

[50] An increase in almond acres increases the demand for pollination services, which in turn results in an increase in the demand for queens and packages.

[51] To limit clutter in table 6, we do not display the results of a specification with only a linear time trend and the CCD dummy variable. As with the results in model 2 in the middle section of the table, the results from that specification provide no support for a dramatic increase in queen prices following 2006.

specification. In model 2, when a linear trend and almond acres are included as controls, the CCD effect is no longer positive and significant.

In table 6, we analyze package bee prices in models directly analogous to the analysis of queen prices in table 5. The results are substantively the same as for queen prices. The top portion of the table indicates that the five-seller average package prices in the post-CCD period were higher than in the pre-CCD period. In the middle section of the table, the OLS specification in model 1 indicates that for two of the three pre-CCD period comparisons the difference in prices was significant, but that in the shortest pre-CCD period, the difference was not significant. In the GLS specification of model 1, the CCD effect is not significant in any of the three periods. When we control for a linear time trend and almond acres in model 2, the estimated coefficients on the CCD variable are all negative.

The bottom section of table 6 displays disaggregates to individual sellers and displays a panel analysis of package prices from the five sellers, with fixed seller effects and CCD coefficients shared across sellers. The results are similar to those in the middle section of the table—in model 1, whereas the OLS results indicate a significant increase in package prices for two of the three pre-CCD periods, both the estimated coefficients and the t-ratios are smaller in the GLS specification. In model 2, where we control for linear effects of time and almond acres, the estimated coefficients on the CCD variable are (again) all negative.

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 disastrous impacts on beekeeping, then one would expect to observe not only decreases in colony numbers (which was not found), but also changes in the prices of inputs used to adapt. Numerous studies have documented that CCD has resulted in substantially increased winter mortality.[52] Such increases result in increases in the demand for packaged bees and queens as beekeepers replace greater numbers of lost colonies resulting from CCD. The preceding statistical analysis suggests there is no evidence that this increased demand has resulted in increased queen or packaged bee prices. We infer from these results that the supply (even in the short run) of packaged bees and queens is sufficiently elastic that any increases in demand of the magnitude associated with CCD have not resulted in measurable increases in prices.

III.D. The Effects of CCD on Pollination Fees

Beekeepers supply the services of bees for two commercial purposes: to provide pollination services for farmers and to produce honey. Bee disease, such as CCD, that increases the costs of beekeeping is expected to increase the price of the industry's outputs—honey and pollination services. Honey is traded internationally and domestic price effects seem less likely than do price effects on non-traded pollination services.[53] In this section, we examine the price of pollination services for evidence of CCD impacts.[54]

[52] See, for example, Burgett *et al.* (2009), Caron *et al.* (2010), Pernal (2008), and vanEnglesdorp *et al.* (2007, 2008, 2010).

[53] In fact, plots of honey prices (available on request) do not support the hypothesis that CCD has caused them to increase.

[54] The jointness of supply of pollination services and honey has implications for the equilibrium pricing of pollination services. A formal model is developed and econometrically analyzed in Rucker, Thurman, and Burgett (2012). A summary of the implications for empirical analysis of pollination fees is as follows.

Pollination fees for different crops will vary based on the volume and value of nectar provided by the crop for the purposes of making honey–better honey crops will pay smaller pollination fees. Pollination fees for individual crops will vary over time with the price of honey, but the sign of the effect is ambiguous. Pollination fees should vary positively with such identifiable factors that affect the costs of beekeeping as fuel prices for migratory beekeepers and costs of disease control. Finally, aggregate pollinated acreage varies over the crop year, and to the extent that larger acreage represents increased seasonal demand for pollination, fees should *ceteris paribus* be positively related to pollinated acres, the largest employer of bees being almonds in late February and early March.

Our empirical strategy is to analyze panel data on fees by crop for two distinct groups of beekeepers responding to two separate but 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 since then Oregon and Washington (PNW) beekeepers, have been asked to report the fees they received for pollinating crops. This survey has often garnered responses from beekeepers responsible for 60 to 70 percent 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 7, 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 pollination 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 7 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 $59 to $89 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 Colony Collapse Disorder, and CCD may be 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 7 shows, almond fees rose earlier: in 2005 and 2006. In keeping with the sprit of our three previous empirical exercises, we estimate parsimoniously specified regression equations for pollination fees.[55] At the end of this section, we discuss further the timing issue for almond fee increases.

Data on California pollination fees are displayed in figure 8. Although the California survey has a shorter history than the PNW survey, and covers a somewhat different set of crops, there is substantial overlap in period and crop. An important characteristic of the California crops is that, whereas the only crop pollinated by PNW beekeepers in February is almonds, California beekeepers provide services for two other "early" crops—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 that of almond fees. Figure 8 confirms this expectation. There, we plot fees for almonds, plums, early cherries, and average fees for seven crops that are pollinated after almond pollination is completed. As was seen in the plot of PNW fees, California almond fees increase dramatically in 2005 and 2006 and stayed high afterwards. 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 demonstrate substantial variability after 2007, though the average of the 2007-2013 fees is significantly higher than the average of fees in the years preceding 2005. For the crops that are pollinated after almonds, the plot of average fees displays no dramatic increase after 2006.

Statistical analysis of the PNW and California pollination fees are presented in tables 7 and 8. In our treatment of colonies, honey, and queen and package prices, we examined results from three different pre-CCD periods. For pollination fees, the sample period is more limited (in particular, for California, data are not available until 1996) and our approach is slightly different. To analyze PNW fees, we split the data into two, rather than three, periods: a longer 1987-2013 sample and a shorter

[55] For a more completely specified reduced form regression analysis of the determinants of pollination fees, see Rucker et al. (2012).

2000-2013 sample. For California, we do not split the pre-CCD period, instead focusing our analysis on the full 1996-2013 time span for which we have data.

The PNW and California panels are nearly balanced, but contain holes due to survey non-response. Compared to a total potential number of observations of 11 crops x 27 years = 297, our data from the PNW surveys comprise 276 usable observations. For California, we have 173 usable observations, from a potential maximum of 10 crops x 18 years = 180.

Table 7 reports the estimated impacts of CCD on PNW pollination fees. The top panel indicates that for both time periods, average almond fees received by PNW beekeepers after 2006 are substantially higher than the pre-2007 average. For the other 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 7 displays the results from two regression models. Model 1 is a GLS regression that includes crop fixed effects and two binary CCD variables (one for almond fees and one for fees for all other PNW crops).[56]

$$\text{Table 7, Model 1: } Fee_{it} = \alpha_i + \varphi_{Almonds} d_i^A CCD_t + \varphi_{NA}(1 - d_i^A) CCD_t + \varepsilon_{it}, \quad i = 1, \ldots, 11;\ t = 1, \ldots, T$$

$$d_i^A = 1 \text{ for almond observations.}$$

The estimated CCD impact for almond fees is roughly \$70 and is highly significant for the 1987-2013 period, but is only marginally significant for the shorter pre-CCD period. Consistent with the impression gained from figure 7, 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 also includes almond acres, as well as a linear time trend to account for possible pre-existing trends. The CCD effect on almond fees is about \$63 and statistically different from zero

[56] To reduce clutter in tables 7 and 8, we do not present OLS results. They are available on request.

for both sample periods. The estimated CCD effect for other crop fees is small in magnitude and not significantly different from zero for either sample period.

Table 8 presents estimates from a parallel analysis of California pollination fees. The top panel indicates that fees for almonds increased substantially. Consistent with our expectation that fees for plums and early cherries will move with almond fees, both are also considerably higher following the appearance of CCD. Fees for other (later) crops also increase after 2006, but by a relatively small magnitude.

The bottom panel of table 9 displays results from several GLS regression specifications. Beyond only examining a single period for the California fees, the primary difference between these specifications and the PNW specifications is that, in addition to the CCD effects we estimate for almond and all other (non-early) crop pollination fees, we also estimate separate 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, plums, and early cherries. 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 a linear trend and almond acres, the estimated CCD impact is not statistically different from zero. In the second column for models 1 and 2, we estimate a single CCD effect coefficient for all three of the early crops. A test of the null hypothesis that the three early crop coefficients are equal to each other is rejected for model 1, but not for model 2.

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 almond acres, we estimate that almond fees in the PNW and California increased by \$63 and \$53. Plum and early cherry fees in

California increased by $44 and $26.[57]

The timing of the increase in early-crop pollination fees (see figures 7 and 8) 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 that was unreported prior to 2007. See Mussen (2007) for a discussion of drought related factors leading to a short supply of bees in 2005 and 2006. No such suspicions of a pre-2006 effect are raised from the colony number, honey production, or package and queen price data. If we assume that the run-up in almond fees in 2005 was related to widespread pollinator health problems , then a reasonable specification that maintains the spirit of our specifications above would be one that includes **only** a 0-1 dummy variable for the post-2004 years (and no post-CCD 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 in recent years.

The empirical results reported in this section do not support claims that Colony Collapse Disorder has been disastrous for beekeepers nor that it is wreaking havoc in pollination markets that follow almond pollination. We do identify significant early-season pollination fee effects in years following CCD. There are other possible impacts operating through pollination markets, which we mention here. Because pollination fees are an important component of costs for almond producers, the

[57] Rucker *et al.* (2012) estimate impacts of CCD on almond pollination fees for PNW beekeepers in the range of $16 - $20, which is roughly one-third of our estimated effects in tables 7 and 8. That study employs a more complete reduced form specification for identifying the determinants of pollination fees, and we attribute most of the differences between our estimates and those earlier estimates to their treatment of the increase in almond pollination fees in the two years preceding the first reported cases of CCD. The approach used by Rucker *et al.* was to include a binary 0-1 variable to distinguish between years prior to and after the run-up in pollination fees that started in the winter of 2004/2005. Insofar as that earlier increase in pollination fees was the result of factors other than CCD (and insofar as the impacts of those factors continued beyond 2006), then the estimates in tables 7 and 8 are biased upwards because they attribute those increases to CCD. Indeed, when we estimate these models with a post-2004 dummy variable, the impacts attributable to CCD are more in line with those of Rucker *et al.* (2012) (results available on request).

argument could be made that various impacts of CCD might manifest themselves in almond markets. First, almond prices could rise and production could fall, because of a pollination-cost induced decrease in the supply of almonds. Second, almond yields, and yields of other crops, could fall because of bees of lesser vitality early in the pollination season. Appendix I 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.

To this point, we identify the impacts of CCD with a dummy variable to distinguish between observations before and after the appearance of CCD in the winter of 2006/2007. In Appendix II, we discuss an alternative approach that offers a robustness check and potentially superior identification strategy. Results from this approach provide qualitatively similar conclusions regarding the economic impacts of CCD. As we discuss in the appendix, the data we were able to obtain for this test have shortcomings and so we focus on the discrete CCD effects in the text.

IV. Evaluating the Costs of CCD

In this section, we develop back-of-the-envelope estimates of the impacts of CCD on consumer prices and on beekeeper costs and revenues based on an assumption of fixed coefficient technologies.

IV.A. CCD's Effect on Consumers

Tables 7 and 8 suggest point estimates of the effect of CCD on almond pollination fees near \$60. Current (2013) almond fees are roughly \$150, suggesting that the implied no-CCD almond fee would be \$150 - \$60 = \$90. The implied percentage increase in almond fees due to CCD is then (60/90) × 100 = 66.7%. Further, with a pollination fee for almonds of \$90 per colony and a stocking density of two colonies per acre, the current (absent CCD) cost per acre of pollinating almonds is 2 ×

$90 = $180. Suppose (based on recent data) that the yield of almonds is 2,300 pounds per acre and that the farm-gate price of almonds is $2.50 per pound. Then revenue per acre is 2,300 × $2.50 = $5,750 and the farm-gate cost share of pollination in almonds is $180/$5,750 = 0.031 or 3.1 percent.[58]

Next, suppose that Smokehouse Almonds at the retail level sell for $7 per pound and that one pound of Smokehouse Almonds requires 1.67 pounds of raw almonds (the rate of conversion from at-the-farm and in-the-shell almonds to retail shelled almonds).[59] Then the cost share of farm almonds in the production of Smokehouse Almonds is (1.67 × $2.50)/$7 = 0.596.[60] Thus, the cost share of pollination services in retail Smokehouse Almonds is 0.031 × 0.596 = 0.018 or 1.8 percent.

The stipulated 66.7 percent increase in almond pollination fees due to CCD therefore causes the cost of Smokehouse Almonds to increase by a proportion of 0.667 × 0.018 = 0.012. One and two-tenths percent of the $7/lb retail price of Smokehouse Almonds is 8.4¢, the implied increase in the shelf price of the can of almonds. Similar calculations could be made for other almond-containing products, or products made from other pollinated crops. For example, for plums and early cherries, similar calculations suggest that the retail price of these fruits has increased by less than one cent per pound as a result of CCD.[61] Given the high pollination fees paid by almond growers and the relatively high cost share of pollination in almond production, as well as the high proportion of raw almonds per

[58] In the absence of reliable external data on economic costs, we assume a long-run competitive equilibrium with zero profits. Thus, costs per acre are equal to the revenues per acre of $5,750.

[59] The conversion rate between in-shell and shelled almonds of 1.67 is the rate employed in Agricultural Statistics in recent years. See, for example, USDA NASS, Agricultural Statistics (2013), table 5.81.

[60] As with the previous calculation, this calculation is based on the assumption of zero profits in the production of Smokehouse Almonds.

[61] Note that because our regression results indicate there is no evidence of a statistically significant post-2006 CCD effect on pollination fees for crops other than almonds, early cherries, and plums, these calculations are straightforward—our estimated impacts for other products made from pollinated crops is $0.00.

pound of retail almonds, our almond calculation should provide something of an upper bound on what one would find for other commodities and products.

Insofar as economic costs are actually less than revenues, almond producers make economic profits, and the cost share of almonds in the preceding calculations will underestimate the impacts of CCD on consumers. To understand the impacts of this possibility, suppose costs are less than revenues for almond growers, and that the farm-gate cost share of almonds is actually double the share used above. The impacts of this adjustment translate into a doubling of the estimated impact of CCD on almond prices, or 16.8¢ per can of almonds.

An aggregate estimate of the impacts of CCD on almond consumers can be obtained as follows. The farm-gate value of the almond crop in 2013 was $5.8 billion. Applying the estimated 66.7 percent increase in fees for pollination services—an input with a 3.1 percent cost share—and assuming zero economic profits for almond producers, suggests an increase in farm-gate costs of (0.667 x 0.031 x $5.8 billion) = $120 million. If all of this cost increase is passed on to consumers, then how are U.S. consumers impacted by CCD? Over the past five years, 33 percent of U.S. almonds have been consumed in the United States. At the time of writing, the U.S. population is 319 million, implying a per person CCD impact of [(0.33x$120 million)/319 million persons)] = $0.124 per person. Again, if one prefers to double our estimate of the cost share of pollination in almond production, that results in a doubling of the per person estimate of the impacts of CCD. Either of the preceding methods of estimating the impact s of CCD on consumers suggest very small effects.

IV.B. CCD's Effect on Beekeepers

Consider first how CCD affects beekeeper costs. Responses to questions in the PNW survey about replacement methods indicate that beekeepers used the making increase (or splits) method for almost 80 percent of the colonies replaced. What are the costs associated with this replacement method? Suppose a beekeeper inspects his hives and finds that 100 of them are dead. To replace them, assume he purchases 100 queens to place with the new splits (or nucs) produced from the healthy parent colonies. Recent advertisements in the *American Bee Journal* suggest 100 queens will cost about $18 each.[62] In addition, about 20 minutes of labor will be required per colony to remove the four or five frames of brood, bees, and honey stores from the parent colony to stock the nuc colony. If labor costs are assumed to be $15 per hour, the labor cost per colony is $5 and the total cost of each split is $18 + $5 = $23.

Several studies (including Burgett *et al.* (2009)) estimate that PNW winter mortality rates increased from about 15 percent prior to the appearance of CCD to an average of roughly 30 percent over the eight winters since the appearance of CCD in the fall of 2006. Assuming that CCD is responsible for all of the 15 percentage point increase, about half the colony mortality since the 2006-2007 winter is attributable to CCD. Consider the impacts of this increase in mortality rates on a PNW commercial beekeeper who has, say, 1,000 colonies in the late summer and has commitments to provide 1,000 colonies for almond pollination in February. To meet his almond commitment with an (initial) expected mortality rate of m=0.15, the beekeeper will have to split $(m_0/(1-m_0))\cdot 100 = 17.65$ percent of his colonies.[63] The beekeeper in this example would split 177 of his colonies, go into the winter with 1,177 colonies, and come out with 1,000 (= 1,177 ·0.85) colonies. He would meet his Spring almond pollination commitments and then, before he pollinates crops near his home base in

[62] For the five package and queen producers we use for the analysis in section IV.C above, the average price for quantities of 100 or more queens in March of 2014 was $17.90. Based on conversations with industry sources, we estimate shipping costs for queens to be $0.30 per queen and round the total to $18.

[63] To see this, let S be the required split rate. C is the number of colonies in the fall and also the desired number of colonies for almond pollination, and m is the mortality rate (implying that 1-m is the survival rate). If the beekeeper splits the fraction S of his colonies, then he enters the winter with C + S x C colonies. To determine the required split rate, solve for S in (C + SC)(1-m) = C to get S = (m/(1-m)).

Washington or Oregon, could split more colonies. With each of these splits, the initial healthy hive typically has enough of its bee population intact to pollinate the next scheduled crop (for example, tree fruit in the PNW). The splits themselves will likely be strong enough for later pollination sets such as berries and seed crops or, alternatively, for honey production.

The beekeepers who responded to the PNW survey in 2008 owned 62,100 out of the USDA's estimated 100,000 colonies in Washington and Oregon in that year. Assuming that the beekeepers responding to the survey are representative of the non-responding PNW beekeepers, the demise of about 15,000 (= 100,000 x 0.15) colonies in the PNW was due to CCD. The product of the replacement cost per lost colony and the number of colonies lost due to CCD—$23×15,000 = $345,000—represents an estimate of the aggregate annual costs borne by PNW beekeepers as a result of CCD-induced increases in the number of splits required to maintain colony numbers since the winter of 2006-2007.

Another potential cost of CCD to beekeepers is foregone pollination fees from not having enough hives to meet pollination commitments. To estimate these costs, consider again the beekeeper with 1,000 colonies in late summer of, say, 2006 who expects a 15 percent mortality rate and splits 177 colonies to enter the winter with 1,177 colonies.[64] How does the onset of CCD impact this beekeeper? Suppose that in February of 2007, the PNW beekeeper takes his colonies to California and there, upon examining his colonies, finds that his winter mortality rate is 30 percent rather than the 15 percent he expected, leaving him with only 824 (= 1,177×0.70) colonies. He has two options, given that there is not enough time for him to successfully split colonies before almond pollination commences. First, he can partially fulfill his contract for 1,000 colonies with the 824 colonies that survived the winter and

[64] Note that splitting during late summer involves little or no foregone pollination or honey income.

renege on the remainder of the contracted colonies. If he chooses this option, his CCD-induced losses from foregone almond pollination fees of, say, \$150 per colony are \$26,400 (= 176 ×\$150).[65]

The beekeeper's second option is to purchase the additional 176 colonies required to meet his contractual obligation of 1,000 colonies for almond pollination. U.S. package and queen producers typically do not offer their products until later in the spring. One source of replacement bees for almond pollination in the first few years after CCD appeared was Australian package and queen suppliers. The beekeeper in our example could order 176 packages (with newly fertilized queens) from an Australian supplier and meet his obligations for almond pollination. Anecdotal evidence and industry participants indicate that the cost of Australian packages purchased under these circumstances were about \$150 each. The costs to the beekeeper of this option are \$26,400 (= 176×\$150)—the same as the costs of the first option. Under this option, the beekeeper pays for the Australian packages and just breaks even on the pollination transaction. In contrast with the first option, he avoids any future costs resulting from lost reputational capital with the almond orchard owner.[66]

Consider, finally, anticipatory actions beekeepers can take once higher post-CCD overwinter mortality rates are taken to be the norm. One mitigating action the beekeeper in the above example can take when he is convinced that the winter mortality rate has risen from m_0 = 15 percent to m_1 = 30 percent, is to split more colonies. With 1,000 fall colonies and almond pollination commitments for

[65] This calculation abstracts from possible future costs to the beekeeper due to lost reputational capital he may have developed with the almond orchard owner. Commercial beekeepers often contract with the same orchard owners year after year, so these costs might be non-trivial and could manifest themselves in the form of lost contracts or reduced pollination fees as the orchard owner adjusts for the possibility of repeated future failure by the beekeeper to provide the contracted number of colonies. Also, assuming the beekeeper wishes to return his colony numbers to 1,000, he will likely split 176 colonies between the time almond pollination ends and when fruit tree pollination in Oregon and Washington begins.

[66] In addition, he will not have to split 176 colonies between almond pollination and tree fruit pollination in Oregon or Washington.

1,000 colonies in the spring, his new split rate will be $m_1/(1-m_1) \cdot 100 = 42.86$ percent. With this higher split rate, he incurs increased splitting costs in the fall, but he avoids the costs associated with foregone pollination fees in the spring.[67] The full costs to beekeepers during the initial period after the appearance of CCD are thus either (1) the sum of the foregone almond pollination income from the unexpectedly high winter mortality rate, reputational costs, and the additional split costs after almond pollination, or (2) the costs of Australian packages. After beekeepers adjust their expectations regarding the winter mortality rate, the cost of CCD is simply the increased split costs incurred going into the winter.

To estimate these costs in the aggregate, consider the 25 beekeepers who responded to the 2008 PNW survey. They owned a total of 62,100 colonies as of October 1, 2007, or an average of 2,484 colonies each. Linking the average PNW beekeeper to the beekeeper in the example above, suppose 2,484 is the number of colonies the average PNW beekeeper had going into the winter.[68] Assuming these beekeepers unexpectedly lost 15 percent of their bees to CCD on average, the total estimated CCD cost per beekeeper is the sum of the foregone pollination fees due to the higher-than-expected mortality rate and the additional split costs, or $(0.30 - 0.15) \cdot 2{,}484 \cdot \$150 + 0.15 \times 2{,}484 \times \$23 = \$55{,}890 + \$8{,}570 = \$64{,}460$.[69] This is the short-run, limited-adaptation cost. After the average PNW beekeeper adjusts to the new higher mortality rate, the costs of CCD are simply the costs due to the optimal split rate increasing from 18 to 43 percent. For the average PNW beekeeper responding to the

[67] Imports of Australian bee packages were banned in December of 2010. Insofar as commercial beekeepers had adjusted their fall split rates by then, this ban likely had little impact on them.

[68] Note that, assuming an expected mortality rate of 0.15, the desired number of colonies for spring almond contracts is C such that $C + SC = 2{,}484$. Recalling that $S = [m/(1-m)]$ and solving for C yields $C = 2{,}111$.

[69] This is the cost to beekeepers who renege on their shortfall of contracted colonies. The calculation does not attempt to estimate lost reputational capital costs.

2008 survey, these long-run costs are (0.43 - 0.18) · 2,111 · \$23 = \$12,138.

Possibly offsetting the increased costs to beekeepers are increased beekeeper revenues from higher almond pollination fees, and 72 percent of the colonies in the 2008 PNW survey were rented out for almond pollination. Suppose, as in the previous subsection, we take the almond fee increase due to CCD to be \$60. Then the average PNW beekeeper who exits the winter with 2,484 colonies and uses 72 percent of them (0.72 × 2,111 = 1,520) to pollinate almonds, gains an increase in revenue of 1,520 × \$60 = \$91,200. The change in net revenue before the average beekeeper adjusts his expectations and split rates is \$91,200 - (\$55,890 + \$8,570) = \$26,740, implying that the average PNW commercial beekeeper benefits from the equilibrium effects of CCD.[70] The extent to which these ostensible gains will be bid down by expansion and entry depends on the elasticity of supply of beekeeping services. The factor in least elastic supply is almost certainly beekeepers' skill and management.

V. Conclusions

Colony Collapse Disorder has been portrayed as an environmental disaster that is decimating honey bee populations in the United States and elsewhere. While the issues related 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 find no evidence of an increase in pollination fees following the advent of CCD. For almonds, the fee increase attributable to CCD is non-trivial from the perspective of almond growers and beekeepers, but translates into a small increase in prices paid by consumers.

[70] After the average beekeeper adjusts his expectations and split rates the change in his net revenue will be \$91,200 - \$12,138 = \$79,062.

Generalizing our conclusions to other situations of adaptation to environmental change requires an appreciation of the importance of institutions. In the context of CCD, the key institution is well-functioning markets for the services of managed pollinators and for beekeeping inputs. Acting within these markets, U.S. beekeepers have adjusted quickly to a sudden and large environmental shock. Concern over the general phenomenon of pollinator decline is not, however, limited to the United States. The extent and sophistication of markets that enable adaptation in other countries is unclear to us at this point; previous analyses have all focused on the United States.

Finally, what about wild pollinators? Managed pollinators, mainly honey bees (but also greenhouse bumblebees, alfalfa leafcutter bees, and a few others) are strategically distributed 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. When markets for managed pollinators exist, our findings suggest the potential for quick responses by beekeepers to limit any negative impacts on the agricultural sector. When such markets do not exist, the increased demand for managed pollination services may provide the impetus for new markets to develop. The pace and scope of such development will depend on transaction costs related to such factors as farm sizes and transportation infrastructure. On the other hand, market-based solutions to preserve native pollinator habitat may not be easily developed.

In conclusion, we note that there are now—and have been for some time—industry participants, observers, and scientists who downplay the significance and uniqueness of CCD. They suggest that the attention this affliction has received is diverting focus from broader, more important pollinator health issues and concerns. Such suggestions do not diminish the significance of our fundamental findings. No informed observer disputes that a striking increase in winter mortality rates for managed bees took place in the mid-2000s. Whether this increase was the result of CCD or other environmental changes does not alter our findings that markets adjusted sufficiently quickly that the economic impacts of the increased mortality rates are limited.

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*. doi:10.1016/j.cub.2008.08.066.

Auffhammer, Maximilian and Wolfram Schlenker. 2014. "Empirical Studies on Agricultural Impacts and Adaptation," *Energy Economics* 46: 555-561.

Barreca, Alan, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S. Shapiro. January 10, 2015. "Adapting to Climate Change: The Remarkable Decline in the U.S. Temperature-Mortality Relationship Over the 20th Century," forthcoming, *Journal of Political Economy*.

Bator, Francis M. "The Anatomy of Market Failure." *Quarterly Journal of Economics* 72 (1958): 351-364.

Bromenshenk, Jerry J., Colin B Henderson, Charles H. Wick, Michael F. Stanford, Alan W. Zulich, *et al.* 2010. "Iridovirus and Microsporidian Linked to Honey Bee Colony Decline," PloS ONE 5(10) at http://www.plosone.org/article/info:doi/10.1371/journal.pone.0013181. Accessed February 10, 2011.

Burgett, Michael. "Pacific Northwest Pollination Survey." Various issues of *USDA Honey Market News*.

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*, Vol. 149, No. 6, June 2009, pp. 573-575.

Caron, Dewey, Michael Burgett, Randal R. Rucker, and Walter N. Thurman. 2010. "Honey Bee Colony Mortality in the Pacific Northwest: Winter 2008/2009," *American Bee Journal* (March 2010): 265-269.

Caron, Dewey and Ramesh Sagili. 2011. ""Honey Bee Colony Mortality in the Pacific Northwest: Winter 2009/2010," *American Bee Journal*, Vol. 151, No. 1, January 2011, pp. 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): 143-164.

Champetier, Antoine, Daniel A. Sumner, and James E. Wilen. 2010. "The Bioeconomics of Honey Bees and Pollination," University of California, Davis, Agricultural Issues Center, Working Paper, August 2010.

Cheung, Steven N.S. "The Fable of the Bees: An Economic Investigation." *Journal of Law and Economics* 16(1973):11-33.

Columbia University's 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., D. R. Tarpy, Y. Chen, L. Jeffreys, D. Lopez, J. S. Pettis, D. vanEngelsdorp, and J. D. Evans. 2012. "Pathogen Webs in Collapsing Honey Bee Colonies." *PLoS ONE*, **7**(8): e43562. doi:10.1371/ journal.pone.0043562.

Daberkow, Stan, Randal R. Rucker, Walter N. Thurman, and Michael Burgett. 2009. "U.S. Honey Markets: Recent Changes and Historical Perspective," *American Bee Journal*. (December): 1125-1129.

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 2011): 152-185.

Favre, Daniel 2011. "Mobile Phone-Induced Honeybee Worker Piping," *Apidologie*, http://www.scribd.com/doc/56187984/Daniel-Favre-Mobile-Phone-Induced-Honey-Bee-Worker-Piping, published on-line April 13, 2011. Accessed April 1, 2011.

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: 593-924.

Hsiang, Solomon and Daiju Narita. 2012. "Adaptation to Cyclone Risk: Evidence from the Global Cross-Section" *Climate Change Economics* 3(2).

Kerr, Jeremy T., Alana Pindar, Paul Galpern, Laurence Packer, Simon G. Potts, Stuart M. Roberts, Pierre Rasmont, Oliver Schweiger, Sheila R. Colla, Leif L. Richardson, David L. Wagner, Lawrence F. Gall, Derek S. Sikes, Alberto Pantoja. 2015. "Climate Change Impacts on Bumblebees Converge Across Continents." Science. 349(July 10, 2015): 177-180 at http://www.sciencemag.org/content/349/6244/177.abstract,

Kleijn, David, *et al.* (57 co-authors). June 2015. "Delivery of Crop Pollination Services is an Insufficient Argument for Wild Pollinator Conservation. *Nature*. DOI: 10.1038/ncomms8414.

Kurukulasuriya, Pradeep and Robert Mendelsohn. 2008. "Crop Switching as a Strategy for Adapting to Climate Change." *Afr. J. Agric. Econ.* 1(2): 105-25.

Laidlaw, Harry. 1992. "Queen Rearing," in Graham, *The Hive and the Honey Bee*, chapter 8.

Maori, E., S. Lavi, R. Mozes-Koch, Y. Gantman, Y. Peretz *et al.* 2007. "Isolation and Characterization of Israeli Acute Paralysis Virus, a Dicistrovirus Affecting Honey Bees in Israel: Evidence for Diversity due to intra- and inter-species Recombination. *J. Gen. Virol.* 88: 3428–3438 at http://vir.sgmjournals.org/cgi/reprint/88/12/3428

Meade, J.E. "External Economies and Diseconomies in a Competitive Situation." *Economic Journal* 5 (1952): 54.

Morse, Roger A. and Nicholas W. Calderone. 2000. "The Value of Honey Bees as Pollinators of U.S. Crops in 2000," *Bee Culture*, March 2000. http://bee.airoot.com/beeculture.

Morse, Roger A. and K. Flottum. 1997l. *Honey Bee Pests, Predators, and Diseases.* A. I. Root Co., Medina, Ohio.

Mussen, Eric. "BSI: The Case of the Disappearing Bees," Public Lecture, University of California-Davis, October 17, 2007. Summary article (accessed January 27, 2015) and video of lecture available at http://169.237.77.3/news/dssericmussen.html.

Muth, Mary K. and Walter N. Thurman. 1995. "Why Support the Price of Honey?" *Choices* 2nd Quarter, 1995: 13-17.

Muth, Mary K., Randal R. Rucker, Walter N. 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.

National Research Council. 2007. *Status of Pollinators in North America*. Washington, D.C.: The National Academies Press.

Nordhaus, Hannah. 2011. *The Beekeeper's Lament: How One Man and Half A Billion Honey Bees Help Feed America*. HarperCollins Publishers, New York.

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): 480-485.

Olmstead, Alan L. and Paul W. Rhode. 2008. *Creating Abundance: Biological Innovation and American Agricultural Development*. Cambridge Univ. Press, New York.

Pernal, S.F. 2008. CAPA statement on honey bee losses in Canada (spring 2008) – final revision. Canadian Assoc. of Professional Apiculturists.

Pollan, Michael. 2007. "Our Decrepit Food Factories," *New York Times*, December 16, 2007.

Portnykh, Margarita. 2015. "The Effect of Weather on Mortality in Russia." unpublished working paper, Clemson University.

Potts, Simon G., Jacobus C. Biesmeijer, Claire Kremen, Peter Nuemann, Oliver Schweiger, and William E. Kunin. 2010. "Global Pollinator Declines: Trends, Impacts and Drivers." *Trends in Ecology and Evolution.* 25(6): 345-353.

Ratnieks, Francis L. and Norman L. Carreck. 2010. "Clarity on Honey Bee Collapse." *Science*. 327(8): 152-153.

Robinson, W.S., R. Nowogrodzki, and R.A. Morse. 1998. "The Value of Honey Bees as Pollinators of U.S. Crops." *American Bee Journal* (June 1989):411-23 (Part I) and (July 1989):477-87 (Part II).

Rucker, R., W. Thurman, and M. Burgett. 2012. "Honey Bee Pollination Markets and the Internalization of Reciprocal Benefits,"*American Journal of Agricultural Economics* 94(2012): 956-977.

ScienceDaily, "Economic Value of Insect Pollination Worldwide Estimated at U.S. $217 Billion," Sept.15, 2008, http://www.sciencedaily.com/releases/2008/09/080915122725.htm (accessed January 12, 2009),

Shimanuki, H. (1997) "Synonymy in Bee Diseases," in: Morse, R. A., and K. Flottum, editors. *Honey Bee Pests, Predators, and Diseases*. A. I. Root, Medina, Ohio: 534–537.

Spleen, A.M., E. J Lengerich, K. Rennich, D. Caron, R. Rose, J. S Pettis, M. Henson, J. T Wilkes, M. Wilson, J. Stitzinger, K. Lee, M. Andree, R. Snyder, and D. vanEngelsdorp, 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., Karen Rennich, Michael E. Wilson, Dewey M. Caron, Eugene J. Lengerich, Jeff S. Pettis, Robyn Rose, John A. Skinner, David R. Tarpy, James T. Wilkes, and Dennis vanEngelsdorp. 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, "As bees go missing a $9.3B crisis lurks," Fortune, August 28, 2007: 2:55 p.m. EDT. Accessed June 8, 2008 online at http://money.cnn.com/magazines/fortune/fortune_archive/2007/09/03/100202647/index.htm.

Underwood, Robyn M. and Dennis vanEngelsdorp. 2007. "Colony Collapse Disorder: Have We Seen This Before?" *Bee Culture* 135(7):12-15.

United States Department of Agriculture, National Agricultural Statistics Service (NASS). "2013 Agricultural Statistics Annual." http://www.nass.usda.gov/Publications/Ag_Statistics/2013/index.asp.

United States Department of Agriculture, National Agricultural Statistics Service (NASS). February 2008. "Honey." http://usda.mannlib.cornell.edu/usda/nass/Hone//2000s/2008/Hone-02-29-2008.pdf.

United States Department of Agriculture, National Agricultural Statistics Service (NASS). March 2014. "Honey." http://usda.mannlib.cornell.edu/usda/current/Hone/Hone-03-21-2014.pdf.

vanEngelsdorp D., J.D. Evans, C. Saegerman, C. Mullin, and E. Haubruge *et al.* 2009. "Colony Collapse Disorder: A Descriptive Study," PLoS ONE 4(8): e6481. at http://www.plosone.org/article/info:doi/10.1371/journal.pone.0006481. Accessed February 10, 2011.

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.

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. January 2010. "A Survey of Honey Bee Colony Losses in the United States, Fall 2008 to Spring 2009." *Journal of Apicultural Research* Vol. 49(1): 7-14.

vanEngelsdorp, D., J. Hayes, R.M. Underwood, D. Caron, and J. Pettis. January 2011. "A Survey of Managed Honey Bee Colony Losses in the USA, Fall 2009 to Winter 2010." *Journal of Apicultural Research*, Vol. 50(1): 1-10.

vanEngelsdorp, D., D. Caron, J. Hayes, R. Underwood, M. Henson, K. Rennich, A. Spleen, M. Andree, R. Snyder, K. Lee, K. Roccasecca, M. Wilson, J. Wilkes, E. Lengerich, and J. Pettis. February 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*, Vol. 51(1): 115-124.

vanEngelsdorp, D., Nathalie A. Steinhauer, Karen Rennich, Michael E. Wilson, Dewey M. Caron, Eugene J. Lengerich, Jeff S. Pettis, Robyn Rose, John A. Skinner, David R. Tarpy, Dominic Travis, and James T. Wilkes for the Bee Informed Partnership. 2014. "Preliminary Results: Honey Bee Colony Losses in the United States, 2013-2014." Accessed online on August 11, 2014 at http://beeinformed.org/2014/05/colony-loss-2013-2014/.

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, 2014. Accessed online on January 16, 2015 at https://www.whitehouse.gov/the-press-office/2014/06/20/presidential-memorandum-creating-federal-strategy-promote-health-honey-b.

White House, Pollinator Task Force. 2015. "National Strategy to Promote the Health of Honey Bees and Other Pollinators," May 19, 2015. Accessed online on June 14, 2015 at https://www.whitehouse.gov/sites/default/files/microsites/ostp/Pollinator%20Health%20Strategy%202015.pdf.

Wilson W. T. and D. M. Menapace. 1979. "Disappearing Disease of Honey Bees: a Survey of the United States," *American Bee Journal* 119: 184–186.

Figure 1. U.S. Bee Numbers: 1939−2013
(millions of colonies)

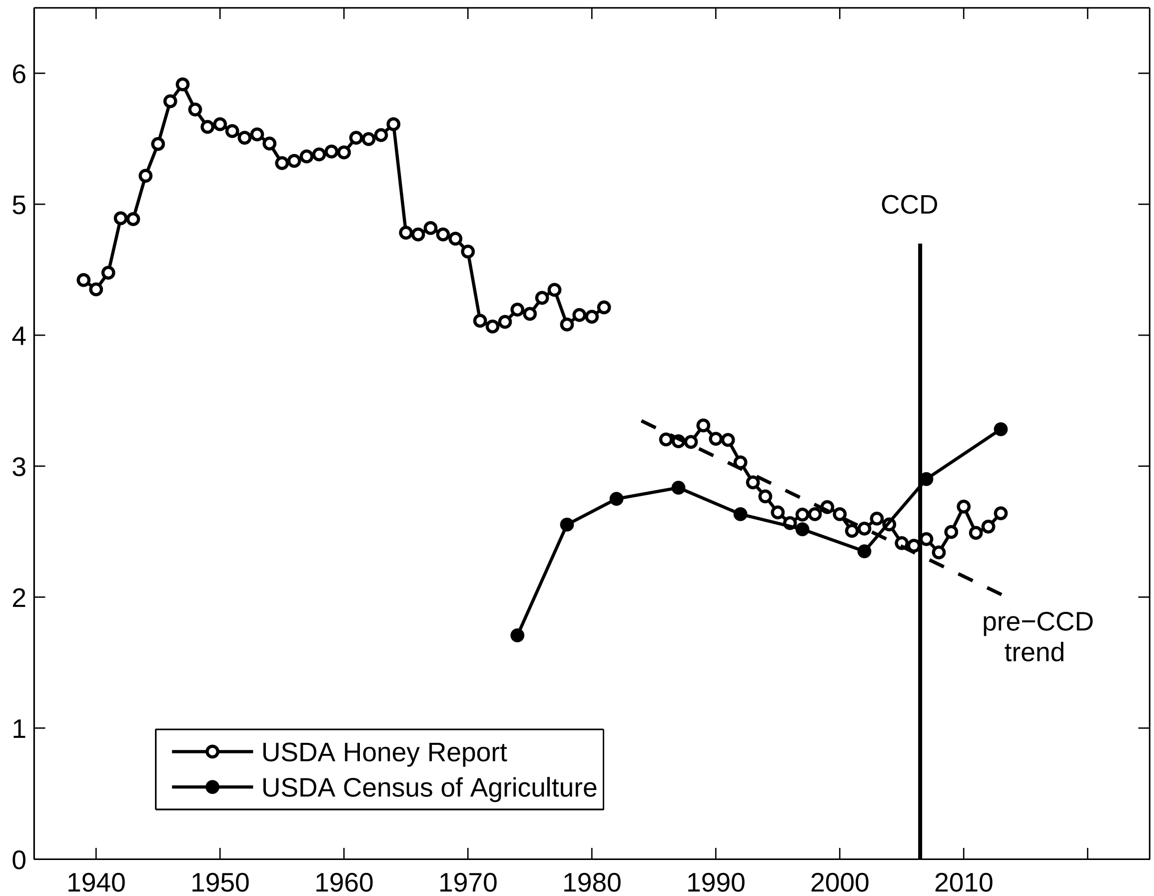


Figure 2. USDA Colony Numbers: 1939−2013
Top 5 States in 2013
(thousands of colonies)

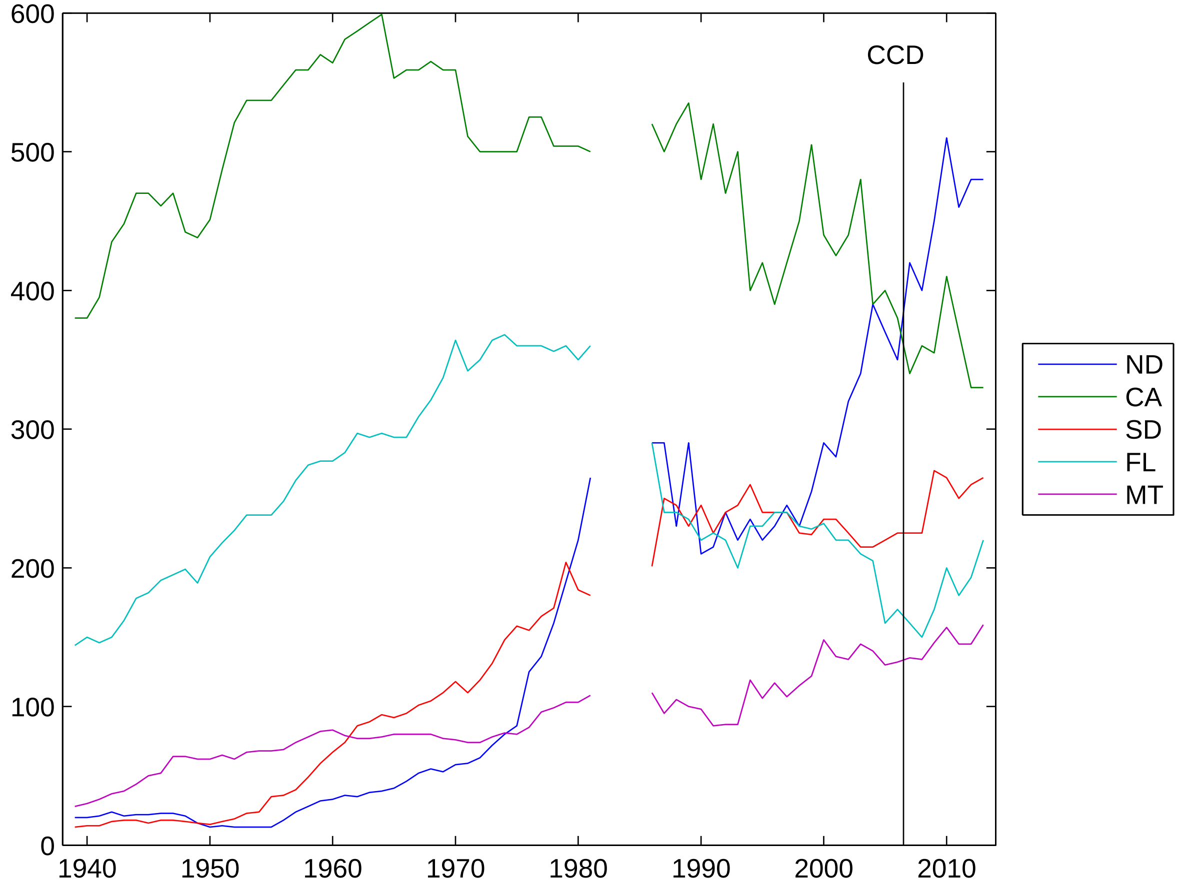


Figure 3. U.S. Honey Production: 1939−2013
(millions of pounds)

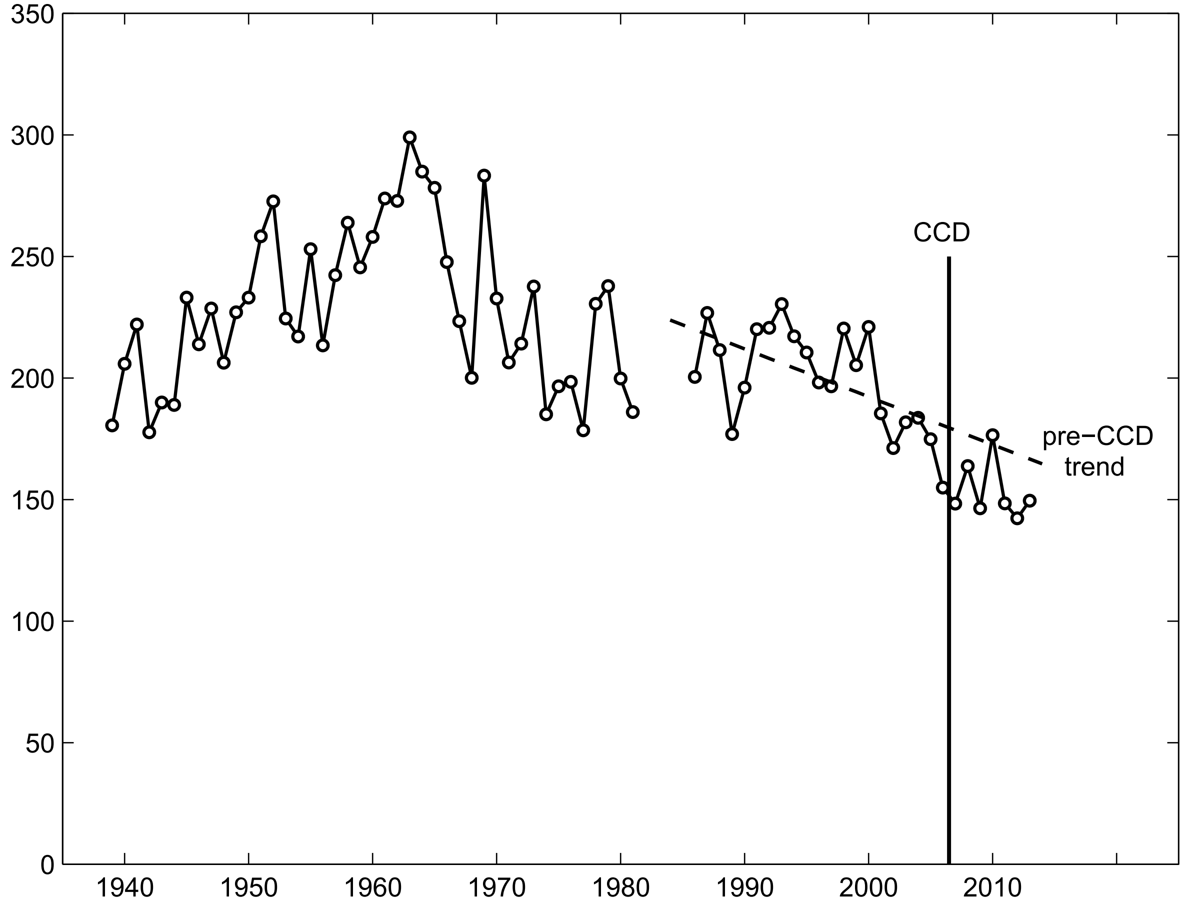


Figure 4. Honey Production: 1939−2013
Top Five States
(millions of pounds)

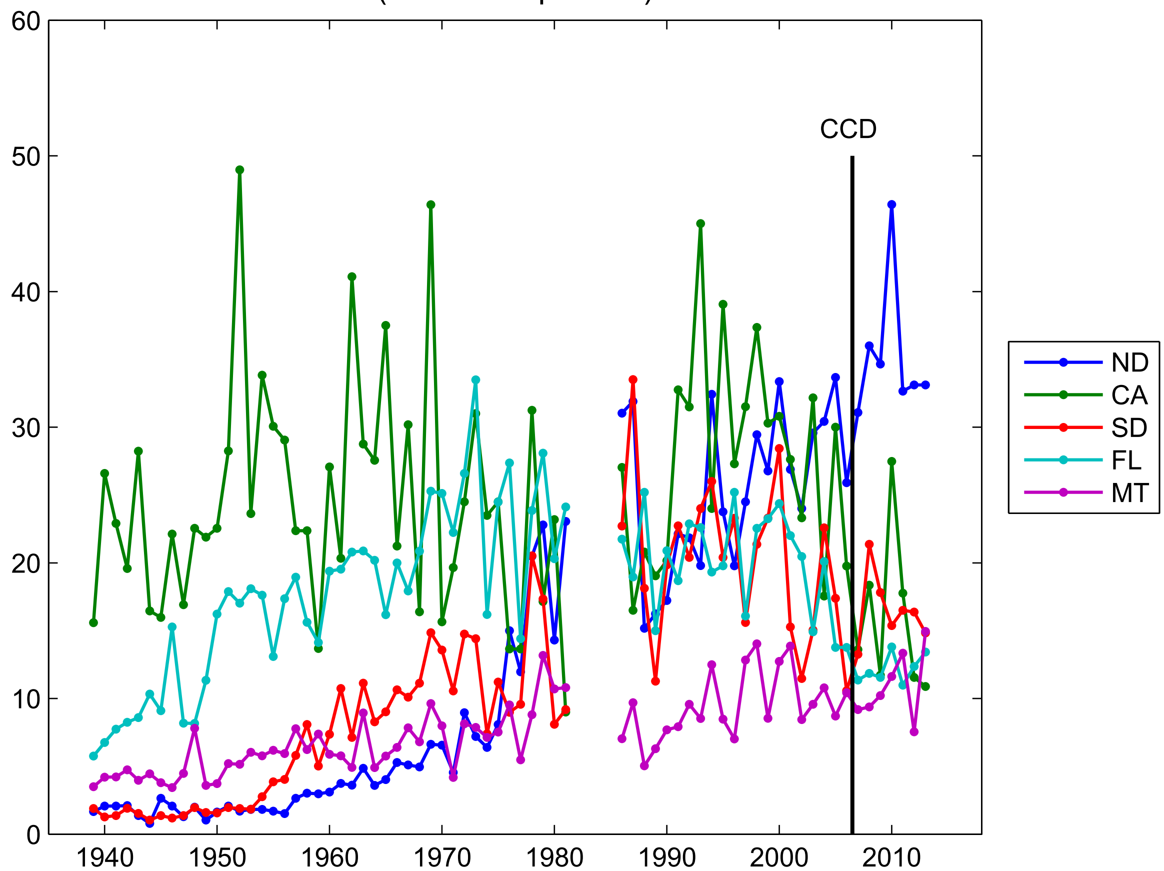
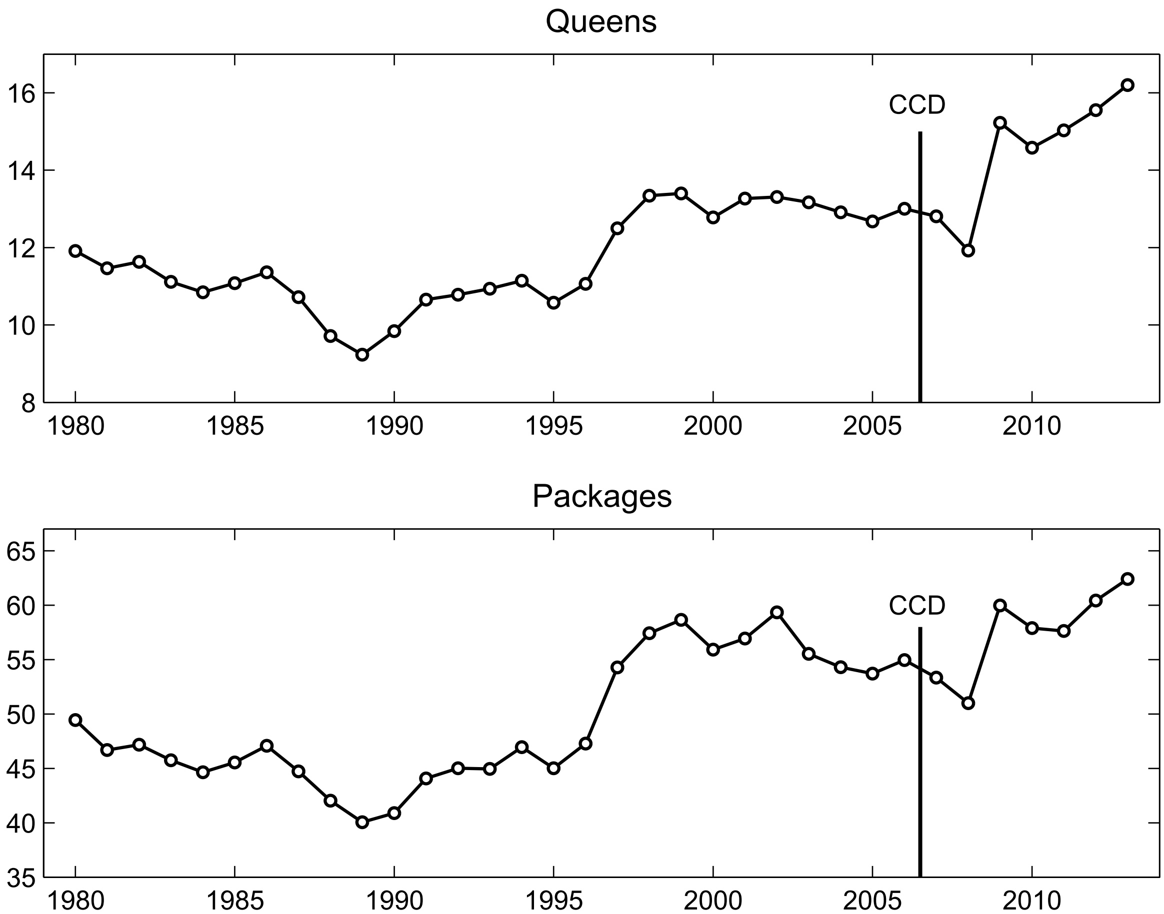
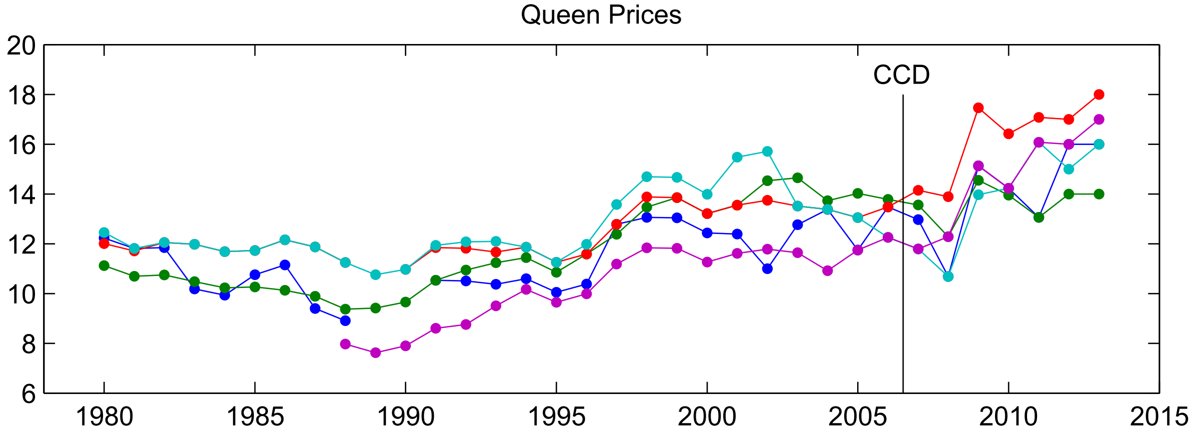


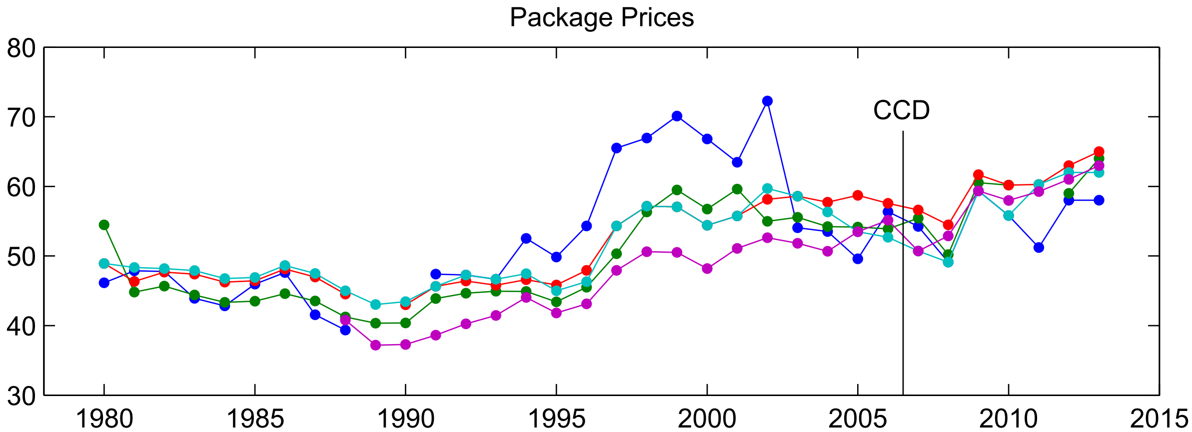
Figure 5. Real Queen and Package Bee Prices



Note: Both queen and package prices are averages (across five sellers) for quantities of 100 or more.
Prices are in 2013 dollars.

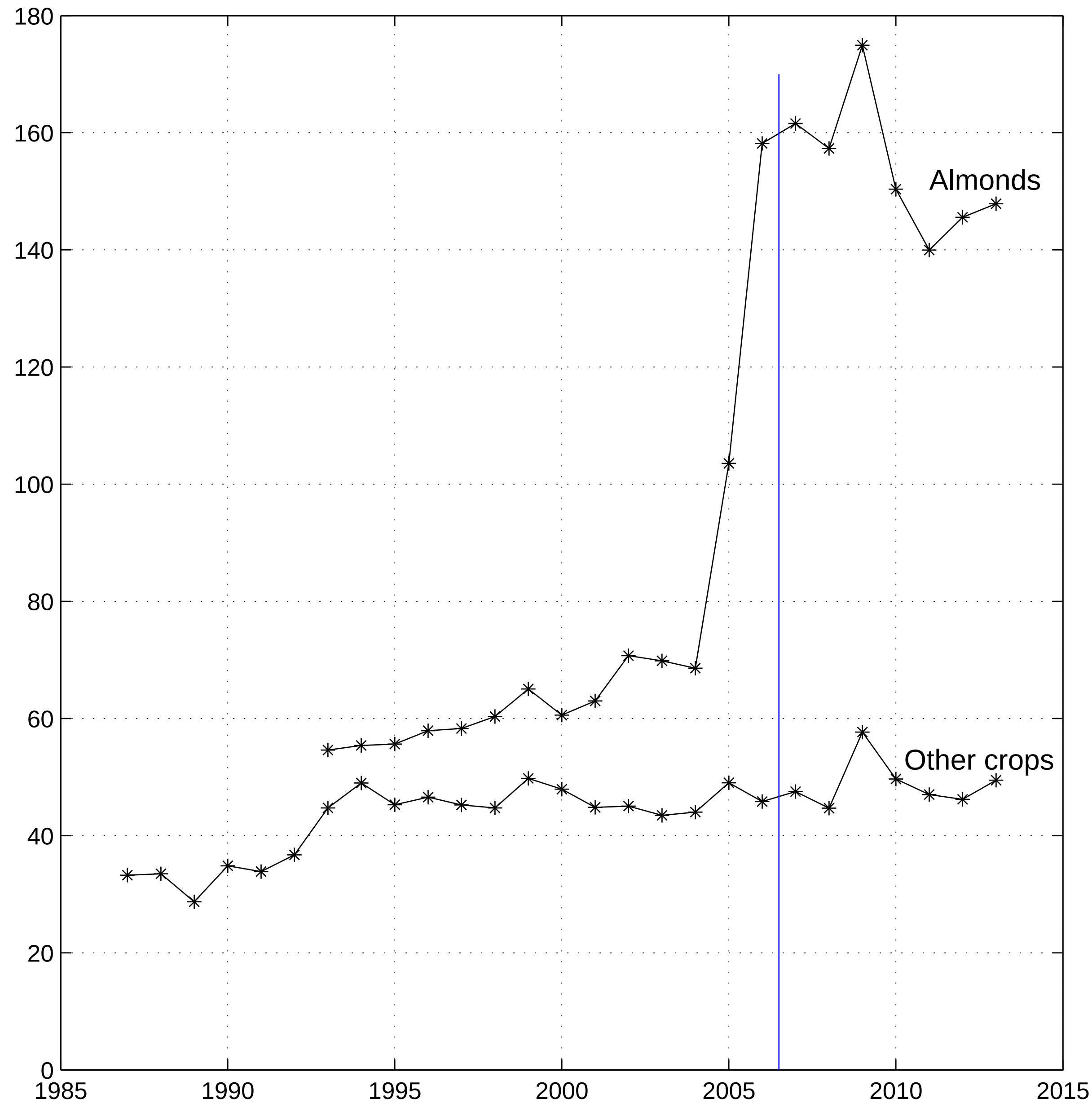
Figure 6. Real Queen and Package Bee Prices
Five Individual Seller's Advertised Prices





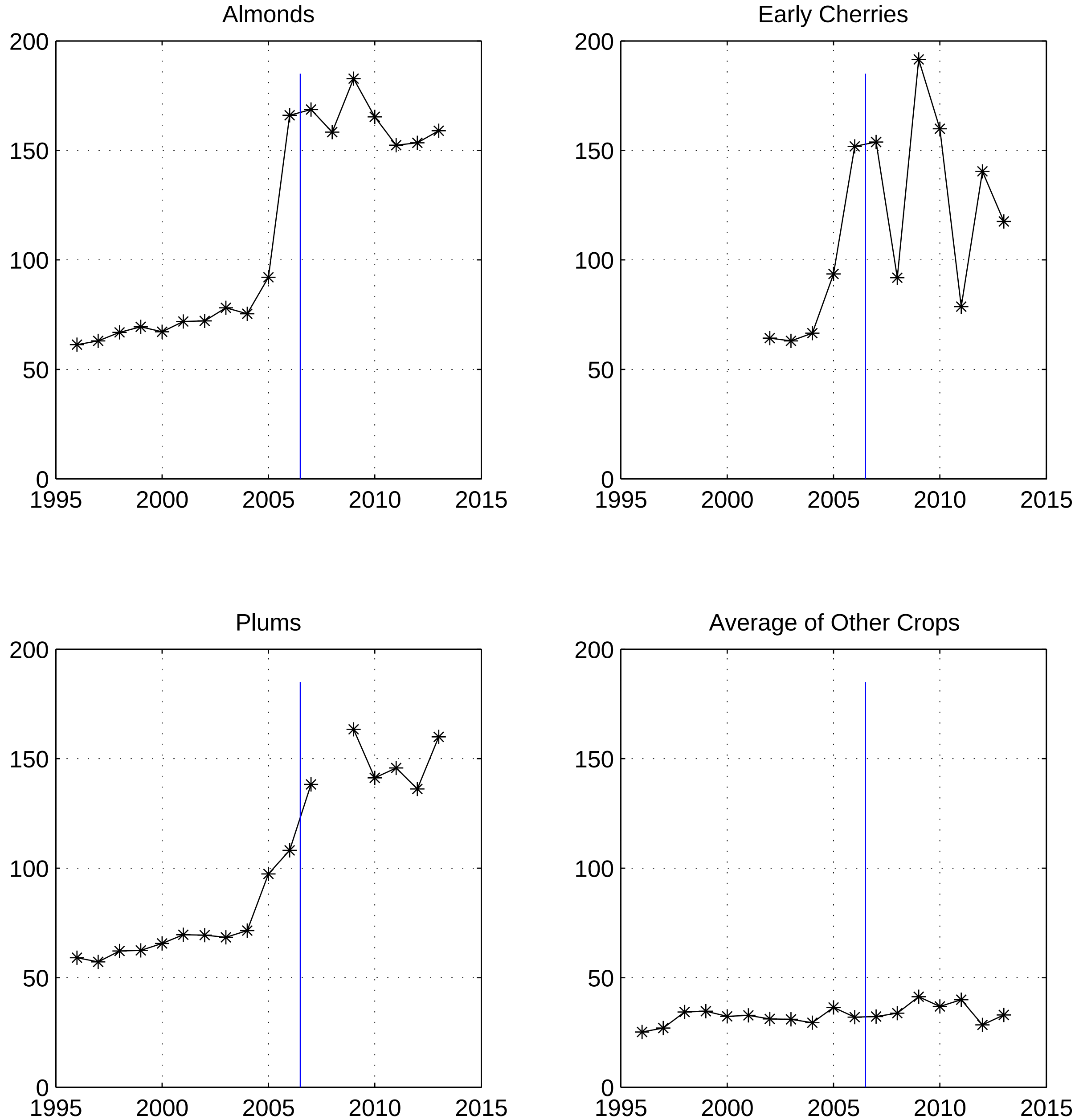
Note: Prices are for quantities of 100 or greater in 2013 dollars.

Figure 7. Real Pacific Northwest Fees (1987−2013)



Other (non−early) crops: average of pears, cherries, apples, and blueberries.

Figure 8. Real California Fees (1996−2013)



Other (non−early) crops: apples, avocados, melons, prunes, sunflowers, vegetable seed, alfalfa seed.

Table 1. Effects of CCD on Aggregate U.S. Colony Numbers

(revised 1/2/15)

Regression discontinuity by varying subperiods

Colony averages over sub-periods

	1986-2013		1990-2013		2000-2013	
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
Difference		-256		-161		7

Model 1: Colony regressions -- intercept and CCD dummy

	1986-2013		1990-2013		2000-2013	
	CCD effect	**t-ratio**	**CCD effect**	**t-ratio**	**CCD effect**	**t-ratio**
OLS	-256	-2.26	-161	-1.73	7	0.12
GLS	-30	-0.28	-61	-0.56	10	0.15

Model 2: Colony regressions -- trends before and after

	1986-2013					1990-2013					2000-2013				
	Trend before	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**	**Trend before**	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**	**Trend before**	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**
OLS	-43	-11.71	41	3.34	5.71	-40	-8.01	39	3.01	4.84	-34	-2.55	31	2.74	2.95
GLS	-42	-6.81	40	2.17	3.67	-42	-5.54	41	2.24	3.58	-34	-2.57	30	2.77	2.98

Model 3: Colony regressions -- trends before and after, with almond acres control

	1986-2013					1990-2013					2000-2013				
	Trend before	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**	**Trend before**	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**	**Trend before**	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**
OLS	-58	-6.90	-16	-0.52	1.66	-79	-5.04	-64	-1.56	0.55	-12	-0.36	71	1.22	2.40
GLS	-49	-4.49	14	0.35	1.96	-69	-3.88	-34	-0.73	1.09	-10	-0.30	74	1.24	2.39

Notes:

Colonies are measured in thousands.

GLS models specify an AR1 disturbance.

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

(revised 1/2/15)

Regression discontinuity by varying subperiods

Model 1: State-specific CCD effects with state fixed effects

	State CCD effects					
Sub-period	**Negative**	**Sig. neg.**	**Positive**	**Sig. pos.**	**Sum across states**	**S.e. of sum**
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 trends pre- and post-CCD with fixed effects

	Pre-CCD trends by state				Post-CCD trends by state				Trends sig. dif. post-CCD	
Sub-period	**Sig. neg.**	**Sig. pos.**	**Sum across states**	**S.e. of sum**	**Sig. neg.**	**Sig. pos.**	**Sum across states**	**S.e. of sum**	**lower**	**higher**
1986-2013	29	2	-42.0	5.2	3	7	40.2	16.2	2	20
1990-2013	32	2	-41.3	6.3	3	11	40.1	15.5	2	19
2000-2013	15	6	-33.7	13.3	11	12	30.5	11.2	4	11

Model 3: State-specific trends pre- and post-CCD, with almond acres controls and fixed effects

	Pre-CCD trends by state				Post-CCD trends by state				Trends sig. dif. post-CCD	
Sub-period	**Sig. neg.**	**Sig. pos.**	**Sum across states**	**S.e. of sum**	**Sig. neg.**	**Sig. pos.**	**Sum across states**	**S.e. of sum**	**lower**	**higher**
1986-2013	23	1	-54.3	9.4	14	9	-3.5	34.2	8	10
1990-2013	27	2	-72.9	17.1	14	1	-44.5	44.3	8	6
2000-2013	9	5	-13.5	32.8	3	7	67.7	57.2	1	12

Notes:

Sample comprises the 39 states with complete colony time series over 1986-2013. Colonies are measured in thousands.

All coefficient estimates are GLS with an AR1 specification for the disturbances;
standard errors are corrected for contemporaneous correlations across states.

Hypothesis tests are reported at the 10% level with two-sided alternatives.

Table 3. Effects of CCD on U.S. Honey Production

(revised 1-24-15)

Regression discontinuity by varying subperiods

Honey production averages over sub-periods

	1986-2013		1990-2013		2000-2013	
Post-CCD	2007-2013	152.1	2007-2013	152.1	2007-2013	152.1
Pre-CCD	1986-2006	197.2	1990-2006	196.4	2000-2006	179.9
Difference		-45.1		-44.3		-27.8

Model 1: Honey regressions -- intercept and CCD dummy

	1986-2013		1990-2013		2000-2013	
	CCD effect	**t-ratio**	**CCD effect**	**t-ratio**	**CCD effect**	**t-ratio**
OLS	-45.1	-5.51	-44.3	-5.25	-27.8	-3.16
GLS	-38.2	-3.44	-34.9	-3.01	-27.8	-3.10

Model 2: Honey regressions -- trends before and after

	1986-2013					1990-2013					2000-2013				
	Trend before	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**	**Trend before**	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**	**Trend before**	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**
OLS	-2.2	-3.89	-4.7	-2.51	-1.15	-3.3	-5.22	-3.6	-2.17	-0.13	-7.3	-3.62	-1.4	-0.84	1.77
GLS	-2.1	-2.85	-4.5	-1.87	-0.83	-3.3	-4.66	-3.6	-1.99	-0.14	-7.0	-3.99	-1.5	-1.05	1.89

Model 3: Honey regressions -- trends before and after, with almond acres control

	1986-2013					1990-2013					2000-2013				
	Trend before	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**	**Trend before**	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**	**Trend before**	**t-ratio**	**Trend after**	**t-ratio**	**t for diff.**
OLS	0.9	0.75	6.7	1.51	1.61	0.3	0.13	5.8	1.03	1.42	-8.7	-1.65	-3.9	-0.43	0.88
GLS	0.9	0.64	6.5	1.33	1.42	0.4	0.17	6.0	1.01	1.37	-8.6	-1.87	-4.6	-0.57	0.83

Notes:

Production is measured in millions of pounds.

GLS models specify an AR1 disturbance.

Table 4. Effects of CCD on Honey Production - Panel Results from 39 States

(revised 3-11-15)

Regression discontinuity by varying subperiods

Model 1: State-specific CCD effects with state fixed effects

	State CCD Effects					
Sub-period	**Negative**	**Sig. neg.**	**Positive**	**Sig. pos.**	**Sum across states**	**S.e. of sum**
1986-2013	35	28	4	2	-43.1	9.2
1990-2013	34	28	5	3	-43.7	8.7
2000-2013	34	21	5	3	-27.7	8.1

Model 2: State-specific trends pre- and post-CCD with fixed effects

	Pre-CCD trends by state				Post-CCD trends by state				Trends sig. dif. post-CCD	
Sub-period	**Sig. neg.**	**Sig. pos.**	**Sum across states**	**S.e. of sum**	**Sig. neg.**	**Sig. pos.**	**Sum across states**	**S.e. of sum**	**lower**	**higher**
1986-2013	28	2	-2.14	0.61	11	1	-4.66	2.04	4	4
1990-2013	26	1	-3.38	0.59	13	1	-3.61	1.56	6	11
2000-2013	15	1	-6.95	1.73	14	4	-1.55	1.45	5	8

Model 3: State-specific trends pre- and post-CCD, with almond acres controls and fixed effects

	Pre-CCD trends by state				Post-CCD trends by state				Trends sig. dif. post-CCD	
Sub-period	**Sig. neg.**	**Sig. pos.**	**Sum across states**	**S.e. of sum**	**Sig. neg.**	**Sig. pos.**	**Sum across states**	**S.e. of sum**	**lower**	**higher**
1986-2013	15	7	0.92	1.16	8	8	6.78	4.29	7	6
1990-2013	13	5	0.09	2.03	8	2	5.50	5.29	5	7
2000-2013	5	3	-8.54	4.38	1	4	-4.88	7.73	0	9

Notes:

Sample comprises the 39 states with complete honey production time series over 1986-2013. Production is measured in millions of pounds.

All coefficient estimates are GLS with an AR1 specification for the disturbance; standard errors are adjusted for contemporaneous correlation across states.

Hypothesis tests reported at the 10% level with two-sided alternatives.

Table 5. Effects of CCD on Queen Bee Prices: (revised 3/3/15)

Regression discontinuity by varying subperiods

Queen price averages over sub-periods

	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

Model 1: Regressions of price on intercept and CCD dummy (5-seller averages)

	1980-2013 (n = 34)		1990-2013 (n = 24)		2000-2013 (n = 14)	
	CCD effect	t-ratio	CCD effect	t-ratio	CCD effect	t-ratio
OLS	*$2.83*	5.15	*$2.39*	4.03	*$1.45*	2.47
GLS	*$1.25*	1.65	*$1.59*	1.93	*$1.18*	1.51

Model 2: Controlling for linear effects of time and almond acres (5-seller averages)

	1980-2013 (n = 34)		1990-2013 (n = 24)		2000-2013 (n = 14)	
	CCD effect	t-ratio	CCD effect	t-ratio	CCD effect	t-ratio
OLS	*-$0.78*	-0.83	*-$1.17*	-1.34	*-$1.84*	-2.56
GLS	*-$0.65*	-0.77	*-$0.96*	-1.07	*-$2.20*	-5.15

Note: GLS estimates model the regression disturbance as an AR1.

Panel analysis of time series of queen prices from five sellers

Model 1: Regressions of price on CCD dummy with fixed seller effects

	1980-2013 (n = 157)		1990-2013 (n = 117)		2000-2013 (n = 68)	
	CCD effect	t-ratio	CCD effect	t-ratio	CCD effect	t-ratio
OLS	*$2.54*	8.67	*$2.10*	6.72	*$1.18*	3.41
GLS	*$1.36*	2.02	*$1.24*	1.99	*$0.57*	1.03

Model 2: Fixed seller effects and controlling for linear effects of time and almond acres

	1980-2013 (n = 157)		1990-2013 (n = 117)		2000-2013 (n = 68)	
	CCD effect	t-ratio	CCD effect	t-ratio	CCD effect	t-ratio
OLS	*-$0.81*	-1.79	*-$1.16*	-2.36	*-$1.76*	-3.43
GLS	*-$1.12*	-1.80	*-$1.02*	-1.67	*-$1.95*	-4.48

Note: GLS estimates model the regression disturbance with contemporaneous correlation across sellers and a time series AR1 component.

Table note: Advertised prices for queen bees in quantities of 100 or greater, in 2013 real prices, taken from March issues of the *American Bee Journal* .

Table 6. Effects of CCD on Package Bee Prices (revised 3/3/15)

Regression discontinuity by varying subperiods

Package price averages over sub-periods

	1980-2013		1990-2013		2000-2013	
Post-CCD	2007-2013	57.52	2007-2013	57.52	2007-2013	57.52
Pre-CCD	1980-2006	49.19	1990-2006	51.48	2000-2006	55.81
Difference		*$8.33*		*$6.04*		*$1.71*

Regression analysis of time series of average package price across five sellers

Model 1: Regressions of price on intercept and CCD dummy (5-seller averages)

	1980-2013 (n = 34)		1990-2013 (n = 24)		2000-2013 (n = 14)	
	CCD effect	t-ratio	CCD effect	t-ratio	CCD effect	t-ratio
OLS	*$8.33*	3.54	*$6.04*	2.42	*$1.71*	1.01
GLS	*$1.15*	0.42	*$2.66*	0.85	*$1.28*	0.58

Model 2: Controlling for linear effects of time and almond acres (5-seller averages)

	1980-2013 (n = 34)		1990-2013 (n = 24)		2000-2013 (n = 14)	
	CCD effect	t-ratio	CCD effect	t-ratio	CCD effect	t-ratio
OLS	*-$5.14*	-1.37	*-$5.18*	-1.45	*-$6.01*	-2.66
GLS	*-$3.49*	-1.15	*-$4.21*	-1.25	*-$6.65*	-3.75

Note: GLS estimates model the regression disturbance as an AR1.

Panel analysis of time series of package prices from five sellers

Model 1: Regressions of price on CCD dummy with fixed seller effects

	1980-2013 (n = 156)		1990-2013 (n = 116)		2000-2013 (n = 67)	
	CCD effect	t-ratio	CCD effect	t-ratio	CCD effect	t-ratio
OLS	*$7.67*	6.15	*$5.50*	4.24	*$1.39*	1.26
GLS	*$2.59*	1.12	*$3.71*	1.68	*$2.41*	1.58

Model 2: Fixed seller effects and controlling for linear effects of time and almond acres

	1980-2013 (n = 156)		1990-2013 (n = 116)		2000-2013 (n = 67)	
	CCD effect	t-ratio	CCD effect	t-ratio	CCD effect	t-ratio
OLS	*-$5.15*	-2.81	*-$5.25*	-2.65	*-$5.94*	-3.84
GLS	*-$6.02*	-2.03	*-$4.46*	-2.29	*-$6.71*	-6.36

Note: GLS estimates model the regression disturbance with contemporaneous correlation across sellers and a time series AR1 component.

Table note: Advertised prices for 3-pound packages of bees in quantities of 100 or greater, in 2013 real prices, taken from March issues of the *American Bee Journal* .

Table 7. Effects of CCD on Pollination Fees: A Pacific Northwest Panel of 11 Crops

(revised 4/2/15)

Fee averages over sub-periods

	1987-2013			2000-2013		
	Years	**Almonds**	**Other crops**	**Years**	**Almonds**	**Other crops**
Post-CCD	2007-2013	153.94	47.92	2007-2013	153.94	47.92
Pre-CCD	1987-2006	71.54	38.53	2000-2006	84.91	44.29
Difference		*$82.40*	*$9.39*		*$69.03*	*$3.63*

Regression analysis

Model 1: Regressions of price on CCD dummies with crop fixed effects

	1987-2013 (n = 276)		2000-2013 (n = 147)	
	CCD effect	**t-ratio**	**CCD effect**	**t-ratio**
Almonds	*$75.77*	13.83	*$64.69*	1.65
Other crops	*$6.16*	2.73	*$2.66*	1.39

Model 2: Fixed effects and controlling for linear effects of time and almond acres by crop

	1987-2013 (n = 276)		2000-2013 (n = 147)	
	CCD effect	**t-ratio**	**CCD effect**	**t-ratio**
Almonds	*$63.45*	6.13	*$62.02*	12.34
Other crops	*$1.97*	0.70	*$0.93*	0.56

Notes:

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, blueberries, cherries (not early), cranberries, crimson clover, cucumbers, pears, radishes, red clover, and squash

Table 8. Effects of CCD on Pollination Fees: A California Panel of 10 Crops (1996-2013)

(revised 6/22/15)

Fee averages over sub-periods

		Early Crops			
	Years	**Almonds**	**Plums**	**Cherries**	**Other crops**
Post-CCD	2007-2013	162.85	147.49	133.38	35.08
Pre-CCD	1996-2006	80.3	71.92	87.84	31.47
Difference		*$82.55*	*$75.57*	*$45.54*	*$3.61*

Regression analysis

Model 1: Regressions of price on CCD dummies with crop fixed effects

Early crops separate (n = 173)

		CCD effect	t-ratio
Early crops	**Almonds**	*$76.02*	8.52
Early crops	**Plums**	*$69.79*	13.32
Early crops	**Cherries**	*$41.58*	3.05
	Other	*$3.41*	3.85

Early crops merged (n = 173)

	CCD effect	t-ratio
Early	*$66.24*	13.16
Other	*$3.31*	3.74

H_o: Early crop effects are identical (p = 0.0001)

Model 2: Fixed effects and linear time and almond acre effects by crop

Early crops separate (n = 173)

		CCD effect	t-ratio
Early crops	**Almonds**	*$52.71*	3.97
Early crops	**Plums**	*$43.91*	6.52
Early crops	**Cherries**	*$25.98*	2.69
	Other	*$2.44*	1.22

Early crops merged (n = 173)

	CCD effect	t-ratio
Early	*$42.82*	6.39
Other	*$0.33*	0.32

H_o: Early crop effects are identical (p = 0.28)

Notes:

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

APPENDIX I - not for publication

Other Economic Series Potentially Affected by CCD

In this appendix, plots of several data series are presented and discussed. In the text, we discuss and analyze a number of market level factors that would most obviously be affected by CCD. These include colony numbers, honey production, queen and package prices and pollination fees. It is also conceivable that a number of other variables might be affected by CCD. A number of these are discussed below.

Almond production is heavily reliant on honey bee pollination. The pollination cost share for almonds is high relative to other crops, so any CCD-induced increase in almond pollination fees may result in an increase in almond prices. Figure AI-1 displays almond prices (in 2010 dollars) from 1919 - 2012. The vertical line (here and in the other figures presented below) is drawn between 2006 and 2007, so the data point just to the right of the line represents the first observation that might have been affected by the onset of CCD. As can be seen, the almond prices in figure AI-1 do not increase in 2007 or after.

If CCD adversely affected the number or health of honey bees, then both almond production and yields might be expected to fall. Figures AI-2 and AI-3 present almond production and yield data, and again it is clear that there is no drop in either of these in 2007 or after. Nor has there been a decline in almond acres, real revenue per acre of total real revenues, as evidenced by figure AI-4 - A1-6.

Another possibility is that the trip to pollinate almonds in California weakens bees and reduces their effectiveness as pollinators when they return to their home base. When bees travel from Washington and Oregon to California and then return home the first crops they pollinate include apples, pears, and cherries. If the trip to California weakens PNW bees then yields for these crops could be reduced. Figures AI-7 to AI-9 show yields for each of these three crops. As with the other series we examine here and in the text, there is no evidence of a sharp sustained drop in apple, cherry, or pear yields following the appearance of CCD.[1]

We conduct cursory statistical analyses of the impacts of CCD on each of the series plotted in this appendix. These efforts provide results consistent with the those reported for the series discussed in the text—there is no indication that CCD had a significant negative impact on any of the series discussed in this appendix.[2]

---

[1] Note that there is a fall in cherry yields following 2006. Note also, however, that (1) this drop appears large—at least in part—because of the unusually high yield for cherries in 2006 and (2) cherry yields returned to pre-2006 levels after 2008.

[2] These preliminary results are available from the authors on request.

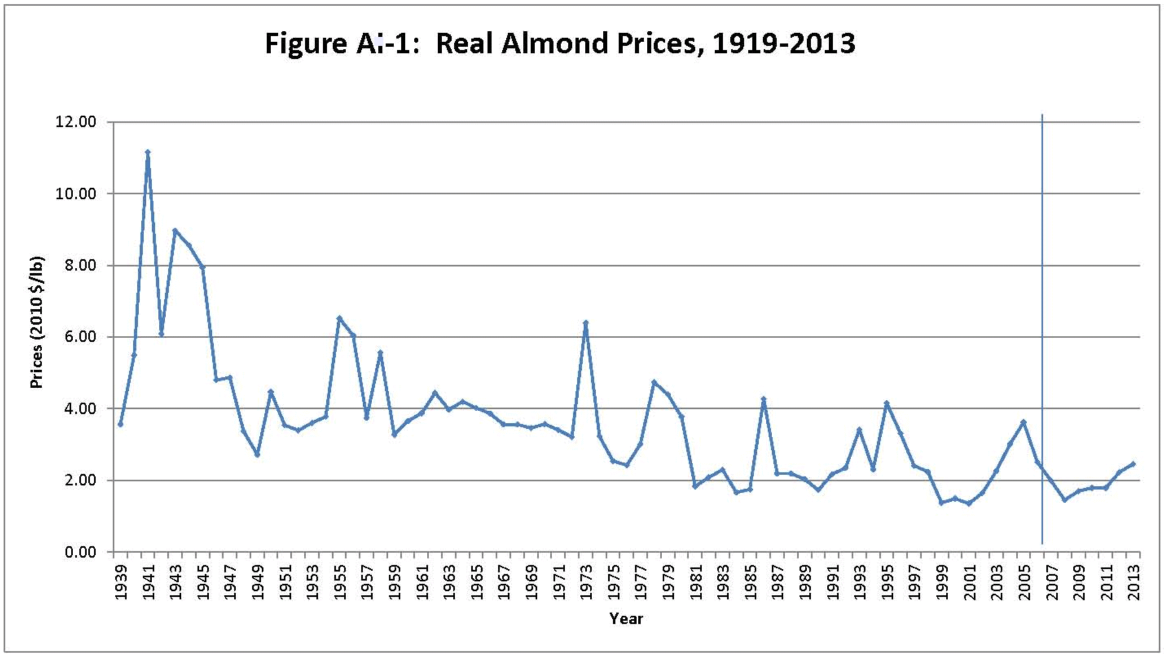


Figure AI-1: Real Almond Prices, 1919-2013

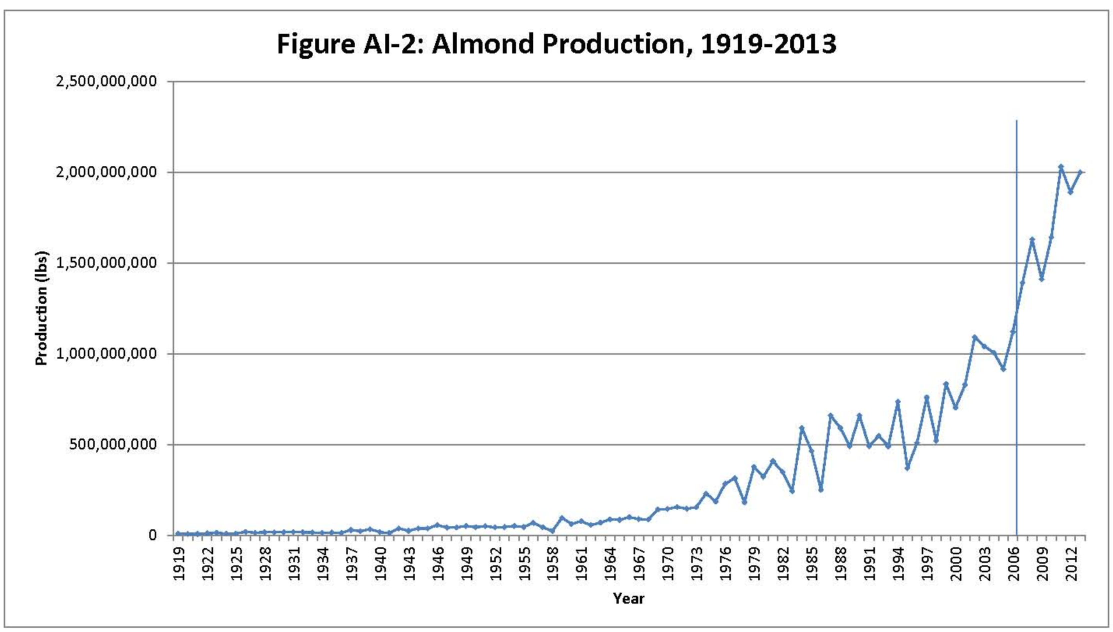


Figure AI-2: Almond Production, 1919-2013

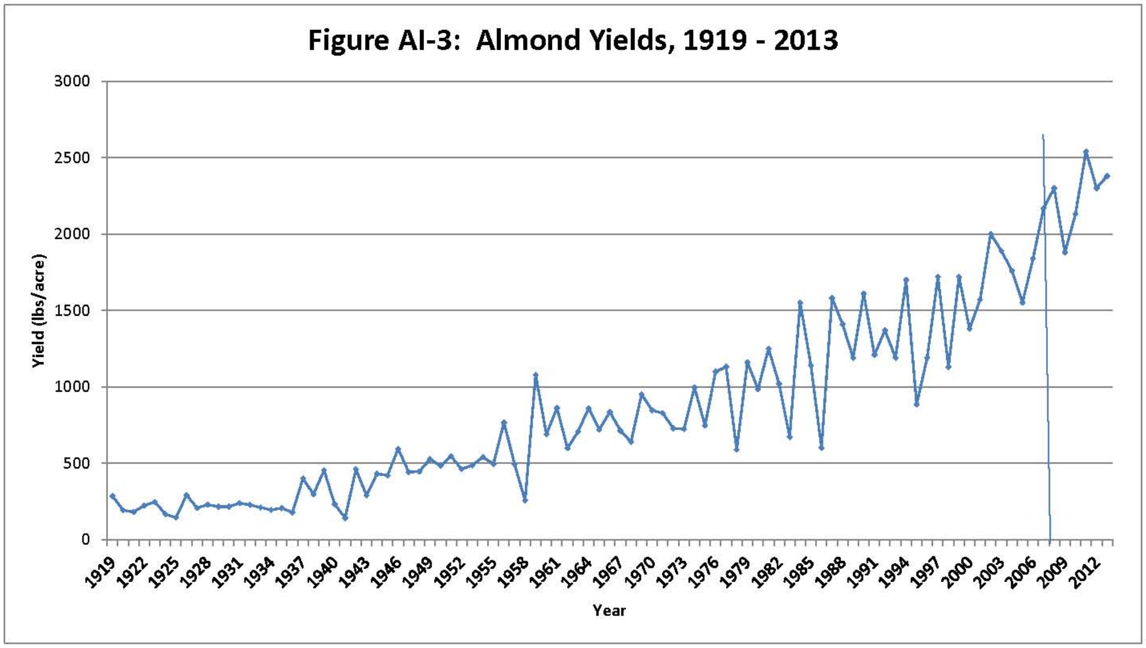


Figure AI-3: Almond Yields, 1919 - 2013
Yield (lbs/acre)
Year
3000
2500
2000
1500
1000
500
0
1919
1922
1925
1928
1931
1934
1937
1940
1943
1946
1949
1952
1955
1958
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003
2006
2009
2012

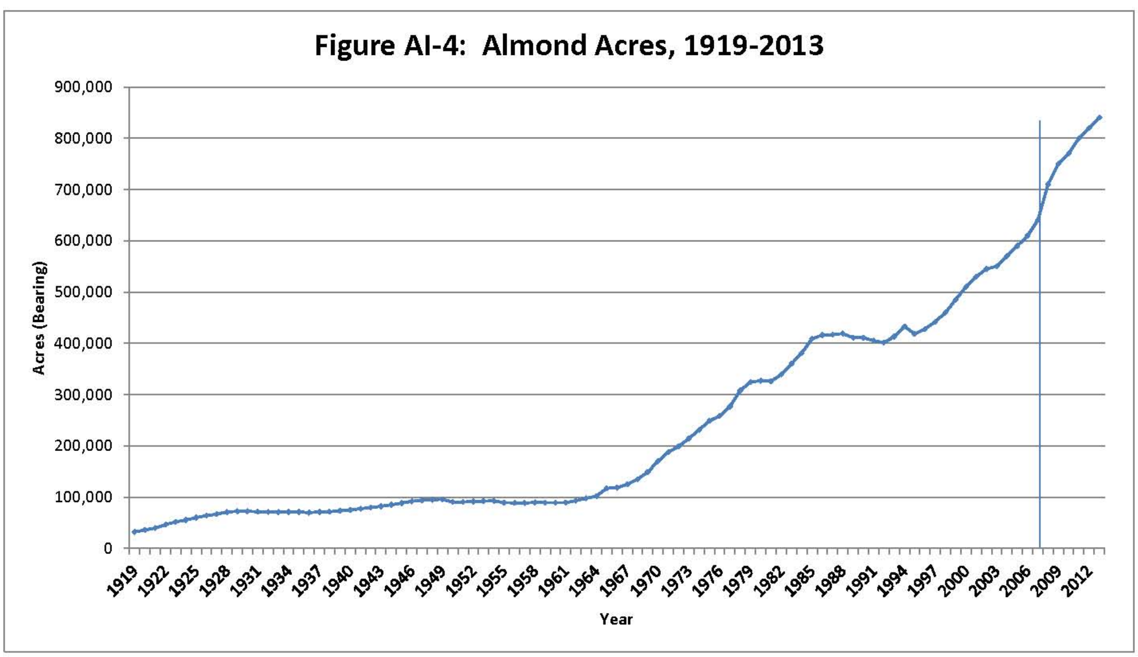


Figure AI-4: Almond Acres, 1919-2013
Acres (Bearing)
Year
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1919
1922
1925
1928
1931
1934
1937
1940
1943
1946
1949
1952
1955
1958
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003
2006
2009
2012

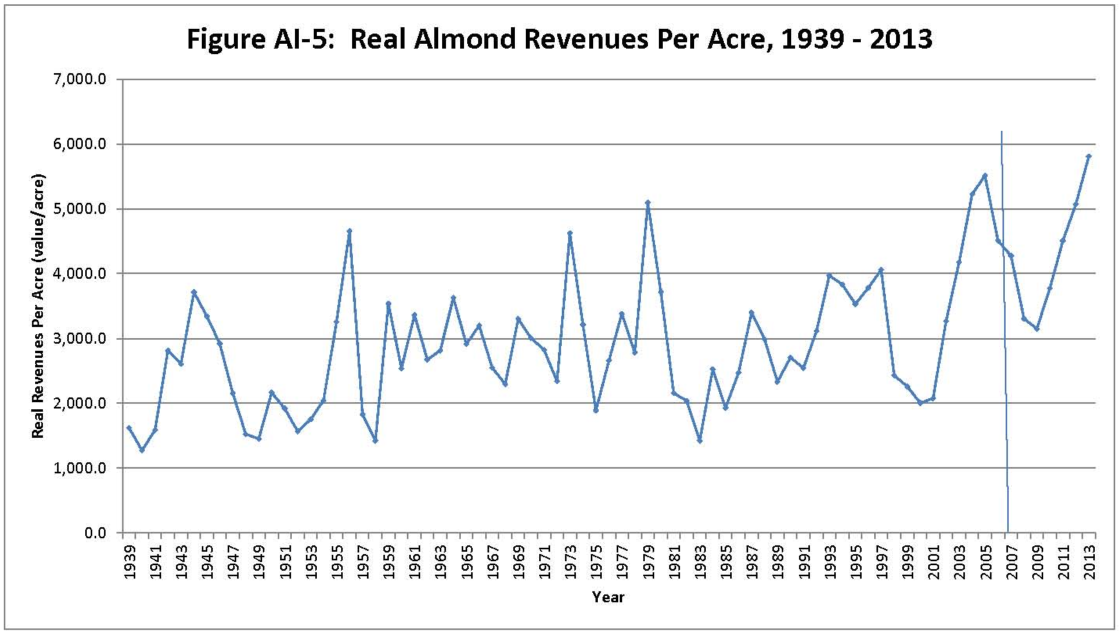


Figure AI-5: Real Almond Revenues Per Acre, 1939 - 2013
Real Revenues Per Acre (value/acre)
Year

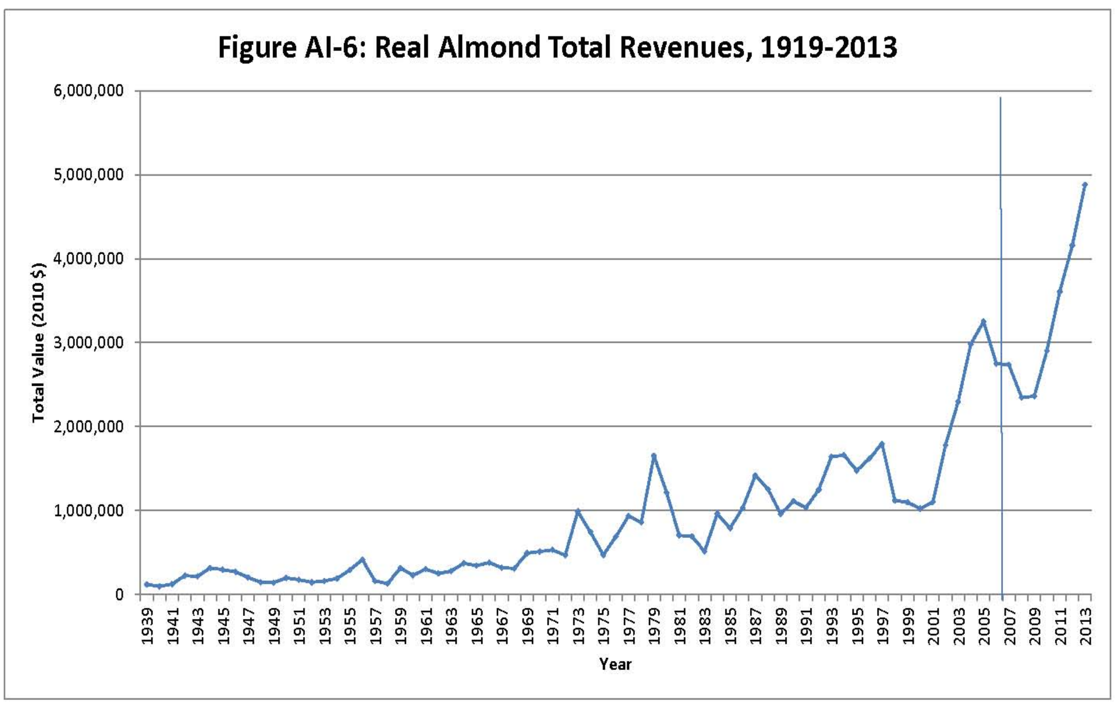


Figure AI-6: Real Almond Total Revenues, 1919-2013
Total Value (2010 $)
Year

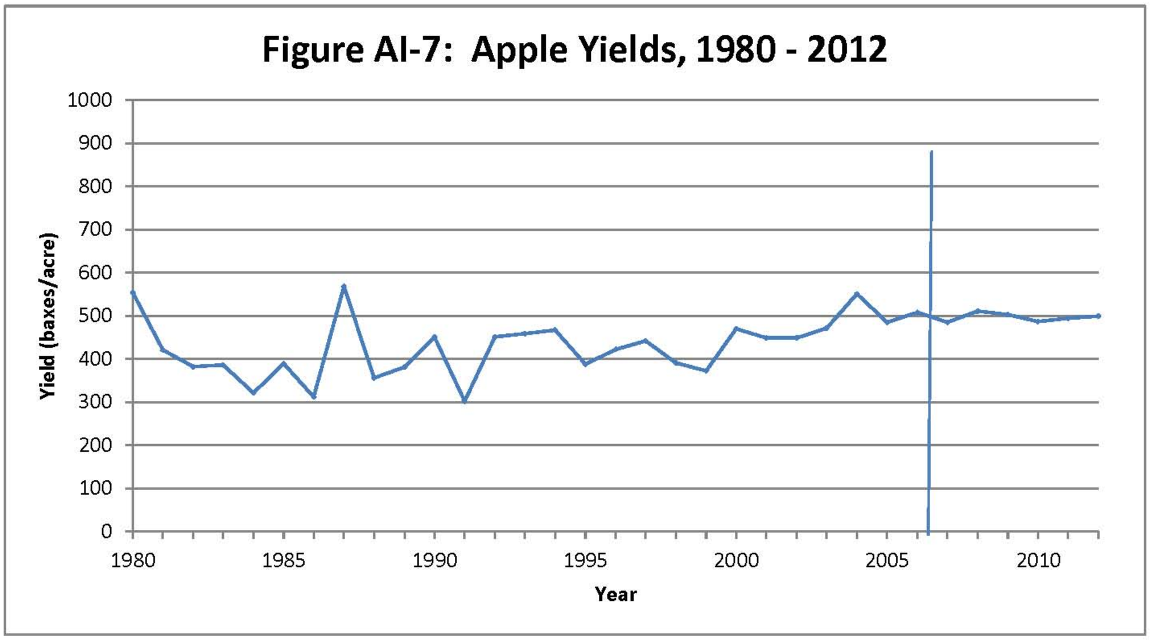


Figure AI-7: Apple Yields, 1980 - 2012
Yield (baxes/acre)
1000
900
800
700
600
500
400
300
200
100
0
1980
1985
1990
1995
2000
2005
2010
Year

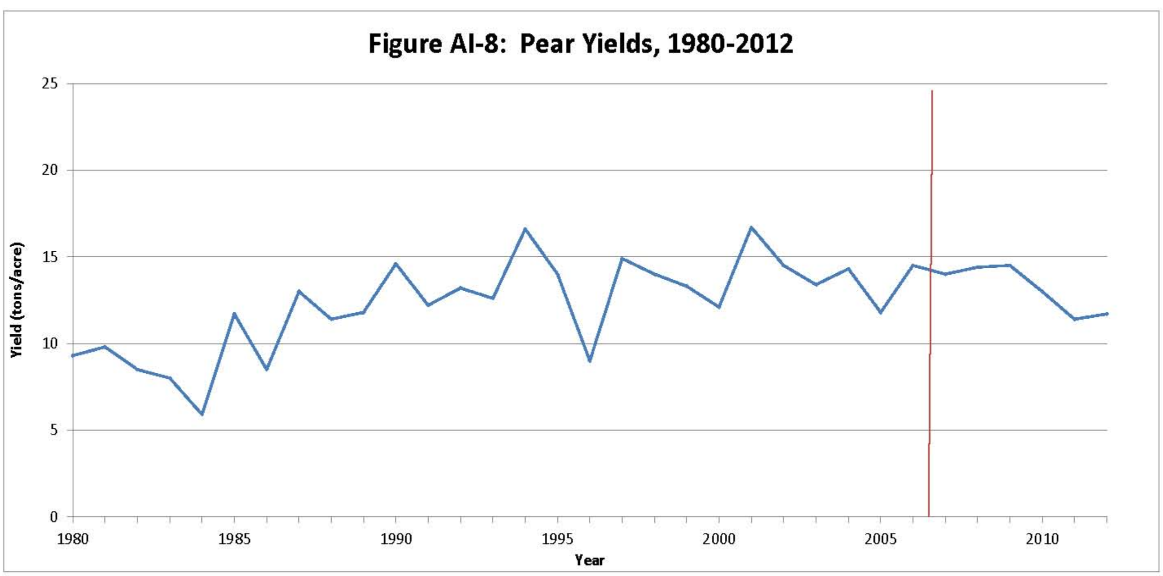


Figure AI-8: Pear Yields, 1980-2012
Yield (tons/acre)
25
20
15
10
5
0
1980
1985
1990
1995
2000
2005
2010
Year

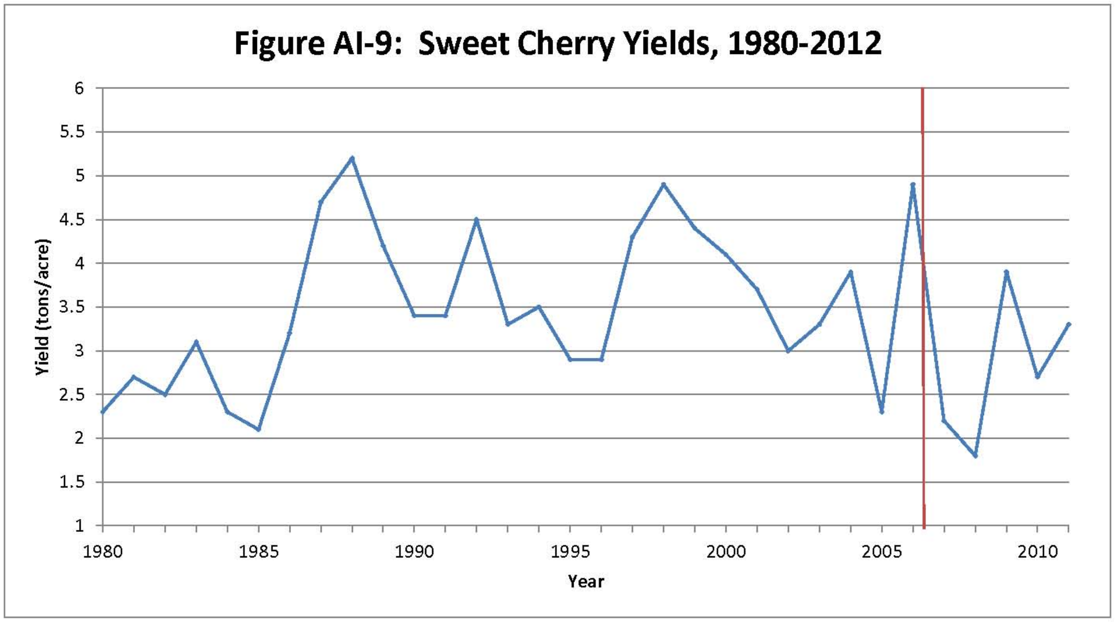


Figure AI-9: Sweet Cherry Yields, 1980-2012
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
Yield (tons/acre)
1980
1985
1990
1995
2000
2005
2010
Year

APPENDIX II - not for publication

Examining an Alternative Identification Strategy

To this point, we have identified the impacts of CCD with a simple zero-one dummy variable to distinguish between observations before and after the appearance of CCD in the winter of 2006/2007. In this appendix, we briefly examine an alternative approach that offers a better identification strategy, at least in principle. The results from this approach provide qualitatively similar conclusions regarding the economic impacts of CCD. As we discuss, however, the data we were able to obtain for this test have shortcomings. As a result, we do not undertake a full-scale analysis with them.

Since shortly after the winter of 2006/2007, annual surveys of beekeepers have been conducted for the purpose of gathering information on winter mortality rates. Annual publications have provided U.S. and state-level summary information.[1] One statistic reported each year has been the colony-weighted average of mortality rates across responding beekeepers in each state.[2] With the exception of the first year of the survey, the annual publications also report another statistic—the percentage of all colony mortalities in that year that "were lost without dead bees in the hive or apiary," which the authors interpret as measuring the mortality rate due to CCD. This measure is reported as a single aggregate number across all the survey respondents, and is not reported on a state-by-state basis. From these two statistics, we construct

[1]These reports are those by van Englesdorp et al. cited in the text in ***footnote 4.***

[2]The authors of the annual survey publications refer to this statistic as "Total Losses." The authors also report a statistic they refer to as "Average Losses," which appears to the simple average of mortality rates across responding beekeepers in each state. The value of this statistic is typically greater than the value of Total Losses, which reflects the fact that the mortality rate of small (non-commercial) beekeepers is higher than the mortality rate of larger (commercial) beekeepers.

the variable **Losses From CCD** as the product of the colony-weighted average loss rate (which is a percentage) for a given state and year, multiplied by the aggregate U.S. percentage of colonies lost with no dead bees present. This variable varies from state to state in a given year, with the interstate variation within a year resulting solely from variation in the average loss rate across states.[3] The value of this variable, which we express as a percentage, differs from year to year for a given state, both because the annual estimates of state-level average losses vary and because the estimate of the aggregate loss rate due to CCD varies from year to year.

Given these caveats, the **Losses From CCD** variable nonetheless provides a measure of the incidence of CCD with more variation than the simple zero-one CCD dummy variable used in portions of our analysis discussed in the text. As such, it has the potential to provide insights into a possible source of interstate differences in the time paths of colony numbers. Accordingly, we estimate several preliminary regressions to determine whether our results regarding the economic impacts of CCD are altered if we use this measure of the incidence of CCD.

Tables AII-1, AII-2, and AII-3 display results from series of regressions that are analogous to the regression results reported in tables 1 and 2 in the text. Table AII-1 presents regression results for aggregate U.S. colony numbers.[4] The two regressions in model 1 have only

---

[3]Although there may be considerable variation across states in the reported percentage of colonies lost due to CCD, our requests to obtain the data necessary to determine and account for this variation were stonewalled by the principal investigator on the federally funded project under which the annual surveys are conducted.

[4]As mentioned above, no information for 2007 is available on the percentage of colonies lost without dead bees in the hive or apiary. For the results presented in this appendix, we use the average of this percentage from the other post-2006 years in our data (0.4214) as our estimate of the 2007 value. We justify this choice by the fact that when we regress this percentage on a trend variable, the estimated coefficient is not significantly different from zero. Our qualitative conclusions are not affected if we simply exclude 2007 from our analysis.

an intercept and the **Losses From CCD** as right hand side variables. Although, the OLS specification indicates a negative and statistically significant impact of the variable of interest on colony numbers, when the regression error is modeled as an AR(1) process, the significance of this effect disappears.[5] The regression results reported in models 2 and 3 add first, a trend variable, and then almond acres. In none of the four regression results displayed for these two models is the estimated coefficient on the **Losses From CD** variable negative and significant.

Response to the annual surveys has varied over time, with the number of responses from beekeepers—as well as both the number of colonies managed by the respondents and the number of states represented by those beekeepers—generally increasing over time. For the first year of the survey, the beekeeper responses needed to determine state-level average losses were only reported for ten states. For these ten states, the surveys have yielded average loss estimates for all seven years of the survey. There are 18 states for which there are six or seven annual estimates of these losses.

Table AII-2 displays colony numbers regression results using data for the ten states for which there are average loss estimates for all seven years of the annual survey. In this table, the annual state-level observations are treated as a panel. Again, both OLS and GLS estimates are reported. As can be seen, in models 1 and 2, the estimated coefficient on the **Losses From CCD** variable is insignificant in all specifications. In model 3, the estimated coefficient in the OLS regression is negative and marginally significant, but when an AR(1) error is specified, the estimated coefficient becomes insignificant. Table AII-3 reports results from a panel regression

[5] The AR(1) coefficient in this specification (and in most of the other specifications discussed below) is highly significant (e.g., it has a t-value of 7.5 in the model 1 specification).

analysis using the 18 states that report average losses for either six or seven years. Again, when the autoregressive structure of the error term is estimated, there is no evidence that an increase in our measure of the annual state level losses from CCD had a negative and significant impact on colony numbers.[6]

It is possible that mortality rates increased after 2006 because of factors other than CCD and that total mortality rates affect colony numbers. To examine this possibility we estimate regression specifications that include a measure of the total colony losses (following 2006) from all sources in place of the **Losses From CCD** variable discussed above. As we mention in the text, the average winter mortality rate prior to the appearance of CCD was about 15 percent. The measure we use for the increase in mortality from all sources since the winter of 2006/2007 is thus the average annual loss rate reported in each state since 2006 minus 15 percent. We name this variable **Adjusted Loss** and include it as a right hand side variable in place of the **Losses From CCD** variable used above.

Table AII-4 displays results from models similar to those in tables AII-1 - AII-3 above using a panel of the 18 states with estimates of these losses for six or seven years. As can be seen, although the estimated coefficients on the variable of interest (**Adjusted Loss**) is negative and significant in two of the three OLS specifications, when the error term is modeled as an AR(1), the estimated coefficient on the variable becomes indistinguishable from zero. The

---

[6]We also estimate separate regressions for each of the 18 states with six or seven observations on **Losses From CCD** using the specifications in tables AII-1 - AII-3. There are very few instances where the estimated impacts of an increase in the losses from CCD have negative and significant impacts on colony numbers (in the 54 GLS specifications estimated for models 1 - 3, there are only three instances where the estimated coefficient on **Losses From CCD** is significant at the 0.05 level, and two of those coefficients are positive).

results in table AII-4 do not support an argument that pollinator health issues defined more broadly than CCD have resulted in reductions in colony numbers.

Given that (1) we do not have estimates of losses from CCD annually by state, and (2) the preliminary regression results reported above provide no indication that this alternative identification strategy yields results different from those discussed in the text, we do not investigate this approach further.

TABLE AII-1. MODEL 1: U.S. COLONY NUMBER REGRESSIONS, 1986-2013

OLS WITH LOSS_FROM_CCD ONLY.

Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Approx Pr > |t|
Intercept	1	2790	58.96	46.54	<.0001
LOSS_FROM_CCD	1	-17.99	8.12	-2.22	0.036

Estimates of Autoregressive Parameters

Lag	Coefficient	Standard Error	t Value
1	-0.8324	0.111	-7.51

GLS WITH AR(1) TERM. LOSS_FROM_CCD ONLY.

The AUTOREG Procedure
Yule-Walker Estimates

Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Approx Pr > |t|
Intercept	1	2782	116.09	23.97	<.0001
LOSS_FROM_CCD	1	-0.52	5.66	-0.09	0.927

TABLE AII-1. MODEL 2: U.S. COLONY NUMBER REGRESSIONS, 1986-2013

OLS WITH LOSS_FROM_CCD & TREND.

The AUTOREG Procedure

Dependent Variable COL_NUM_1000

Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Approx Pr > |t|
Intercept	1	3213	66.95	47.99	<.0001
TREND	1	-36.20	4.94	-7.33	<.0001
LOSS_FROM_CCD	1	12.02	6.21	1.94	0.06

Estimates of Autoregressive Parameters

Lag	Coefficient	Standard Error	t Value
1	-0.697	0.146	-4.76

GLS WITH AR(1) TERM. LOSS_FROM_CCD & TREND.

The AUTOREG Procedure

Yule-Walker Estimates

Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Approx Pr > |t|
Intercept	1	3163	115.2518	27.44	<.0001
TREND	1	-29.5017	7.2118	-4.09	0.0004
LOSS_FROM_CCD	1	5.2686	5.5078	0.96	0.3483

TABLE AII-1. MODEL 3: U.S. COLONY NUMBER REGRESSIONS, 1986-2013

OLS WITH LOSS_FROM_CCD, TREND, & ALMOND_ACRES.

The AUTOREG Procedure

Dependent Variable COL_NUM_1000

Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Approx Pr > |t|
Intercept	1	2361	168.2734	14.03	<.0001
TREND	1	-70.8268	7.4136	-9.55	<.0001
ALM_ACRES_1000	1	2.5928	0.4920	5.27	<.0001
LOSS_FROM_CCD	1	-3.5152	5.2235	-0.67	0.5074

Estimates of Autoregressive Parameters

Lag	Coefficient	Standard Error	t Value
1	-0.352207	0.195153	-1.80

Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Approx Pr > |t|
Intercept	1	2459	210.7294	11.67	<.0001
TREND	1	-65.6171	9.6981	-6.77	<.0001
ALM_ACRES_1000	1	2.2548	0.6166	3.66	0.0013
LOSS_FROM_CCD	1	-0.5986	5.6530	-0.11	0.9166

TABLE AII-2, MODEL 1: PANEL COLONY NUMBER REGRESSIONS, 1986-2013

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD
10 STATES WITH 7 OBSERVATIONS

The PANEL Procedure
Fixed One Way Estimates

Dependent Variable: COLONY_NUMBERS

Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Pr > |t|	Label
Intercept	1	11004.37	6471.1	1.70	0.0902	Intercept
LOSS_FROM_CCD	1	102.0883	282.1	0.36	0.7178	

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD & AR(1) ERROR
10 STATES WITH 7 OBSERVATIONS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
INTERCEPT	1	-3224.73900	36608	-0.09	0.9299
LOSS_FROM_CCD	1	51.48663	171.41392	0.30	0.7641
AR(1)		0.923	0.027	33.92	0.000

TABLE AII-2, MODEL 2: PANEL COLONY NUMBER REGRESSIONS, 1986-2013

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD & TREND
10 STATES WITH 7 OBSERVATIONS

The PANEL Procedure
Fixed One Way Estimates

Dependent Variable: COLONY_NUMBERS

Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Pr > |t|	Label
Intercept	1	10896.86	7648.3	1.42	0.1554	Intercept
TREND	1	8.555327	322.9	0.03	0.9789	
LOSS_FROM_CCD	1	96.0858	362.2	0.27	0.7910	

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD, TREND & AR(1) ERROR
10 STATES WITH 7 OBSERVATIONS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
INTERCEPT	1	-80252	54140	-1.48	0.1395
LOSS_FROM_CCD	1	-2.86691	172.86086	-0.02	0.9868
TREND	1	2874.35143	1495.36991	1.92	0.0557
AR(1)		0.923	0.027	33.92	0.000

TABLE AII-2, MODEL 3: PANEL COLONY NUMBER REGRESSIONS, 1986-2013

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD, TREND, & ALMOND ACRES
10 STATES WITH 7 OBSERVATIONS

The PANEL Procedure
Fixed One Way Estimates

Dependent Variable: COLONY_NUMBERS

Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Pr > |t|	Label
Intercept	1	-44304.4	16529.3	-2.68	0.0078	Intercept
TREND	1	-2334.36	700.8	-3.33	0.0010	
ALM_ACRES_1000	1	168.2858	44.9531	3.74	0.0002	
LOSS_FROM_CCD	1	-682.429	410.4	-1.66	0.0975	

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD, TREND & AR(1) ERROR
10 STATES WITH 7 OBSERVATIONS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
INTERCEPT	1	-65705	47466	-1.38	0.1675
LOSS_FROM_CCD	1	-2.53231	174.99646	-0.01	0.9885
TREND	1	2514.96687	2777.92568	0.91	0.3661
ALM_ACRES_1000	1	0.72996	75.30132	0.01	0.9923
AR(1)		0.913	0.029	31.83	0.000

TABLE AII-3, MODEL 1: PANEL COLONY NUMBER REGRESSIONS, 1986-2013

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD
18 STATES WITH 6 OR 7 OBSERVATIONS

The PANEL Procedure
Fixed One Way Estimates

Dependent Variable: COLONY_NUMBERS

Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Pr > |t|	Label
Intercept	1	78923.63	5958.6	13.25	<.0001	Intercept
LOSS_FROM_CCD	1	-380.72	197.1	-1.93	0.0539	

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD & AR(1) ERROR
18 STATES WITH 6 OR 7 OBSERVATIONS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
INTERCEPT	1	72516	24593	2.95	0.0034
LOSS_FROM_CCD	1	111.93221	161.61091	0.69	0.4889
AR(1)		0.873	0.025	35.44	0.000

TABLE AII-3, MODEL 2: PANEL COLONY NUMBER REGRESSIONS, 1986-2013

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD & TREND
18 STATES WITH 6 OR 7 OBSERVATIONS

The PANEL Procedure
Fixed One Way Estimates

Dependent Variable: COLONY_NUMBERS

Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Pr > |t|	Label
Intercept	1	85724.93	6447.4	13.30	<.0001	Intercept
TREND	1	-581.899	218.4	-2.66	0.0080	
LOSS_FROM_CCD	1	41.06126	251.8	0.16	0.8705	

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD, TREND & AR(1) ERROR
18 STATES WITH 6 OR 7 OBSERVATIONS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
INTERCEPT	1	63632	29770	2.14	0.0331
LOSS_FROM_CCD	1	95.30409	164.43949	0.58	0.5625
TREND	1	411.12521	754.73191	0.54	0.5862
AR(1)		0.875	0.025	35.56	0.000

TABLE AII-3, MODEL 3: PANEL COLONY NUMBER REGRESSIONS, 1986-2013

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD, TREND, & ALMOND ACRES
18 STATES WITH 6 OR 7 OBSERVATIONS

The PANEL Procedure
Fixed One Way Estimates

Dependent Variable: COLONY_NUMBERS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	49866	12053	4.14	<.0001
LOSS_FROM_CCD	1	-526.72982	296.92420	-1.77	0.0767
TREND	1	-2091.16289	481.65166	-4.34	<.0001
ALM_ACRES_1000	1	110.02792	31.39141	3.51	0.0005

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD, TREND & AR(1) ERROR
18 STATES WITH 6 OR 7 OBSERVATIONS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
INTERCEPT	1	65773	28270	2.33	0.0204
LOSS_FROM_CCD	1	97.93634	166.40758	0.59	0.5565
TREND	1	385.40392	1802.16590	0.21	0.8308
ALM_ACRES_1000	1	-1.65175	64.00140	-0.03	0.9794
AR(1)		0.867	0.025	34.27	0.000

TABLE AII-4, MODEL 1: PANEL COLONY NUMBER REGRESSIONS, 1986-2013

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD
18 STATES WITH 6 OR 7 OBSERVATIONS

The PANEL Procedure
Fixed One Way Estimates

Dependent Variable: COLONY_NUMBERS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	76379	5948.91876	12.84	<.0001
ADJUSTED_LOSS	1	-176.93936	89.18621	-1.98	0.0478

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD & AR(1) ERROR
18 STATES WITH 6 OR 7 OBSERVATIONS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
INTERCEPT	1	73144	24530	2.98	0.0030
ADJUSTED_LOSS	1	50.93066	79.31337	0.64	0.5211
AR(1)		0.872	0.025	35.47	0.000

TABLE AII-4, MODEL 2: PANEL COLONY NUMBER REGRESSIONS, 1986-2013

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD & TREND
18 STATES WITH 6 OR 7 OBSERVATIONS

The PANEL Procedure
Fixed One Way Estimates

Dependent Variable: COLONY_NUMBERS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	86519	7049.57180	12.27	<.0001
ADJUSTED_LOSS	1	38.28835	120.40986	0.32	0.7506
TREND	1	-609.16444	230.67990	-2.64	0.0085

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD, TREND & AR(1) ERROR
18 STATES WITH 6 OR 7 OBSERVATIONS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
INTERCEPT	1	64064	29894	2.14	0.0326
ADJUSTED_LOSS	1	42.36892	80.86346	0.52	0.6006
TREND	1	414.60552	756.10470	0.55	0.5837
AR(1)		0.875	0.025	35.56	0.000

TABLE AII-4, MODEL 3: PANEL COLONY NUMBER REGRESSIONS, 1986-2013

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD, TREND, & ALMOND ACRES
18 STATES WITH 6 OR 7 OBSERVATIONS

The PANEL Procedure
Fixed One Way Estimates

Dependent Variable: COLONY_NUMBERS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	38501	14736	2.61	0.0093
ADJUSTED_LOSS	1	-332.71609	155.55093	-2.14	0.0329
TREND	1	-2229.07470	493.83789	-4.51	<.0001
ALM_ACRES_1000	1	127.10023	34.38375	3.70	0.0002

1-WAY FIXED EFFECT PANEL MODELS WITH LOSS_FROM_CCD, TREND & AR(1) ERROR
18 STATES WITH 6 OR 7 OBSERVATIONS

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
INTERCEPT	1	66715	27567	2.42	0.0159
ADJUSTED_LOSS	1	43.02732	81.46473	0.53	0.5976
TREND	1	225.03208	1765.20865	0.13	0.8986
ALM_ACRES_1000	1	3.46064	63.22077	0.05	0.9564
AR(1)		0.862	0.026	33.74	0.000