The Dynamics of Pollination Markets

Antoine Champetier

University of California, Davis, Agricultural Issues Center

antoine@primal.ucdavis.edu

Selected Paper prepared for presentation at the Agricultural & Applied Economics Association 2010 AAEA,CAES, & WAEA Joint Annual Meeting, Denver, Colorado, July 25-27, 2010

1 Introduction

Domesticated honey bees are livestock and like other species of domesticated animals, their breeding, feeding, and roaming are for the most part controlled by man. As a result, understanding and predicting the impacts of economic and biological changes on the abundance of these pollinators and the services they provide hinges on understanding and predicting the behavior of their keepers. This chapter provides an important extension to the very small literature on the economics of pollination by presenting a model of the economics of beekeeping which incorporates the seasonal variations of honey bee population.

The discussions and implementations of policies on domesticated pollinators in the last half century have often overlooked the importance of the economic behavior of beekeepers. For instance, U.S. honey subsidy programs have in the past been publicly supported on the basis that they encourage pollination of crops and increase social welfare by correcting the externality suggested by Meade (Muth et al. (2003)). Cheung (1973), who argued that the existence of pollination markets solved the externality problem did not succeed in dethroning Meade's argument, at least in the public discourse.[1]

Another example of the lack of analysis of the economic behavior of beekeepers can be found in recent discussions over pollinator declines. The increase in pest and parasite pressure on bee health and the rise in the frequency of colony losses during winter have been designated as the main drivers of a decline in the number of honey producing colonies in the United States, as counted and published in USDA's Honey reports. Although it is clear that biological factors have a large

[1] Muth et al. (2003) analyze the political economy of the honey program but do not articulate the relations between economists's arguments, public discourse, and the equilibrium of the political market.

influence on the economic behavior of beekeepers, the attribution of the causes of declines cannot be safely undertaken without a close look at such behavior. Indeed, shifts in the demand for honey or pollination services alone could explain the observed changes in hive numbers. In addition, biological drivers are not simply exogenous shocks to production costs of beekeeping since the practices in the industry determine to a large extent the spread and damage caused by parasites and other pests.

The little attention paid to the economic nature of modern beekeeping, in academic and policy discussions at least, has resulted in an incorrect interpretation of the data available on colony numbers.[2] The decline in the number of honey bee colonies counted by the USDA and published in the Honey reports have been the main evidence used to support the idea that pollination services have become scarcer in the last few decades. Figure 1 presents these hive counts from 1986 to 2009 along with the ones reported by the U.S. Census of Agriculture.

The hive counts provided by Honey reports and the Census of Agriculture provide conflicting pictures of the evolution of hive numbers in the last two decades. The USDA only counts hives that produce honey but these hives can be counted multiple times if they produce honey in different states. In contrast, the Census of Agriculture counts hives only once and whether or not they produce honey. As a result, although the number of hives declined in the late 80's after the spread of Varroa and tracheal mites according to both sources, only the figures from the Census of Agriculture show an increase between 2002 and 2007. The most notable change for the beekeeping industry during that period was the drastic rise

[2] Variations in the size of colonies can be large and therefore, colony counts do not necessarily provide an accurate measure of honey bee abundance. Recall also that hive generally refers to the wooden box whether colony refers to the group of bees that live in it.

in demand for pollination services in almonds which has driven national averages of pollination revenues to record highs.

Figure 2 shows pollination and honey revenues per hive as well as the sum of the two revenues from 1992 to 2009. The honey revenue per hive does not show any obvious trend because neither honey yields nor honey prices have varied in magnitudes comparable to those of pollination revenues in recent years. The pollination revenue has in contrast increased markedly between 2004 and 2009 following the increase in pollination services for almonds in California. The supply response of beekeepers to the almond rush is only visible in the Census data. It seems that Honey report data, which counts are based on honey production only, provide an increasingly incomplete picture of the beekeeping industry as the share of pollination revenues in beekeeping continue to increase. Unfortunately, the decline in the number of hive counts alone has received public attention in recent years.

As of today, the patterns of pollination fees, honey prices and hive counts from both data sources remain for the most part unexplained. The hypotheses that have been put forward to explain changes in honey bee population have hardly been tested empirically. A better understanding of the economic behavior of beekeepers is necessary not only to predict but also to measure changes in the scarcity of honey bees and of their services in the first place, as illustrated by the discrepancy between data sources for hive counts. Econometric analysis awaits further research and data collection. This chapter presents an economic model of beekeeper behavior which captures the most salient trade-offs between the production of honey and the production pollination services. This modeling represents a first step towards both interpreting current patterns in prices and quantities of pollination services and identifying further data collection requirements.

The jointness of production of honey and pollination services is the most important feature of the economics of beekeeping. Meade (1952) was one of the first to model the jointness of production but Cheung (1973) was the first to provide an empirical analysis of how pollination markets dealt with jointness of production. Muth et al. (2003) and Rucker, Thurman, and Burgett (2008) have since developed the analysis proposed by Cheung (1973). They find that bee wages, which are defined as the value of the marginal products of honey and crops (through pollination services), are paid to beekeepers in pollination fees and honey revenue. Because hives can be easily transported and because there are many participants on both sides of the market, competition between growers and between beekeepers ensures that all bees are paid at the value of their total marginal product. The most important prediction of this literature, and one which seems consistent with observation, is that pollination fees vary inversely with the amount of honey that can be produced from the pollinated crop. Only when a crop does not provide resources for bees to make honey, as with almonds, are pollination fees equal to the bee wage.[3] Conversely, when honey bee pollination does not increase the revenue of from crop production, as often in citrus, the bee wage is equal to the value of the marginal product of honey. In citrus, beekeepers who keep the entire honey output pay a fee to growers which is equal to the value of the marginal product of citrus blossoms in the production of honey.

[3]The extraction of honey from hives is typically done by beekeepers. The monitoring of honey production is therefore costly, which makes it difficult for growers to keep both crop and honey products and pay the entire bee wage to beekeepers.

A second aspect of beekeeping which in contrast, has been not been addressed before in the economics literature, relates to the dynamic nature of the bee stock and its yearly variations. The same hives are used to pollinate and extract honey from several crops in the same year following the bloom sequence of the crops. Throughout the year, the population of bees in hives varies according in particular to the quality and quantity of forage that the crops they are placed on provide. The hauling of hives not only allows competition for bees across crops growers whose crops bloom at the same time but it also enables migratory beekeepers to capture the returns from using the same hives for several crops.

Although Cheung (1973) does provide some intuition regarding the consequences of migration, the importance of the dynamics of the stock of bees has been generally overlooked.[4] Sumner and Boriss (2006) provide some analysis of the effects of seasonality on pollination fees and argue that the increase in demand for pollination services for almonds can explain the increase in fees for crops such as plums, which are also pollinated during early spring.

The importance of seasonality is illustrated in figure 3 which shows pollination fees for representative crops from 1995 to 2009. Figure 3 is based on the same survey data as Sumner and Boriss (2006). Cherries provide a clear illustration of the fact that the jointness of production of pollination services and honey as described by Cheung (1973) and Muth et al. (2003) is not sufficient to explain some patterns of pollination fees. Indeed, the pollination fees for varieties of cherries blooming at the same time as almonds have increased drastically since 2004 whereas the fees for varieties blooming later have not (see figure 3).

[4]Cheung (1973) shows that the sum of the rents collected by a hive during a year across different crops equals the cost of producing the hive. He also controls for seasonality when comparing pollination fees and hive rents across crops.

This chapter shows that taking into account the dynamics of the stock of bees results in an economic model of pollination fees that fits observed data better than static models. According to this view, the pollination markets brought forward by Cheung may be solving the problems generated by the dynamics of the stock of bees in addition to the problem of jointness of production of honey and pollination services.

Section 2 develops a dynamic model of the bee population and the honey stock in a hive. which identifies the trade off that exists between pollination services and honey production. I derive the yearly variations of both the number of bees and the honey stored in the hive and show how the price of honey and pollination fees determine the optimal yearly cycle. The model can be extended to include two or more crops in the bloom season.

Because this dynamic model does not have a closed form solution, appendix 7 presents a seasonal model of pollination market equilibrium in which the stock of bees is simply kept constant throughout the year. This simplification allows the derivation of analytical solutions for the effects of changes in crop acreage, honey prices, and beekeeping costs on pollination fees in a market with multiple crops and bloom periods. An increase in the acreage of one crop always results in an increase in bee wages for all crops blooming at the same time of year and a decrease in bee wages for other blooming periods. An increase in the cost of beekeeping results in an increase of the wage of bees for all seasons and all crops. In contrast, changes in honey prices have ambiguous effects on the wages of bees for a given crop.

2 A dynamic model of honey bee population and honey stock

2.1 Model

This section presents a stylized model of the dynamics of bees and honey in a hive. The solution of this model is a production possibility frontier for honey and pollination service output. The model focuses on the dynamics of the bee and honey stocks within a single year and does not deal with multiple years. It describes how the optimal yearly cycle of bees and honey varies according to the relative prices of honey and pollination services. These prices are exogenous. This is a model of the behavior of a representative beekeeper who repeats an optimal cycle over the years without addressing how she might reach that cyclic equilibrium.

The population of domestic honey bees in a hive can vary from a couple of thousand individuals at the end of winter to several tens of thousands during summer. Although beekeeping practices such as adding or removing bees from hives are common, the most crucial decision of the beekeeper is the schedule of migration of hives and their allocation among different crops. Crops differ in the timing of their bloom, the fees crop growers are willing to pay for the pollination services of bees, and the amount and quality of nectar and pollen that crops provide to bees as food. The revenues of beekeepers come for the most part from the sales of honey and the fees for pollination services.The costs of beekeeping include the cost of equipment and inputs such as empty hives, smokers, and parasite treatments but labor and fuel represent the bulk of costs. For instance, Hoff and Willett (1994) reports that in 1988, labor represented about 30% of costs, fuel and repairs 14%, and overhead 17%. In addition, beekeepers sometimes have to pay location fees although these tend to be relatively small.

I first develop a model for a single crop and identify the nature of the trade-off between honey and pollination services before showing how my model can be extended to deal with multiple crops. Appendix 7 presents a model of pollination market equilibrium where pollination fees are endogenous and allowed to vary.

In the model, the year is divided in two periods. During the active period which lasts from time 0 to T, crops produce nectar and are receptive to pollination, and bees reproduce and forage for food. During the inactive period, bees do not produce honey nor pollinate crops, and a fraction of them dies. For simplicity, in the model the beekeeper harvests honey once a year at the end of the active period. In practice, beekeepers harvest honey more frequently.[5]

When forage, which is the bee food provided by crops, is available, changes in the population of bees $X(t)$ and changes in the amount of honey stored in the hive $H(t)$ are determined by the following differential equations:

$$\frac{dX(t)}{dt} = -\delta X(t) + \alpha(\gamma H(t) - X(t)) \equiv \dot{X}(t) \tag{1}$$

$$\frac{dH(t)}{dt} = -\beta X(t) + \upsilon min(X(t), \bar{X}) \equiv \dot{H}(t). \tag{2}$$

where all parameters (the Greek letters) are strictly positive and t represents time and belongs to the continuous interval $[0, T]$. The first term in equation 1 represents the number of bee deaths per unit of time and I assume that the death rate, δ, is constant throughout the foraging season. The second term represents the births.

[5] In fact, the economic problem of a beekeeper is a fairly complex dynamic optimization. In particular, the adjustment of the location of hives to the availability of nectar sources is crucial since these can vary widely from year to year.

The number of of births per unit of time is an increasing function of the honey stored in the hive but a decreasing function of the population size. The birth rate α is also constant throughout the active season. Note that these parameters reflect the population dynamics of the hive which are driven to a large extent by the laying behavior of the queen. As a result, δ, α, and γ cannot be interpreted like parameters of models of population dynamics that reflect the aggregate result of individual behaviors.[6]

The variation in the stock of honey is a function of the population of bees who consume honey at a rate β and augment the stock of honey at a rate υ by foraging.[7]

In order to represent the fact that crops provide a limited amount of resources to bees per acre, the rate of honey increase $\upsilon X(t)$ cannot exceed a given value $\upsilon\bar{X}$. This specification amounts to adding a carrying capacity to crops and is necessary to avoid corner and trivial solutions. Without the non-linearity introduced by the term $\upsilon min(X(t),\bar{X}$, the beekeeper in the model will either keep no bees or an infinite number of them depending simply on the ratio of input and output prices. This problem is due in part to the assumption that yield increases linearly with bee density. Two alternatives for obtaining an interior solution are to keep the system of equations strictly linear but to include a non-linearity either in the response of yield to bee density or in the costs. The advantage of the specification with a carrying capacity is that is puts the emphasis on the effect of bee densities.

[6] See Schmickl and Crailsheim (2007) for details about the dynamics and feedbacks of bee population. I only include the most important features of the population models from the entomology literature and ignore among others, the issues related to age classes among the bees of a hive, or the difference between pollen and nectar foraging behaviors.

[7] In Schmickl and Crailsheim (2007), both honey and pollen stocks determine the growth rate of the population.

In addition to these coupled equations of motion for the bee and honey stocks, I specify boundary conditions for their cycle. At the end of the foraging season, an amount H_{harv} of honey is harvested by the beekeeper. H_{harv} is equal to the difference between the stocks of honey at the end and beginning of the active season:

$$H_{harv} \equiv H(T) - H(0). \tag{3}$$

H_{harv} is the only control variable in the model. The model does not include honey consumption by bees during the inactive period. H_{harv} can be positive to represent honey extraction or negative to represent feeding, however the rest of the discussion focuses on the extraction case.

In addition, the number of bees available in spring is a fixed fraction ω of the fall population, that is:

$$X(0) = \omega X(T). \tag{4}$$

With these two conditions, equations 1 and 2 can be solved for any quantity of honey harvested H_{harv}. Because the trajectories of both stocks begin and end at the same stock levels by specification, the amount of honey harvested at time T is enough to determine the entire trajectories including the stocks at the beginning of the season $X(0)$ and $H(0)$, and the values at the end of the season $X(T)$ and $H(T)$.

The system made of equations 1, 2, 4, and 3 above can be solved analytically by solving two sets of equations, corresponding to $X(t) \leq \bar{X}$ and $X(t) \geq \bar{X}$.

When $X(t)$ is smaller than $\bar{X}$, the system of equations is homogeneous and solutions are of the form

$$\begin{bmatrix} X(t) \\ H(t) \end{bmatrix} = A_1 \begin{bmatrix} V_1^x \\ V_1^h \end{bmatrix} exp(r_1 t) + A_2 \begin{bmatrix} V_2^x \\ V_2^h \end{bmatrix} exp(r_2 t) \tag{5}$$

where r_1 and r_2 are the eigen values of the matrix of parameters:

$$D = \begin{pmatrix} -(\delta+\alpha) & \alpha\gamma \\ (\upsilon-\beta) & 0 \end{pmatrix}$$

and V_1 and V_2 the corresponding eigen vectors.[8] A_1 and A_2 depend on initial conditions.

When $X(t)$ is larger than $\bar{X}$, the solution is of the form

$$\begin{bmatrix} X(t) \\ H(t) \end{bmatrix} = \bar{A}_1 \begin{bmatrix} \bar{V}_1^x \\ \bar{V}_1^h \end{bmatrix} exp(\bar{r}_1 t) + \bar{A}_2 \begin{bmatrix} \bar{V}_2^x \\ \bar{V}_2^h \end{bmatrix} exp(\bar{r}_2 t) + \begin{bmatrix} \frac{\upsilon}{\beta} \\ \frac{\upsilon(\delta+\alpha)}{\alpha\gamma\beta} \end{bmatrix} \bar{X} \tag{6}$$

where the last term is a singular solution of the system of non-homogeneous equations. Here again $\bar{r}_1$ $\bar{r}_2$ are the eigen values and $\bar{V}_1$ $\bar{V}_2$ the eigen vectors of the parameter matrix:

$$\bar{D} = \begin{pmatrix} -(\delta+\alpha) & \alpha\gamma \\ -\beta & 0 \end{pmatrix}$$

. $\bar{A}_1$ and $\bar{A}_2$ depend on initial conditions.

There is no closed form solution for the four constants A_1, A_2, $\bar{A}_1$, and $\bar{A}_2$ in the equations of the segments of trajectories 5 and 6. These constants, which

[8] The value of the parameters must be such that r_1 and r_2 are two distinct real numbers, which that $(\delta+\alpha)^2 - 4\alpha\gamma(\upsilon-\beta)$ is strictly positive.

are required to describe the entire trajectories of bee population and honey, are function of the time τ at which $X(t)$ reaches $\bar{X}$ which does not have a closed form solution. In other words, the constants for each segment of the trajectories do not have a closed form expression because the boundary condition at τ, which is the end point of the segment for trajectories in 5 and the starting point for trajectories in 6 do not have a closed form expression. Section 2.2 describes the properties of the solutions that can be derived from the analysis of a phase diagram. Section 2.3 then describes numerical solutions to this model.

2.2 Theoretical results

Figure 4 represents the phase diagram for two yearly cycles of bees and honey. The vertical axis represents honey and the horizontal axis represents the population of honey bees in the hive. The cycle in the top right corner is the annual trajectory resulting from no honey harvest whereas the cycle in the center of the figure is the annual trajectory resulting from a strictly positive value of honey harvest. The gray dashed lines represent nullclines, corresponding to $\dot{H} = 0$ and $\dot{X} = 0$. The position of $\bar{X}$ is also indicated with a vertical dashed line. In each quadrant delimited by the nullclines, the direction of the gradients for X and H is given by two small gray dotted arrows.

When no honey is harvested, the inactive period results in a drop in the number of bees. Following equation 3, the bees in the hive do not deplete the stock of honey during the inactive period and therefore, when no honey is harvested the trajectory during the inactive period is represented by a horizontal line. This section of the trajectory and the rest of the cycle corresponding to no harvest or $H_{harv} = 0$, is drawn at the top right corner of figure 4. Note that the cycle corresponding to $H_{harv} = 0$ does not go through the long run equilibrium point which lies at the intersection of the nullclines $\dot{X}(t) = 0$ and $\dot{H}(t) = 0$. As indicated at the top of the honey stock axis, there is second nullcline for H, but any equilibrium on that nullcline This equilibrium would only be reached if the active season season was infinitely long. Here the trajectory which would end at that equilibrium point is interrupted by the inactive period when the population of bees drops by a factor ω.

When a positive amount of honey is extracted, the trajectory during the inactive period is an upward sloping line in the state variable space. The stocks of honey and the population of bees are designated by H_0 and X_0 at the end of the inactive period. Although H_0 is the lowest point of the cycle for honey, the population of bees may at first decrease if the point (H_0, X_0) is below the nullcline defined by $\dot{X}(t) = 0$ and reaches a minimum only at the point where the trajectory crosses that nullcline. From there, the population of bees increases at a rate $-\beta X(t) + \upsilon$ and the stock of honey increases at a rate of $(\beta + \upsilon)$ until the colony reaches the carrying capacity $\bar{X}$. After $\bar{X}$, the rate of honey accumulation then switches to β for the rest of the active period.

For any given set of parameters, including the length of active period and the carrying capacity of the crop, there is a maximum amount of honey that can be collected. If a more than the maximum sustainable quantity of honey is collected every year, both bee population and honey stock are gradually driven to zero. This upper limit to honey harvest is an increasing function of the carrying capacity of the crop.

Before turning to the relationship between the trajectories of bee numbers and honey stock over time and the amount of honey harvested, it is useful to say a word on the interpretation of the state variables X and H. In particular, by specifying the net birth rate as $\alpha(\gamma H(t) - X(t))$, I represent some of the biological feedbacks that exist in the queens laying rate for instance. Nevertheless, the population of bees in the model can also be interpreted as the population of a representative hive for the beekeeping industry as a whole. Accordingly, X and H can be simply scaled up to represent the population of bees and the stock of honey for the entire industry.

2.3 Numerical simulations of variations in bee population and honey stock

Figure 5 shows the numerical solutions of the cyclic trajectories for five different amounts of harvested honey H_{harv}.[9] Panel (a) represents the numerical counterpart of the illustrative phase diagram shown in figure 4. Panels (b) and (c) in 5 show the trajectories in time of honey and bees. As the amount of honey extracted increases, the sizes of both stocks at the beginning of the active period decrease. Note that some for some cycles, the population of bees in the hive my at first decreases during the first part of the active period. This patterns depends on whether the starting point of these trajectories is above or below the nullcline $\dot{X}(t) = 0$.

Figure 6 shows the production possibility frontier corresponding to the three panels of figure 5. The average bee population over the length of the active season is given as a function of the honey harvested. This average can be used as proxy

[9]See figure note for parameter and honey harvest values.

for the pollination service provided by the hive since foraging is proportional to hive size in first approximation.[10]

The relationship between the average population of bees and the honey extracted corresponds to the production possibility frontier which identifies a trade-offs that a beekeeper faces between her two outputs, honey and pollination services. Recall that for each value of H_{harv}, there is only one feasible cycle and therefore, the production possibility frontier is well defined. The five dots in 6 correspond to the five trajectories represented in the three panels of figure 5. The rest of the points that form the downward sloping production possibility frontier correspond to all the other possible trajectories which for clarity are not represented in the panels of figure 5. With the parameters used in the simulations of figure 5, the maximum amount of honey that can be harvested is $H_{max} = 125$ units, point past which the average population in the hive drops to zero. Past this point, a yearly cycle is not feasible. At the other end of the possibility frontier, the average bee population reaches its maximum $X_{max} = 49$ when no honey is harvested.

3 The economic problem of the beekeeper and the optimal yearly cycle

The two following sections use the production possibility frontier derived above from the population model to describe the economic optimum of honey and pollination services production.

[10]This is not true in practice for at least two reasons. First, the proportion of the bees in a colony that are active foragers is not constant with the number of bees in the colony. The allocation of tasks among individuals follows a complex pattern and is based among other things on the age of the bees. Second, the foraging activity of a hive as a unit depends in particular on the amount of honey and pollen stored in its combs.

3.1 Honey-pollination trade-off for a single crop

As described above, figure 6 shows the production possibility frontier for honey and average population of bees which is a proxy for pollination services. The production possibility frontier is given in the output space by definition and it can therefore be used to identify the optimal production point for the beekeeper if the quantity of inputs is fixed. This simplification does not represent a loss of generality because the inputs for the production of a hive, aside from the nectar and pollen collected by bees, can be considered fixed and independent in first approximation of both the amount of honey harvested and the number of bees in the hive.

With these simplifications, the economically optimal production point corresponds to the point where the slope of the production function in output space is equal to the output price ratio as illustrated in figure 6. Because some bees are always necessary to produce any honey, pollination services are always provided to the crop even when their price, which is equal to the value of the marginal product of pollination services in crop production is equal to zero. The maximum amount of honey that can be produced is labeled H_{max} on the horizontal axis of figure 6. It is optimal for the beekeeper to produce at that point if the ratio of honey price over pollination service price is greater in absolute value to the slope of the tangent to the production possibility frontier at H_{max}. This corner solution is includes the case where the crop does not benefit from pollination, as is generally the case in citrus for instance.

The other corner solution corresponds to the absence of honey harvest. It is optimal to produce only pollination services when the output price ratio is smaller than the slope at X_{max}. Almond trees are an example of this case because the price of almond honey is about null and the value of the marginal product of pollination services for almonds high.

When considering only one crop, the dynamic model reproduces the trade-off involved in the joint production of honey and pollination services as described by Cheung (1973) and others. The model provides additional intuition when more than one crop is considered, as in the next section.

3.2 Honey-pollination trade-off for two crops

A variety of situations can be considered by adding crops with different carrying capacities and different values of the marginal product of pollination services. This section illustrates how the numerical model can be used to analyze the case of two crops blooming sequentially. The active period of the cycle is divided in two periods of equal length $T/2$. The two crops can differ in two aspects: their carrying capacity and the price their growers are willing to pay for pollination services. In this example, the price of honey does not vary across crops. The carrying capacity of a crop is equal to the product of the acreage by the nectar production per acre divided by the number of hives placed on the crop. Here I assume that both crop prices and acreage are exogenous and fixed. In a more complete model of pollination market both should be treated as endogenous (see appendix 7). Also, I assume that both crops have the same carrying capacity but that the value of the marginal product of pollination services is higher for the first crop (e.g. because of a higher crop price). The average population of bees in the hives must be calculated for each half of the season for every possible value of the control variable H_{harv}. Instead of graphing the production possibility frontier in output quantity space, it is easier now to depict the trade-off in the revenue space.

Figure 7 shows the average bee populations for the first and second half of the foraging season separately, corresponding to the two crops. The annual pollination revenue is equal to the sum of the pollination revenues of each period. Both revenues are equal to the average bee population multiplied by the price of pollination services. The optimal mix of pollination services and honey outputs is found where the slope of the revenue trade-off curve is equal to -1, which is the slope of isoprofit lines in the revenue space. Because the carrying capacities of the two crops are equal and the bee population is growing, the average bee population during the first half of the season is almost surely lower than in the second half of the season, which can be easily seen in panel (c) of figure 5.[11]

This figure illustrates one of the hypotheses for the drastic increase in the almond pollination fees that has occurred in the last decade. Only a very high pollination fee for the first crop, relative to the price of honey can make it optimal for the population of bees to be large in the first part of the yearly cycle because the amount of harvested honey that must be forgone is large.[12] Almonds pollination provides a good illustration of this case.

Other cases deserve to be addressed in further work, in particular with multiple crops blooming both simultaneously and sequentially. The use of the production possibility frontier is a less useful tool for describing the beekeeper's trade-offs when the prices of honey and pollination services are endogenous.

In appendix 7 I develop a model of pollination markets order to provide some intuition on the effect of considering the seasonality of the stock of bees on

[11] A higher carrying capacity in the first crop is not sufficient however to guaranty that average bee populations rank the other way around since the drop in bees and honey always occurs just before the first.

[12] The substitution of syrup for nectar, which is not included in the model, may reduce this effect. However, syrup and nectar are not perfect substitutes both in terms of bee health and for honey production.

equilibrium prices and quantities of beekeeping inputs and outputs with multiple crops blooming both simultaneously and sequentially. That model ignores the fact that crops, through the food they provide to bees, are inputs for the maintenance and growth of bee stock. Leaving aside this fact means that bees are simply providers of services rather than a renewable stock for which growth depends on the crops serviced. Moreover, the feedbacks that exist between the dynamics of the bee population in the hive and the stock of honey stored are disconnected by assuming that honey production is specific to each crop. Despite these simplifications, the predictions of the market model in the appendix help explain the patterns of pollination fees, in particular those resulting from the rise of demand for almond pollination. An increase in acreage and therefore in the demand for pollination services for a crop, results in an increase in the wages of bees for all crops blooming during the same period and a decrease in wages of bees from other periods.

4 Summary of results

In commercial beekeeping, the same stock of bees forages on several crops during the course of a year. On each crop, the bees may produce honey and may provide pollination services jointly. Modeling the dynamics of the bee population allows one to explain the seasonal patterns observed in pollination markets. These seasonal patterns cannot be explained with a static model of joint production such as those developed in the existing literature on pollination markets (see Cheung (1973) and Muth et al. (2003)). In addition, because the pollen and nectar provided by crops are inputs for the stock of bees, pollination fees cannot be assumed to be the difference between the bee wage and the value of the marginal output of honey. The value of the increase in bee stock must also be considered.

Recall that one of the noteworthy events in pollination markets in the last decade is the steady increase in demand for pollination services from almond growers. The resulting rise in pollination fees for almonds has been steep compared to the increase in almond acreage. The model of bee population dynamics presented in this paper provides a hypothesis to explain this pattern which cannot be explained by evoking only the jointness of production of honey and pollination services for a given crop. The hypothesis is that because almonds bloom early in the active foraging season, a large amount of honey must be forgone in order for the population of honey bees to be large during that bloom. The fact that honey bees do not produce honey on almonds contributes but is not sufficient to explain the steep rise in almond pollination fees.

Furthermore, the results from the seasonal model developed in this chapter are important for the evaluation of policies. Muth et al. (2003) argue that the externality argument provided by Meade is not sufficient to guaranty that honey subsidies will increase the pollination of crops in agriculture. Here I show that in theory at least, honey subsidies may sometimes result in an increase in the amount of pollination services available for some crops. In contrast, research and development designed to reduce the production costs of beekeeping benefit all crops unambiguously. Yet, given the lack of data and the corresponding lack of estimates of the amounts of pollination services provided by honey bees, it is difficult to accurately quantify the returns to investments in cost-reducing efforts.

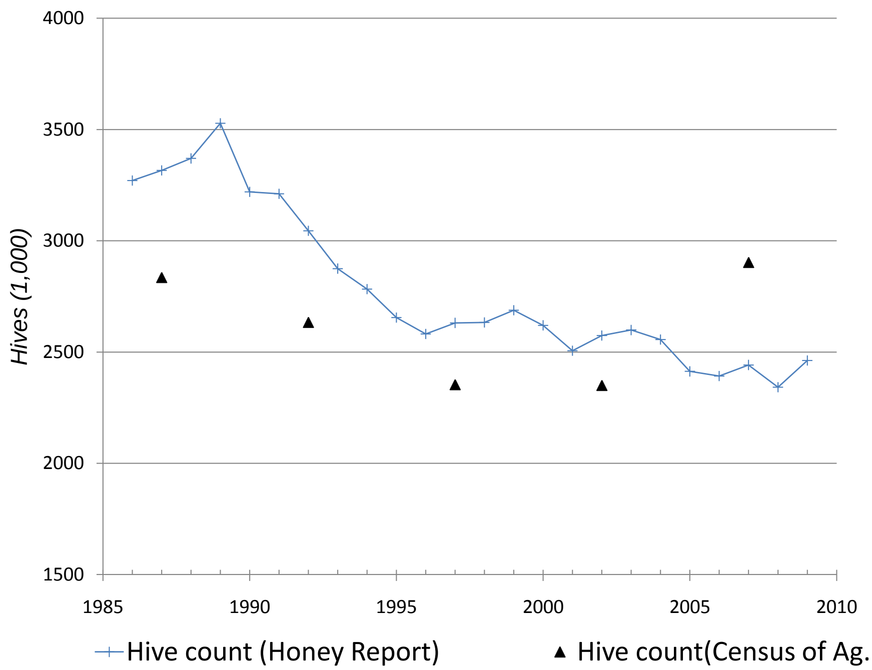
5 Model limitations and extensions

Several other aspects of the economics of beekeeping need to be understood to complete the picture of the management of pollinators in agriculture. One first aspect of , the costs of migration, which depend in particular on fuel costs have not been addressed by economists. In fact, although the general pattern of seasonal migration of beekeepers and their hives is known, hardly any data are available that detail the ows of hives. Existing data from the USDA Honey reports are of limited use because accounting for hives allows for double counting of hives that produce honey in more than one state. The addition of transportation costs in economic models of pollination markets may be important for two reasons. First, although hives are currently being hauled from one coast to the other, changes in relative prices of bee outputs and fuel could result in a separation of the East and West markets. In each of the smaller markets resulting from this fragmentation, the opportunity for beekeepers to find crops that bloom in sequence through the inactive and active periods would be reduced. For instance, pollination fees for almonds may increase if beekeepers who place their hives in the citrus groves of Florida did not find it profitable to drive across the country. Second, the spread of pests and diseases which impose large costs on the beekeeping industry depends on the patterns of migration of hives. Economists have also ignored until now the heterogeneity of hives which is an important aspect of the beekeeping industry. Indeed, the size of hives plays a central role in determining the quantity of pollination services hives provide to crops. Because of the growth of the bee population between early spring and fall, pollination fees measured in dollars per hive cannot be compared across the different blooming periods without adjusting for heterogeneity. In addition, the population of bees can differ across hives at the same period of the year. For instance, price premiums for hives containing more bees are common in pollination contracts for almonds. The size of the population in hives depends on management practices, which include the choice of crops on which they are placed, the frequency of manual queen replacement, or prevention of damages from parasites. The heterogeneity of beekeepers has been well documented for instance by Daberkow, Korb, and Hoff (2009) but the relationship between the characteristics of beekeeping operations and the characteristics of hives remains to be determined. The heterogeneity of hives may spur inferences based on pollination fees and comparisons across crops because the growers of certain crops devote more resources in controlling the quality of the hives they rent than others. For instance, the pollination fees for avocados have not followed the increase in fees brought by the almond boom even though they use bees during the same period as visible in figure 3. It is not possible to determine without a measure of hive size whether the difference between avocado and almond fees is due to the fact that avocados provide more nectar to bees than almonds or if avocado growers are willing to accept smaller hives more readily.

6 Concluding remarks

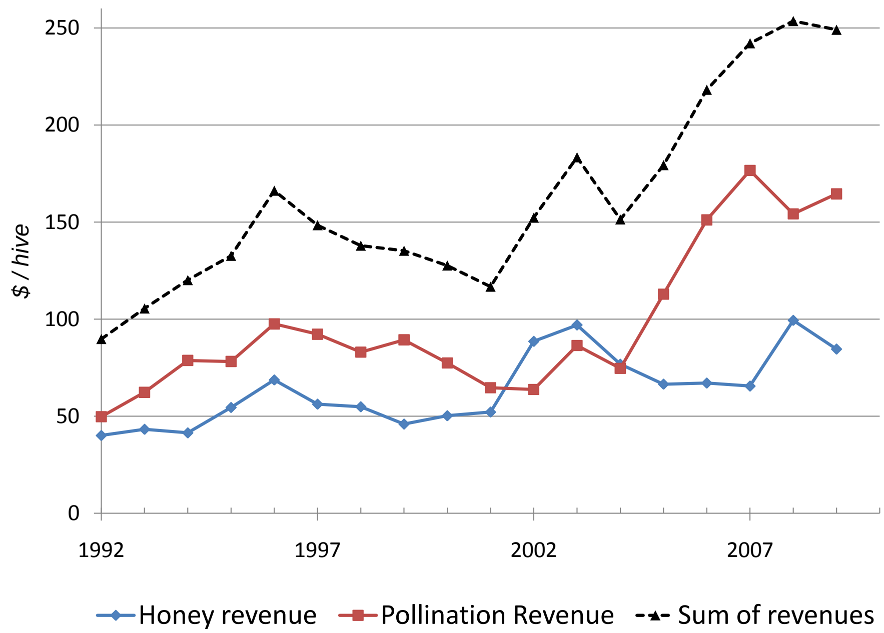
Honey bees differ from other species of insect pollinators in important ways, some of which play a determinant role in shaping the economics of their rearing and use in agriculture. Because the nest of honey bees is easily transported and their yearly active cycle long, honey bees can be used to pollinate multiple crops. Also, because honey bees store honey in a way that can be easily harvested, they produce a honey output in addition to the pollination services they can provide. This chapter develops a dynamic model that show the consequences of these two important characteristics on the economic trade-offs involved in their use. Previous literature had identified the fact that honey and crops are joint outputs of a production process that uses beehives and crop blossoms as inputs. The main novelty of this chapter is that is highlights the fact that crop blossoms are in addition an input for the production of the stock of bees by modeling the dynamics of both the stock of stored honey and the population of bees in a hive. This reciprocity is the consequence of the reciprocity of the pollination relationship itself. The few other species that have been used for pollination in agriculture, as well as the wild species that provide pollination services by diffusing from wild habitat also depend on crops as inputs, at least partially. However, because they are not migratory, the dynamics of their stock is most likely to depend on a the few crops and wild plants withing their foraging range. Also, because pollinator species other than honey bees do not store honey in a harvestable form if at all, their management does not involve the problems of joint output production

The economic problem that pollination markets tackle are complex. Although the efficiency of these spontaneous institutions remains to be fully measured and understood, there is some evidence that they solve not only the problem of jointness of production first outlined by Meade. Indeed, pollination markets may also solve the problem of the management of a renewable and migratory stock which economic value derives from both extraction and the provision of a service. Although the economic importance of honey bees may be smaller than that of other livestock, the study of the economic institutions of beekeeping provides insights on the economic problems involved in domestication more generally.



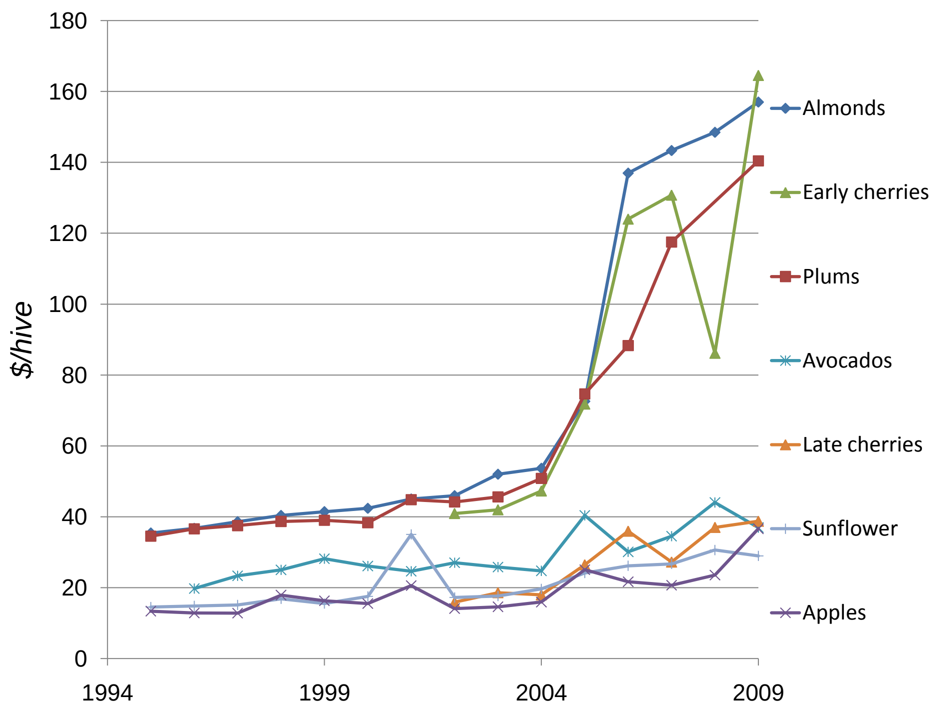
Source: USDA Honey reports, U.S. Census of Agriculture.

Figure 1: Hive numbers in the United States from 1986 to 2009



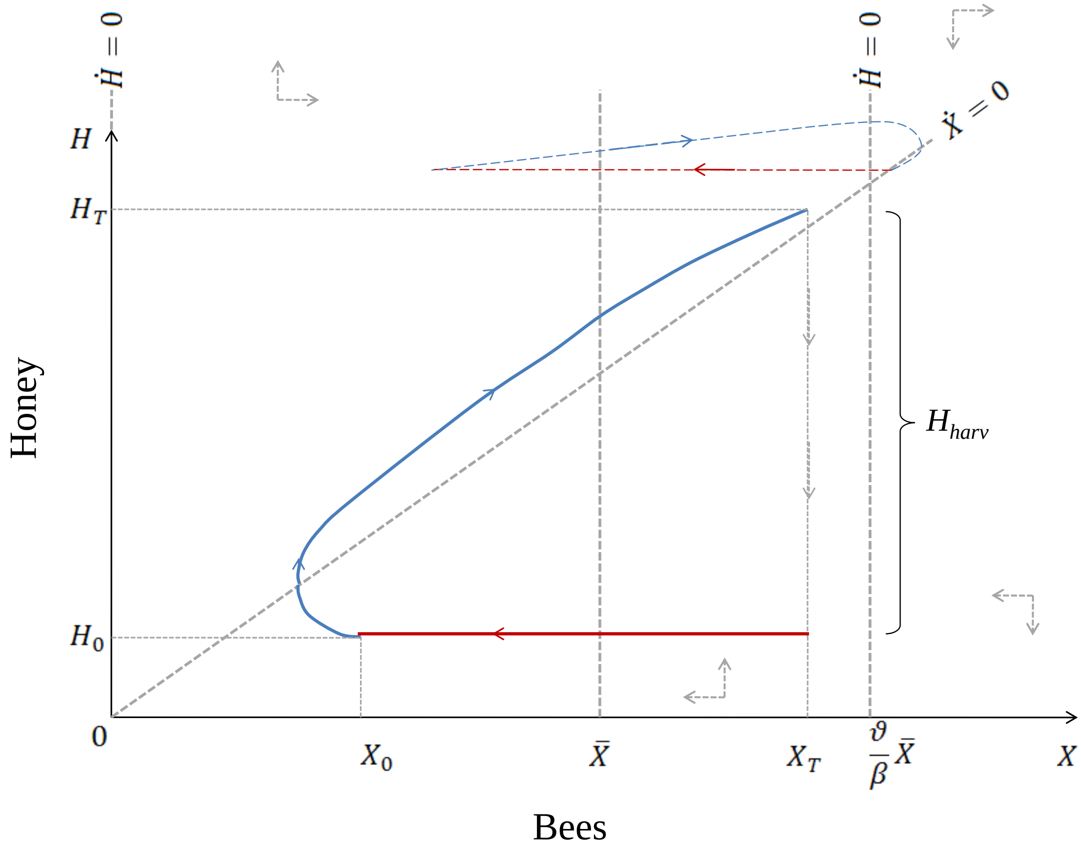
Source: The pollination revenue come from the average pollination revenues per hive reported in Burgett (1999), Burgett (2006), Burgett (2007), and Burgett (2009). The honey yield in pounds per hive and honey prices in per pound used to calculate the honey revenue per hive come from the USDA honey reports. All revenues are nominal.

Figure 2: Beekeeping revenues per hive in the United States from 1992 to 2009



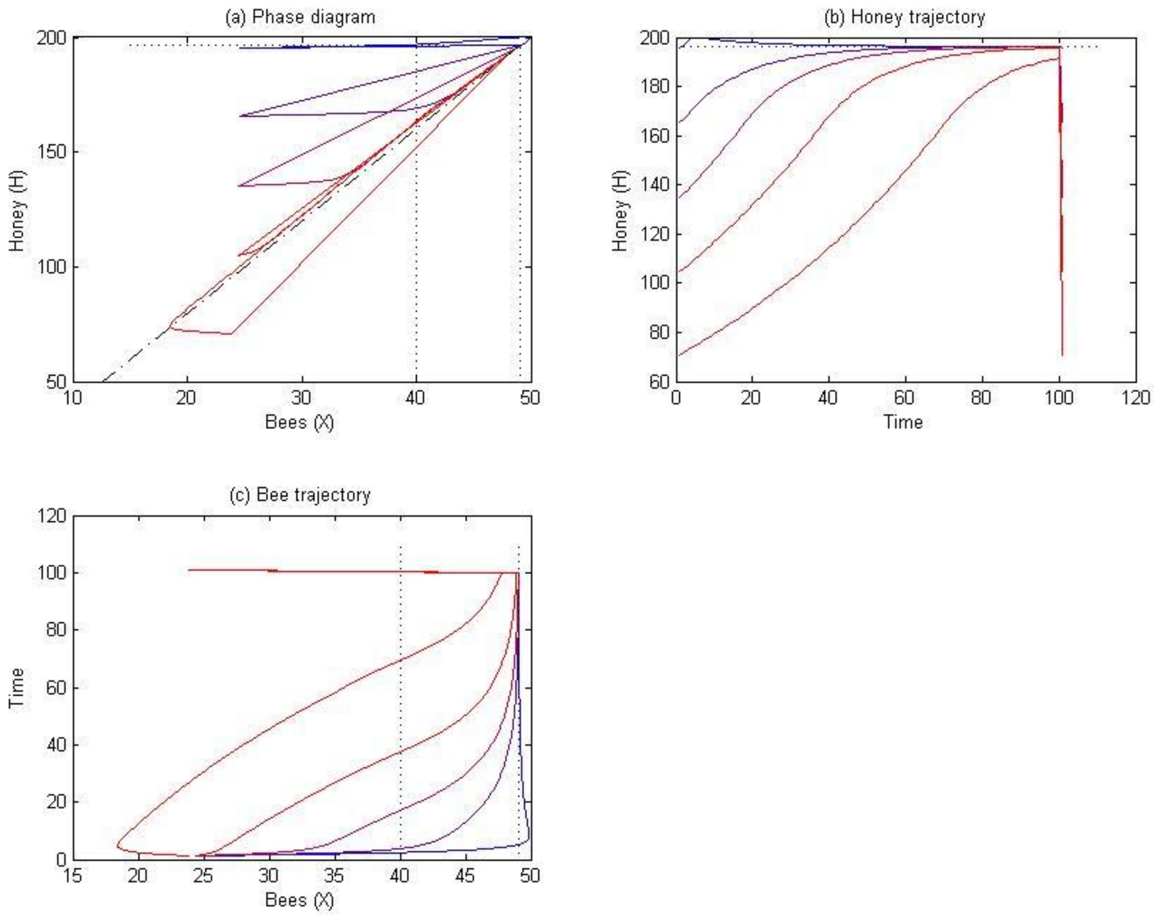
Source: California State Beekeeping Association Pollination Surveys. The figure does not show the pollination fee for plums in 2008 because only two observations are available for that year and crop.
Note: Almonds, plums, early blooming varieties of cherries, and avocado bloom in February and March whereas the other crops bloom later. Avocados are the only early crop to provide enough nectar for the production of honey.

Figure 3: Pollination fees for representative California crops from 1995 to 2009



Note: The cycle in dashed line in the top right corner of the diagram corresponds to the trajectory in the absence of honey harvest, whereas for the solid line, $H_harv = H_T - H_0$ is extracted at time T. The blue, or curved, section of each of the two cycles correspond to the active period whereas the red straight lines are for the inactive period. Grey dashed lines represent nullclines and gray dotted arrows represent the sign of the derivatives $\dot{X}$ and $\dot{H}$ in different areas of the phase diagram delimited by the nullclines.

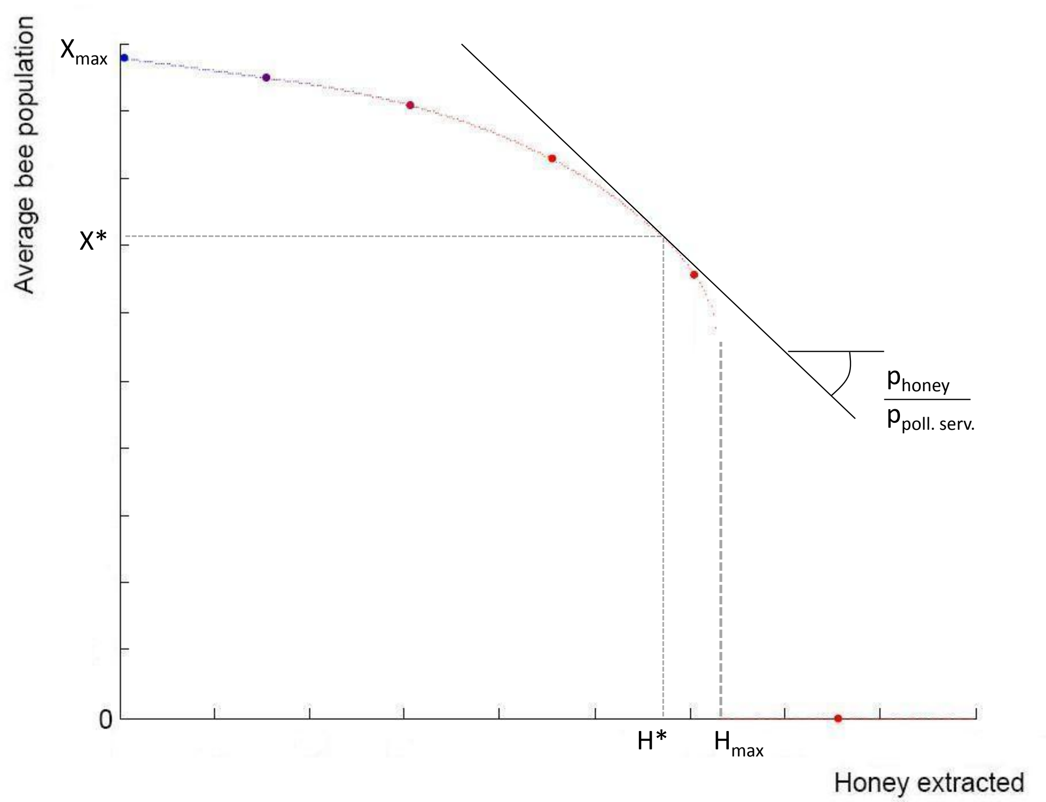
Figure 4: Phase diagram for the yearly cycle of bees and honey stocks in a hive



Values of simulation parameters: $T = 100$, $\bar{X} = 40$, $\upsilon = .27$, $\beta = .22$, $\delta = .1$, $\gamma = .3$, $\alpha = .5$, $\omega = .5$, and $H_h arv = \{0, 30, 60, 90, 120\}$.

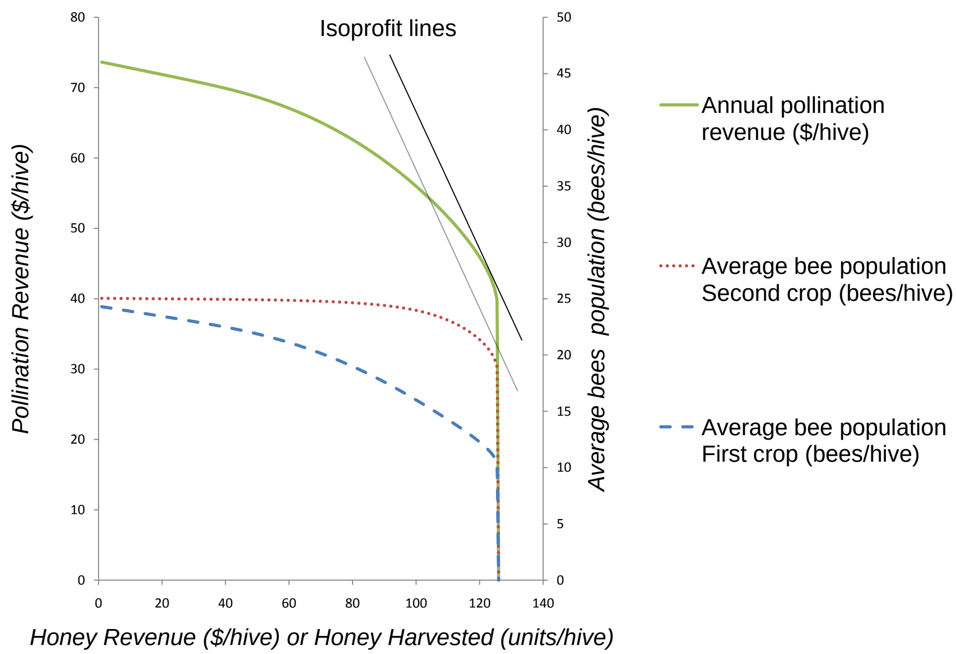
In the diagram of the production possibility frontier, each solid point corresponds to one of the trajectories in the three other diagrams.

Figure 5: Phase diagram, bee and honey trajectories, and production possibility frontier



Values of simulation parameters: $T = 100$, $\bar{X} = 40$, $\upsilon = .27$, $\beta = .22$, $\delta = .1$, $\gamma = .3$, $\alpha = .5$, $\omega = .5$, and $H_harv = \{0, 30, 60, 90, 120\}$.
Each solid point corresponds to one of the trajectories in the three diagrams of figure 5.

Figure 6: Production possibility frontier along honey and hive size dimensions, output price ratio, and optimal production point



Note: The yearly pollination revenue is calculated as the sum of the average bee populations for each crop multiplied by their respective prices for pollination services. Here the price of pollination services for the first crop is twice that of the second. Isoprofit lines have a slope of -1 in the revenue space. Simulation parameters are the same as in figure 5 and the price of honey is equal to 1.

Figure 7: Optimal honey and pollination service outputs for two sequential crops with different price of pollination service

7 Appendix: A seasonal model of pollination markets with a migratory stock of bees

This appendix describes an equilibrium displacement model of pollination markets. The model includes the effects of changes in crop acreage, honey price, and beekeeping costs on the wages of bees. The most important feature of this model is that it takes into account the fact that bees are a stock used as input for crops that bloom sequentially throughout the year.[13] Previous models of pollination markets, such as in Cheung (1973) and Muth et al. (2003), consider that all crops are competing for the same bees. Here, each crop competes only with crops that bloom during the same period. A second important feature of the model is the endogeneity of the input ratio of land and bees.[14]

I find that an increase of the acreage of one crop always results in an increase in the wage of bees for all crops blooming at the same time of year and a decrease of bee wages for other blooming periods. Also, an increase in the cost of beekeeping results in an increase of the wage of bees for all seasons and all crops. In contrast, changes in honey prices have ambiguous effects on the wages of bees for a given crop. My prediction on the effect of changes in honey price contradicts the existing literature. I discuss the consequences of these findings in section 4.

[13]The lifespan of an individual worker bee is a 4 or 5 weeks during the active period of the year. Therefore, although the same hive may be used for several crops blooming months apart, the bees providing the pollination services and collecting nectar are not the same. Here I only refer to the aggregate population of bees in a hive without keeping track of the birth and death of individuals.

[14]Rucker, Thurman, and Burgett (2008) argue that the density of bees per acre is in practice constant for individual crops. In addition, assuming fixed proportions in land and bees is problematic in a seasonal model simply because the additional bees that would result from an increase in acreage in say March must go somewhere in June.

7.A A seasonal model of pollination market with a fixed bee stock

First consider the demand equation for bees. The wage of bees, which is the value of the total marginal product of bees, is equal to the sum of the values of the marginal products of bees for honey and crop production, which can be written as:

$$\forall(t,i),\ w_{t,i} = y'_{t,i}(b_{t,i})p_{t,i} + h'_{t,i}(b_{t,i})p_h \tag{3.A.1}$$

where $w_{t,i}$ is the wage of bees used on crop i of period t. The expressions $y'_{t,i}$ and $h'_{t,i}$ are the increase in crop and honey yield per acre resulting from a marginal increase of bee stocking density $b_{t,i}$). The bee stocking density $b_{t,i}$) is the number of bees per acre and the number of crop blossoms per acre are assumed to be constant. $p_{t,i}$ and p_h are the prices of crop (t,i) and honey. I assume that honey per acre and crop yield per acre are increasing in bee density over the relevant range. Equation 3.A.1 is identical to equation (3) in Rucker, Thurman, and Burgett (2008). A similar concept is used in Cheung's analysis.

The choice of indexing, although not the most intuitive at first, is driven by the ease with which equilibrium conditions can be represented. In the notation, crop $(1,1)$ and crop $(2,1)$ are two different crops blooming in periods 1 and 2. An alternative notation would be to attribute a crop index to each crop but with such notation, market clearing conditions cannot be easily written and require to keep track of which crops bloom when throughout. An additional difficulty resides in dealing with blooming periods of different lengths and with overlaps. Specifically, the bloom period of certain crops can be longer than those of others and hives placed on crops with longer bloom become available only to crops that bloom after end of the bloom of the first crops. For instance, some apple orchards in California start blooming before the end of the almond bloom (Sumner and Boriss, 2006). The notation adopted here can be used to represent these cases by splitting the bloom of, say, almonds in two periods. In that case, crop $(1,1)$ and crop $(2,1)$ may both be almonds, and an additional equation can be added to constrain the number of almond acres and bees used in almonds to be equal across periods.

When pollination markets are competitive, the wage of bees employed on all crops blooming during the same bloom period only differ by the cost of transportation of hives from their location of origin to the crop. Here I ignore these shipping costs. Accordingly:

$$\forall i, \forall t,\ w_{t,i} = w_t \tag{3.A.2}$$

Furthermore, the total wage of bees for the entire year is the sum of the wages collected during each period or:

$$\sum_t w_t = W \tag{3.A.3}$$

where W is the yearly bee wage.

The market clearing conditions for the numbers of bees are characterized by

$$\forall t,\ \sum_i A_{t,i} b_{t,i} = B_t \tag{3.A.4}$$

and

$$\forall t,\ B_t = B \tag{3.A.5}$$

where $A_{t,i}$ is the acreage of crop (t,i) and B_t the number of bees in period t. Equation 3.A.4 is the market clearing condition for each period.[15] Equation 3.A.5 states that the same number of bees are used for each bloom period.

Finally, I write the supply function for bees as a function of the yearly wage and a supply shifter s:

$$B = f(W, s). \tag{3.A.6}$$

By constraining the bee stock to be fixed yearlong and by treating honey as an output similar to the crop output, I ignore many of the complexities of the biology of bees discussed and modeled in section 2. Importantly, the wage of bees, defined as the value of the marginal product of bees, does not include the value deriving from the increase in bee stock. This value is implicit in the dynamic model presented in the section 2. In addition, the production of honey by bees is simplified here since it just comes as an output for each crop. In the fully dynamic model, the trade-off between the production of a honey harvest and the increase in the population of bees is taken into account. I leave the construction of market model that incorporates these features for future work.[16] Figure 3.A.1 provides a graphical representation of the system of equations for a 3 crop 2 periods model.

7.B Displacements of market equilibrium

Writing equations 3.A.2 through 3.A.5 in log-differential form yields a system of linear equations that can be solved to obtain the changes in equilibrium quantities and prices resulting from changes in exogenous variables such as output prices, acreages, and supply shifters. The notation $EX = dX/X$ indicates the

[15] $b_{t,i}$ is a density of bees per acre.

[16] Some of the dynamic characteristics of the stock of bees could be added by changing this equation to $B_{t+1} = f(B_t)$ for instance.

percentage change in variable X. After log-differentiation, equation 3.A.1 becomes:

$$\forall(t,i),\ Ew_{t,i} = \left[\eta^y_{t,i}(1-\alpha_{t,i}) + \eta^h_{t,i}\alpha_{t,i}\right) Eb_{t,i} + (1-\alpha_{t,i})Ep_{t,i} + \alpha_{t,i}Ep_h \qquad (3.A.7)$$

where $\eta^y_{t,i}$ is the elasticity of the marginal product of bees in the production of the crop with respect to bee densities and is equal to $(dy'_{t,i}/db)(b_{t,i}/y'_{t,i})$; $\eta^h_{t,i}$ is the elasticity of the marginal product of the honey with respect to bee densities and is equal to $(dh'_{t,i}/db)(b_{t,i}/h'_{t,i})$; and $\alpha_{t,i}$ is the share of honey in the value of the marginal product of bees, that is $\alpha_{t,i} = (h'_{t,i}p_h)/w_{t,i}$.

Equations 3.A.2 and 3.A.3 become:

$$\forall i, \forall t,\ Ew_{t,i} = Ew_t \qquad (3.A.8)$$

$$\sum_t \omega_t Ew_t = EW \qquad (3.A.9)$$

where ω_t is the share of one period in the total yearly wage, that is $\omega_t = w_t/W$.

The market clearing conditions 3.A.4 and 3.A.5 become:

$$\forall t,\ \sum_i \gamma_{t,i}\,(EA_{t,i} + Eb_{t,i}) = EB_t \qquad (3.A.10)$$

$$\forall t,\ EB_t = EB \qquad (3.A.11)$$

where $\gamma_{t,i}$ is the share of the bee population used in crop i during period t, or $\gamma_{t,i} = (A_{t,i}bt,i)/B_t$.

Finally, the differentiated form of the supply equation is:

$$EB = \varepsilon EW + Es. \qquad (3.A.12)$$

7.C Model with three crop and two bloom periods

This model is linear and can be solved for any number of crops or periods. The model with three crops and two periods suffices to derive four general results. I derive the changes in the wages of bees for a crop resulting from changes in acreage of crops both in other periods and in the same period, change in the price of honey, and changes in the marginal cost of rearing bees: to cover the interesting cases, assume that there are two crops in the first period and only one in the second period.

Equation 3.A.7 can be expanded for the three crops as follows:

$$Ew_{11} = \left(\eta^{y}_{11}(1-\alpha_{11}) + \eta^{h}_{11}\alpha_{11}\right) Eb_{11} + \alpha_{11} Ep_h \tag{3.A.13}$$

$$Ew_{12} = \left(\eta^{y}_{12}(1-\alpha_{12}) + \eta^{h}_{12}\alpha_{12}\right) Eb_{12} + \alpha_{12} Ep_h \tag{3.A.14}$$

$$Ew_{2} = \left(\eta^{y}_{2}(1-\alpha_{2}) + \eta^{h}_{2}\alpha_{2}\right) Eb_{2} + \alpha_{2} Ep_h. \tag{3.A.15}$$

Equations 3.A.8to 3.A.12 become:

$$Ew_{11} = Ew_{12} \tag{3.A.16}$$

$$\omega_1 Ew_{11} + \omega_2 Ew_2 = EW \tag{3.A.17}$$

$$\gamma_{11}\left(EA_{11} + Eb_{11}\right) + \gamma_{12}\left(EA_{12} + Eb_{12}\right) = EB_1 \tag{3.A.18}$$

$$\gamma_2\left(EA_2 + Eb_2\right) = EB_2 \tag{3.A.19}$$

$$EB_1 = EB_2 = EB \tag{3.A.20}$$

$$EB = \varepsilon EW + Es. \tag{3.A.21}$$

Because there is only one crop in period 2, γ_2 is equal to one. In addition, I define:

$$\forall(t,i), mu_{t,i} = \eta^y_{t,i}(1-\alpha_{t,i}) + \eta^h_{t,i}\alpha_{t,i} \tag{3.A.22}$$

and simplify equations 3.A.13 to 3.A.15 to

$$Ew_{t,i} = \mu_{t,i}Eb_{t,i} + \alpha_{t,i}Ep_h \tag{3.A.23}$$

Because $\mu_{t,i}$ is a weighted average of two negative numbers $\eta^y_{t,i}$ and $\eta^h_{t,i}$, it is also negative for all crops and periods. All other parameters are positive.

7.D Analytical solutions

The system of linear equations 3.A.16 to 3.A.23 are solved for the change in bee wage for crop 1 in period 1 Ew_{11} as a function of changes in acreages EA_2 and EA_{12}, beekeeping costs S, and honey price Ep_h. The increase in bee wage resulting from an increase in the acreage of crop 2 in period 2 is given by:

$$\frac{Ew_{11}}{EA_2} = \frac{\mu_{11}\mu_{12}\mu_2\varepsilon(1-\omega_1)}{\Phi} \leq 0 \tag{3.A.24}$$

with

$$\Phi = \varepsilon\omega_1\mu_{11}\mu_{12} - (\gamma_{11}\mu_{12} + \gamma_{12}\mu_{11})(1-\varepsilon(1-\omega_1)\mu_2) \geq 0. \tag{3.A.25}$$

The numerator of is always negative because it contains an odd number of μs and because ω_1 is a share. In the denominator Φ, terms preceded by a positive sign have even numbers of μs and terms preceded by a negative sign have an odd number of μs . As a result, the denominator Φ in expression 3.A.28 is always positive. Accordingly, an increase in acres of crops in other seasons always result in an decrease in the bee wage. This result is intuitive and is a consequence of the returns to scale of beekeeping which use the same bees to pollination and make honey from several crops.

The effect of a change in acreage of crops from the same bloom period is given by:

$$\frac{Ew_{11}}{EA_{12}} = \frac{\gamma_{12}\mu_{11}\mu_{12}\left(1-\varepsilon(1-\omega_1)\mu_2\right)}{\Phi} \geq 0. \tag{3.A.26}$$

The denominator is the same as in expression 3.A.24 and therefore the sign of expression 3.A.26 is the sign of its numerator. $(1-\varepsilon(1-\omega_1)\mu_2)$ is positive because μ_2 is negative. The entire fraction in expression 3.A.26 is therefore positive. An increase in the acreage of crops in the same blooming periods always result in an increase of bee wages for that period. These first two results illustrate the fact that crops are substitute when in the same blooming season and complements when not. That this is consistent with patterns of observed pollination fees in figure 3 of section 1.

Equations 3.A.24 and 3.A.26 show that an increase in acreage of one crop causes an increase in bee wages for all crops of the same blooming period and a decrease of bee wages for crops blooming during other periods. This result can be applied to the increase in almond acreage that has occurred in the last couple of decades. The result is consistent with the patterns of pollination fees shown in figure 3 because pollination fees for crops that bloom at the same time as almonds have increased. However, pollination fees for crops blooming after almonds do not seem to have declined significantly, as equation 3.A.24 predicts. Econometric estimation is required to test further the validity of the equilibrium displacement model developed here.

I now turn to the effect of shifts in the supply of bees on bee wages.

$$\frac{Ew_{11}}{Es} = \frac{-\mu_{11}\mu_{12}}{\Phi} \geq 0. \tag{3.A.27}$$

Here again the denominator is positive. Since the numerator is negative, I find that an increase in the marginal cost of producing bees results in an increase in bee wages for all periods and crops.[17] The denominator is an increasing function of ω_1 and therefore the effect of a supply shift is larger for crops which represent a larger share of the yearly wage of bees.

Finally, the effect of a change in the price of honey on bee wages is ambiguous:

$$\frac{Ew_{11}}{Ep_h} = \frac{(\alpha_{11}\gamma_{11}\mu_{12}\mu_2 + \alpha_{12}\gamma_{12}\mu_{11}\mu_2 - \alpha_2\mu_{11}\mu_{12})\,\varepsilon(1-\omega_1) - (\alpha_{11}\gamma_{11}\mu_{12} + \alpha_{12}\gamma_{12}\mu_{11})}{\Psi} \tag{3.A.28}$$

with

$$\Psi = \varepsilon\omega_1\mu_{11}\mu_{12} - \varepsilon^2(1-\omega_1)^2\mu_{11}\mu_{12}\mu_2 - (\gamma_{11}\mu_{12} + \gamma_{12}\mu_{11})(1 - \varepsilon(1-\omega_1)\mu_2) \geq 0. \tag{3.A.29}$$

The denominator Ψ is positive because as for Φ, the terms preceded by a positive sign have even numbers of μs and terms preceded by negative signs have odd numbers of μs. Furthermore, $(1 - \varepsilon(1-\omega_1)\mu_2)$ is positive as before. In contrast, the sign of the numerator depends on the values of the parameters. In order to gain some intuition on the meaning of expression 3.A.28, it is useful to consider two special cases.

[17] According to the notation, an increase in the marginal cost of beekeeping corresponds to a negative Es.

First, if we assume that the only honey producing crop is the crop of the second period and that bees do not provide any pollination service to that crop, expression 3.A.28 can be simplified using the facts that $\alpha_{11} = \alpha_{12} = 0$ and $\alpha_2 = 1$:

$$\frac{Ew_{11}}{Ep_h} = \frac{-\alpha_2 \mu_{11} \mu_{12} \varepsilon (1 - \omega_1)}{\Psi} \leq 0. \tag{3.A.30}$$

In this case, an increase in the price of honey causes a decrease in the wage of bees for the first period. An increase in the price of honey increases the derived demand for bees in crops that produce honey and since only the crop in the other bloom season produced honey, the wages for the first period decrease.

Consider a second special case in which the only honey producing crop is crop 2 in the first period. In that case, $\alpha_{11} = \alpha_2 = 0$ and $\alpha_{12} = 1$. Therefore, expression 3.A.28 becomes:

$$\frac{Ew_{11}}{Ep_h} = \frac{-\gamma_{12} \mu_{11} \left(1 - \varepsilon (1 - \omega_1) \mu_2\right)}{\Psi} \geq 0. \tag{3.A.31}$$

Here, an increase in the price of honey results in an increase of bee wages for the first period for a similar reason than before except that the increase in derived demand for bees occurs on a crop that competes for bees with crop $(1,1)$. In the general case of expression 3.A.28 the net effect of changes in honey prices depends on the relative changes in derived demand from crops of the same and other bloom periods.

Rucker, Thurman, and Burgett (2008) identify the pollination fee as the bee wage minus the value of the marginal product of honey. In my model, the pollination fee is equal to $\mu_{t,i} Eb_{t,i}$ and the results derived in equations 3.A.24, 3.A.26, 3.A.27, and 3.A.28 can be written in terms of pollination fees using equation 3.A.23. When the price of honey is constant, this is equivalent to dividing the fraction for the bee wage expression by $\boldsymbol{\mu}$ to obtain the proportional change in pollination fees. When the price honey varies, expression 3.A.28 can be also converted to pollination fees but the sign of the relationship remains ambiguous.

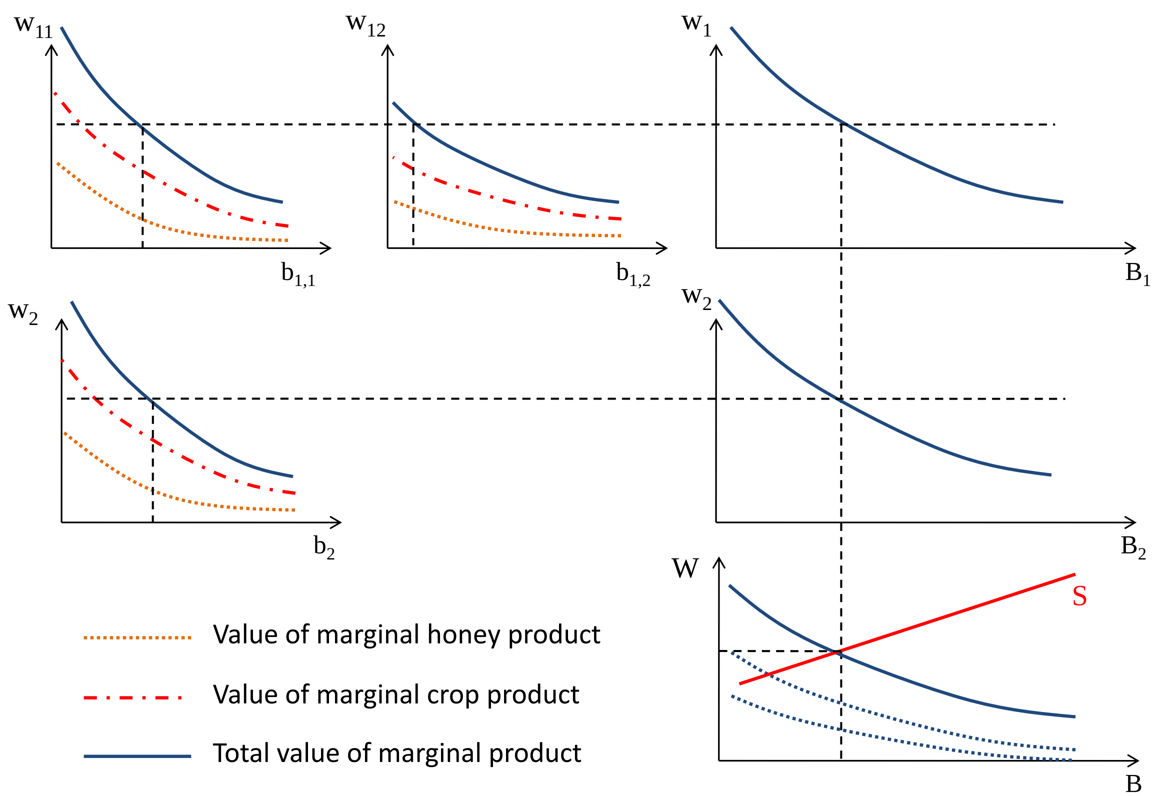


Figure 3.A.1: Diagram of pollination market equilibrium with two periods and three crops

References

Burgett, M. 1999. "Pacific Northwest Honey Bee Pollination Economics Survey 1999." Working paper, Department of Horticulture Oregon State University.

—. 2006. "Pacific Northwest Honey Bee Pollination Economics Survey 2006." Working paper, Department of Horticulture Oregon State University.

—. 2007. "Pacific Northwest Honey Bee Pollination Economics Survey 2007." Working paper, Department of Horticulture Oregon State University.

—. 2009. "Pacific Northwest Honey Bee Pollination Economics Survey 2009." Working paper, Department of Horticulture Oregon State University.

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

Daberkow, S., P. Korb, and F. Hoff. 2009. "Structure of the U.S. Beekeeping Industry: 1982Ű2002." *Journal of Economic Entomology* 102:868–886.

Hoff, F.L., and L.S. Willett. 1994. "The U.S. Beekeeping Industry." Working paper No. AER-680, United States Department of Agriculture.

Meade, J.E. 1952. "External Economies and Diseconomies in a Competitive Situation." *The Economic Journal* 62:54–67.

Muth, M.K., R.R. Rucker, W.N. Thurman, and C.T. Chuang. 2003. "The Fable of the Bees Revisited: Causes and Consequences of the U.S. Honey Program." *Journal of Law and Economics* 65:479–516.

Rucker, R.R., W.N. Thurman, and M. Burgett. 2008. "Internalizing Reciprocal Benefits: The Economics of Honey Bee Pollination Markets." Unpublished, Working Paper.

Schmickl, T., and K. Crailsheim. 2007. "HoPoMo: A model of honeybee intra-colonial population dynamics and resource management." *Ecological Modelling* 204:219–245.

Sumner, D.A., and H. Boriss. 2006. "Bee-conomics and the Leap in Pollination Fees." Working paper, University of California, Agricultural Issues Center, Giannini Foundation of Agricultural Economics.