The Bioeconomics of Honey Bees and Pollination

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Abstract: We model the economic behavior of beekeepers who shift bees from crop to crop to follow successive blooms. On each crop, foraging bees jointly produce honey and pollination services. Accordingly, the supply of pollination services to growers of a given crop depends on both the price of honey and the demand for pollination services from other crops. The within-season population dynamics of bees helps explain seasonality in pollination markets. The bioeconomic model predicts that pollination fees for crops blooming early, such as almonds, are more sensitive to increases in winter losses of bees. Winter loss of bees, in turn, is partly the result of a choice that depends on relative prices of honey and pollination services.

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 article adds to the small literature on the economics of pollination by presenting a model of beekeeper behavior which incorporates within- and between-season dynamics in the size of honey bee populations in hives. Unlike static models, our model explains seasonal patterns in pollination service prices. The model also contributes to understanding the general rise in pollination service prices over the past decade.

In the last half century, policy discussion on domesticated pollinators have often overlooked the importance of the economic behavior of beekeepers. For instance, U.S. honey subsidy programs were 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)). This argument is however disputed by Cheung (1973), who showed that the existence of pollination markets may be sufficient to solve the externality problem.[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 (National Research Council 2007, p. 75). While it is clear that biological factors alone could explain colony losses, we would expect that impacts from biological drivers would be mitigated by economic behavior of beekeepers. It is even plausible that economic behavior alone, such as shifts in the demand for honey or pollination services, could explain the observed changes in hive numbers. Finally, biological drivers are not likely to be simply exogenous shocks to the 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 lack of attention paid to the behavioral determinants of modern beekeeping has also resulted in a faulty interpretation of the data available on colony numbers.[2] The widely reported decline in the number of honey bee colonies has been supported mainly with the use of hive counts by the USDA published in the Honey reports (National Research Council 2007, p. 26). Yet, the hive counts provided by Honey reports and the alternative (but intermittent) Census of Agriculture counts provide conflicting pictures of the evolution of hive numbers in the last two decades. Figure 1 presents hive counts from 1945 to 2009 from both sources. The Honey reports only count hives that produce honey, but these hives are counted multiple times if they produce honey in different states in the same year. 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, the figures from the Census of Agriculture actually show an *increase* between 2002 and 2007. The most notable change for the beekeeping industry during the latter part of the period was the drastic rise 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 and their sum from 1992 to 2009. The honey revenue per hive does not show any obvious trend because neither honey yields nor honey prices have shown large variations in recent years. The pollination revenue increased markedly between 2004 and 2009 following the increase in demand for pollination services for almonds in

California. We would expect beekeepers to respond to rising demand for pollination services by expanding hives, and this supply response of beekeepers to the almond rush is only visible in the Census data. It seems that Honey report data, for which counts are based on honey production only, provide a distorted picture of the beekeeping industry, particularly in recent years as the share of pollination revenues in beekeeping has increased dramatically. The public's perception, in contrast, is of an industry in a decline that is dominated by disease-induced colony collapse, a characterization which on closer examination does not hold up in the aggregate.

These patterns in 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 populations have not been tested empirically. Declines in indicators of bee health, such as the frequency of mite infestation, have been used to explain declines in hive counts but no explicit consideration of economic factors has been proposed.[3] 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. This article takes a step toward structuring econometric and data-based studies by developing an economic model of beekeeper behavior which captures the salient trade-offs between the production of honey and the production of pollination services. This modeling enables us to interpret current patterns in prices and quantities of pollination services, develop hypotheses consistent with economic behavior, and identify further data collection requirements.

The jointness of production of honey and pollination services is among 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. Cheung (1973) assumes that the bees and crop plants are joint inputs for the production of honey and crop harvest. Muth et al. (2003) and Rucker, Thurman, and Burgett (2003) have since developed the analysis proposed by Cheung (1973) maintaining the assumption of a joint-input joint-output production function. 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 two forms: pollination fees and honey revenue. Because hives can be easily transported and because there are many participants on both sides of the market, competition among growers and among 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 per stay.[4] Conversely, when honey bee pollination does not increase the revenue from crop production, as for instance in most citrus crops, the bee wage is equal to the value of the marginal product of honey. In citrus, beekeepers keep the entire honey output and pay a fee to growers. The fee is equal to the value of the marginal product of citrus blossoms in the production of honey.

In the specification of the implicit production function used by Cheung (1973, p. 19) and the contributions that followed, the fact that bees feed on the crops they pollinate is not represented. In this article, we develop an alternative specification for the production function which recognizes that in addition to plants and bees being inputs for the production of honey and crops, the pollen and nectar from crops are inputs in the production of the stock of bees. We show that using an appropriate description of the production of honey and pollinated crops better accounts for observed patterns of price and quantities.

A second important feature of the economics of beekeeping which, in contrast to the jointness of production, has been not been addressed before in the economics literature, relates to the dynamic nature of the bee stock and its within- and between-year variations. The same hives are used to pollinate and produce honey from several crops in a given year tracking the bloom sequence of the crops. Throughout the year, the population of bees in hives varies according to the quality and quantity of forage that crops provide. Hauling hives from crop to crop not only allows competition for bees across crop growers whose crops bloom at the same time, but also enables migratory beekeepers to capture the returns from using the same hives for several crops over a single year.

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. Cheung (1973) also provides some intuition regarding the consequences of migration.[5] Nonetheless, the insights that can be gained from considering the dynamics of the stock of bees have been generally overlooked.

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 survey data from the California State Beekeeper Association.[6] 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 cherry varieties blooming later have not (see figure 3).

Because he did not account for the dynamic nature of the stock of bees, Cheung did not accurately characterize the full set of tradeoffs when he found that pollination markets solved the "externality" problem proposed by Meade (1952). This article shows that accounting for the dynamics of the stock of bees results in an economic model of pollination fees that fits observed data better than do static models. Accordingly, the functioning of pollination market reflects not only the joint production of honey and pollination services, but also the dynamic problem resulting from within-season and between-season allocation of bees. Both jointness of production and dynamics of the stock and allocation of bees are developed next with a dynamic model of the bee population and the honey stock in a hive. The model identifies the trade off that exists between pollination services and honey production when these are interdependent and dynamic. We 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.

A model of honey bee population and honey stock dynamics

This section presents a stylized model of the dynamics of bees and honey in a hive. Solving this model leads us to 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 then utilizes simple assumptions about carryover to connect behavior between years. It describes how the optimal yearly cycle of bees and honey varies according to the relative prices of honey and pollination services, assuming prices are exogenous. This is thus a model of the behavior of a representative beekeeper who repeats an optimal cycle over the years; changes in relative prices would alter both the within-year behavior as well as the between-year carryover.

Coupling bee population and honey stock

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.

We first develop a model for a single crop and identify the nature of the trade-off between honey and pollination services before showing how our model can be extended to deal with multiple crops.

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.[7]

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:

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

$$\frac{dH(t)}{dt} = -\beta X(t) + \mu\, min(X(t), X_{max}) \equiv \dot{H}(t) \tag{2}$$

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 (1) represents the number of bee deaths per unit of time and we assume that the death rate, δ, is constant throughout the foraging season. The second term represents the births. The number 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, α, γ, and δ cannot be interpreted like parameters of models of population dynamics that reflect the aggregate result of individual behaviors.[8]

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 μ by foraging.[9] In order to represent the fact that crops provide a limited amount of resources to bees per acre, the rate of honey increase μX(t) cannot exceed a given value X_{max}. 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 μ min(X(t), X_{max}), 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 feature 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.

Boundary conditions for a steady-state yearly cycle

In addition to these coupled equations of motion for the bee and honey stocks, we specify boundary conditions for their cycle. At the end of the foraging season, an amount H_{harv} of honey is harvested by the beekeeper. This amount, 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. The quantity of honey harvested H_{harv} can be positive to represent extraction or negative to represent feeding, however the rest of the discussion focuses on the extraction case.

In a long run equilibrium in which each cycle repeats itself, 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), (3), and (4) above can be solved analytically by solving two sets of equations, corresponding to $X(t) \leq X_{max}$ and to $X(t) > X_{max}$.

When X(t) is smaller than X_{max}, 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:

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

and V_1 and V_2 the corresponding eigenvectors.[10] A_1 and A_2 depend on initial conditions.

When X(t) is larger than X_{max}, the solution is of the form

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

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

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

$\bar{A}_1$ 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 are required to describe the entire trajectories of bee population and honey, are a function of the time τ at which X(t) reaches X_{max} 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.

Yearly trajectories of bee population and honey stock

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 $\dot{H}(t) = 0$ and $\dot{X}(t) = 0$. The position of X_{max} 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 due to overwintering attrition. Following (3), the bees in the hive do not deplete the stock of honey during the inactive period and therefore, the trajectory during the inactive period is represented by a horizontal line when no honey is harvested. This section of the trajectory and the rest of the cycle corresponding to no harvest or H_{harv} =0, are 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 $\dot{H}(t) = 0$ and $\dot{X}(t) = 0$. As indicated at the top of the honey stock axis, there is second nullcline for H, but any equilibrium on that nullcline would only be reached if the active 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 beginning of the active period which is also 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 in that case only at the point where the trajectory crosses that nullcline. From there, the population of bees increases at a rate $-\beta X(t)+\mu$ and the stock of honey increases at a rate of $(\beta+\mu)$ until the colony reaches the carrying capacity X_{max}. After X_{max}, 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 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 $\alpha(\gamma H(t)-X(t))$, we represent some of the biological feedbacks that exist in the queen's laying rate. 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.

Numerical simulations for bee population and honey stock trajectories

Figure 5 shows the numerical solutions of the cyclic trajectories for five different amounts of harvested honey H_{harv}.[11] Panel (a) represents the numerical counterpart of the illustrative phase diagram shown in figure 4. Panels (b) and (c) in figure 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 for some cycles, the population of bees in the hive may at first decreases during the first part of the active period. This pattern 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 honey harvested is given as a function of the resulting average bee population over the length of the active season. This average can be used as proxy for the pollination service provided by the hive since foraging, and hence pollination, are proportional to hive size in first approximation.[12]

The relationship between the average population of bees and the honey extracted corresponds to the production possibility frontier which identifies tradeoffs 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 seven dots on the production possibility frontier in figure 6 correspond to the seven 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} = 61.1 pounds, a 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 $X_{no\ honey}$ = 67,456 bees when no honey is harvested.

Furthermore, the production possibility frontier is linear for a honey harvest inferior to 41.9 pounds. Indeed, when the amount of honey harvested is low enough, the population of bees in the hive remains throughout the year above the carrying capacity X_{max} and therefore, the entire trajectory of the growing season is given by (6). In that case, the constants in the expression of the population of bees are simply proportional to H_{harv} and the average population of bees is also a linear function of H_{harv}. It is when H_{harv} exceeds the threshold of 41.9 that the trajectory for the bee population switches from (5) to (6) at some time during the active season. It is the specification of a non-linearity in the capacity of crops to provide forage to bees that generates the non-linearity in the production possibility frontier.

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.

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. We discuss later how the analysis that follows extends to the case where the cost of maintaining a hive varies linearly with the average number of bees.

When the cost per hive of beekeeping inputs are fixed, 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 vertical axis of figure 6. It is optimal for the beekeeper to produce at that point if the ratio of pollination service price over honey price is smaller in absolute value to the slope of the tangent to the production possibility frontier at H_{max}. This corner solution 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 larger than the slope at $X_{no\ honey}$. 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.

In our model, the number of bees that die over the winter depends on the relative prices of honey and pollination services. High pollination fees result in a lower bee population drop.

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 difference is that we derive the shape of the production possibility frontier from the dynamics of honey stocks and bee populations. More importantly, our model provides additional insight and a more complete understanding of the economic behavior of beekeepers when more than one crop is considered, as in the next section.

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, we 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. Also, we 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 pollination revenue 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.[13]

Figure 7 illustrates one plausible hypothesis 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.[14] Almonds pollination provides a good illustration of this case.

Other cases deserve to be addressed in further work, in particular with multiple crops which bloom both simultaneously and sequentially and which also differ both in carrying capacity and crop value.

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. In the model developed in this article, this value is taken into account in the production possibility frontier derived from the dynamic model of bee population in a representative hive.

Our model highlights several important characteristics of the supply of pollination services that must be taken into account in the economic analysis of recent trends in pollination markets.

Sequential blooms and bee population

Our dynamic model of bee population and honey stock generates a production function which differs in an important way from the one used by Cheung (1973) and the subsequent contributions to the literature. Bees feed on crops and it is useful to consider bees not only as an input to crop production but as a valuable stock which itself can be increased with the joint use of crop forage and other beekeeping inputs.

The model of bee population dynamics presented in this article provides two related hypothesis to explain the steep rise in pollination fees which cannot be explained by evoking only the jointness of production of honey and pollination services for a given crop.

First, our model shows that the size of the population of bees available for the pollination of any one crop depends on the carrying capacities of all the crops on which the bees will forage during a year. Accordingly, the increase in the population of bees for almonds is constrained by the fact that the acreage of crops on which bees feed after their stay in almonds.

Second, our model shows that crops that bloom early face a steeper supply for pollination services because a large population of bees early in the active foraging season requires a larger quantity of harvested honey to be forgone and a large carrying capacity from crops during the rest of the foraging season. The importance of recognizing that bees use crops as forage has increased as the value of the bee stock has increased relative to the value of harvested honey because of the almond pollination boom.

The importance of variations in bee population size

The number of bees in hives must be measured and tracked. The size of the bee population in a hive, which is known to vary widely both over time and across hives, determines (in a non-linear way) the amount of pollination service the hive provides (Danka, Sylvester, and Boykin, 2006). Measuring the density of bees per acre of crop as opposed to measuring hives per acre would allow better tracking of potentially large variations in pollination services and in the amount of forage available per bee.

Because of the growth of the bee population between early spring and fall, it is misleading to compare pollination fees measured in dollars per hive across the different blooming periods without adjusting for bees per hive. Of course, the number of bees per hive can also differ across hives during the same period of the year. To reflect heterogeneity, price premiums for hives containing more bees are common in pollination contracts for almonds. The number of bees in a hive depends on management practices, which include the choice of crops on which hives are placed, the frequency of manual queen replacement, or prevention of damages from parasites.[15]

Differences in the number of bees per hive may spur comparisons of pollination fees across crops because the growers of certain crops devote more resources to control the quality of the hives they rent. 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 shown in figure 3. It is not possible to determine without a measure of the number of bees per hive whether the difference between avocado and almond fees is because avocados provide more nectar to bees than do almonds or because avocado growers tend to use only hives with fewer bees per hive.[16]

Model limitations and extensions

This article analyzes the economics of the production of honey and pollination services and shows how the jointness of production and the dynamics of the bee population help understand the functioning of pollination markets. Several other aspects of the economics of beekeeping need to be understood to complete the picture of the management of pollinators in agriculture.

Modeling the supply and demand for pollination services

The empirical analysis of the patterns observed in pollination markets requires connecting our bee supply model with a model of demand for pollination services and honey. This article focuses on the dynamic optimization of the management of a single representative hive. The total number of hives that are reared is not determined in the current model to which assumptions about beekeeping input costs and competition need to be added. A complete model of pollination markets where both hive numbers and actual bee populations are tracked is the object of current research.

The results of model have implications for the long lasting discussion on pollination externalities. According to Muth et al. (2003), honey subsidies have been publicly supported because they increase the provision of pollination services when honey and services are considered joint inputs. When the seasonality of crops is considered, the effect of honey subsidies on the amount of pollination services available for any given crop need not always be positive.

Other species of pollinators

Honey bees are only one of the alternative pollinator species that can be managed to pollinate agricultural crops. Substitutions between commercial honey bees, other bee species, and wild pollinators have received increasing attention, from both conservation biologists and farmers (Kremen et al. 2008). Differences and similarities among species of pollinators represent important issues for the economists studying the management of pollination in agriculture.

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. 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 article is to highlight the fact that crop blossoms are, in addition, an input for the production of the stock of bees. We show the importance of this by modeling the dynamics of both the stock of stored honey and the population of bees in a hive. This reciprocity is a 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. However, because many of these species are not conveniently moved by beekeepers, their stock most likely depends on the few crops and wild plants within their local foraging range. Also, because pollinator species other than honey bees do not store honey in a harvestable form, their management does not involve the problems of joint output production of honey.

The costs of migration

Economists have not measured the costs of moving bees from place to place. Nor have economists modeled the implications of bee migration in a spatially explicit way. In fact, although the general pattern of seasonal migration of beekeepers and their hives is known, hardly any data are available that detail the flows 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 inclusion of transportation costs in economic models of pollination markets may be important for two reasons.

First, the spread of pests and diseases, which impose large costs on the beekeeping industry, depends on the patterns of migration of hives.

Second, higher migration costs relative to prices of bee outputs could result in a separation of the regional markets for pollination. In each of the separate markets resulting from this segmentation, the opportunity for beekeepers to find crops that bloom in sequence would be reduced. For instance, pollination fees for almonds would increase if beekeepers who place their hives in the citrus groves of Florida did not find it profitable to drive across the country to earn almond pollination fees.

Concluding remarks

Whereas the model developed above has been tailored to the specific of honey bee management, the scope for our bioeconomic approach is quite broad. Pollination markets tackle the complex problem of jointness of production first outlined by Meade and the management of a renewable and migratory stock the economic value of which derives from both extraction and the provision of a service. These problems are general in the management of livestock and the study of the economic institutions of beekeeping provides insights about the bioeconomic of domestication of species more generally.

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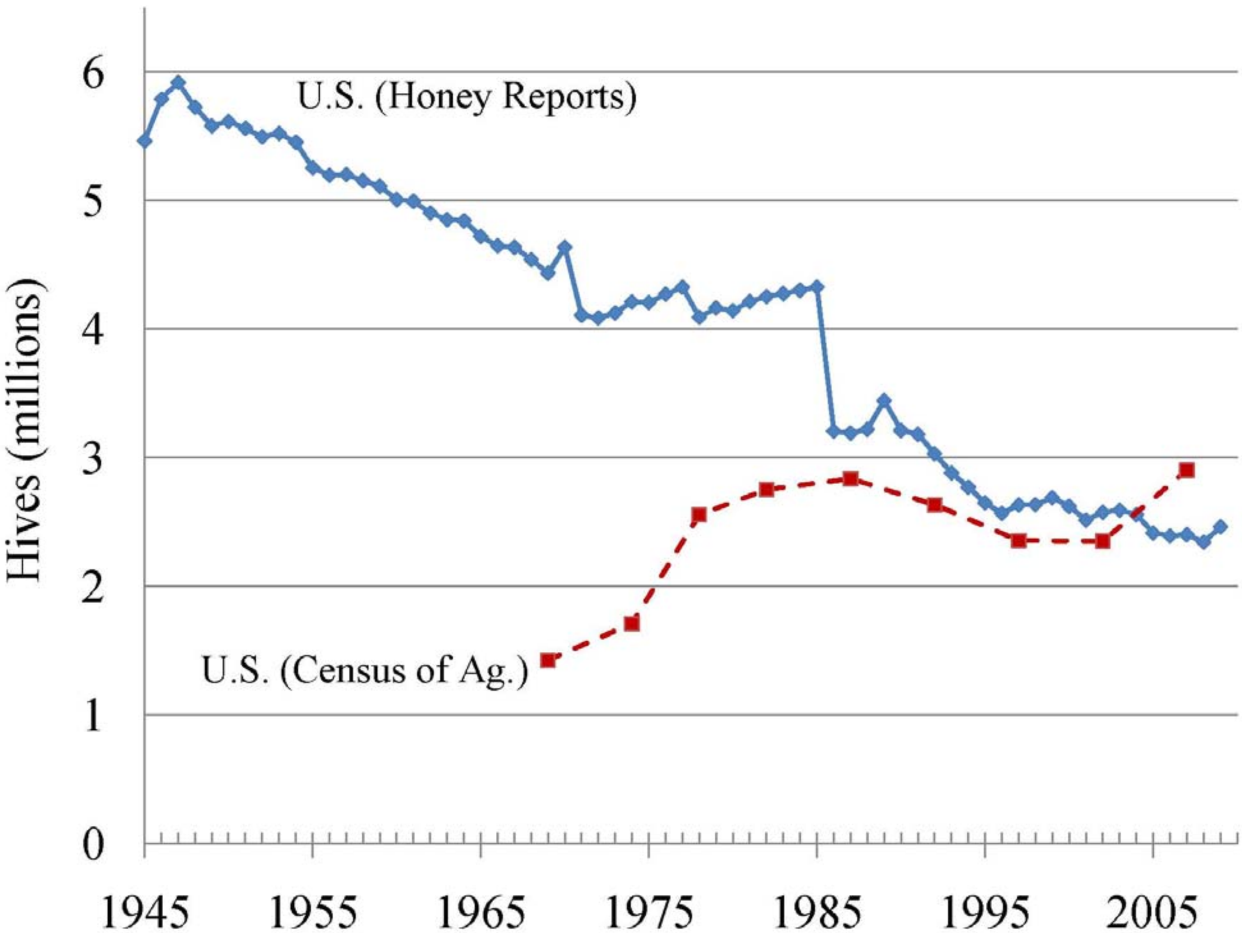
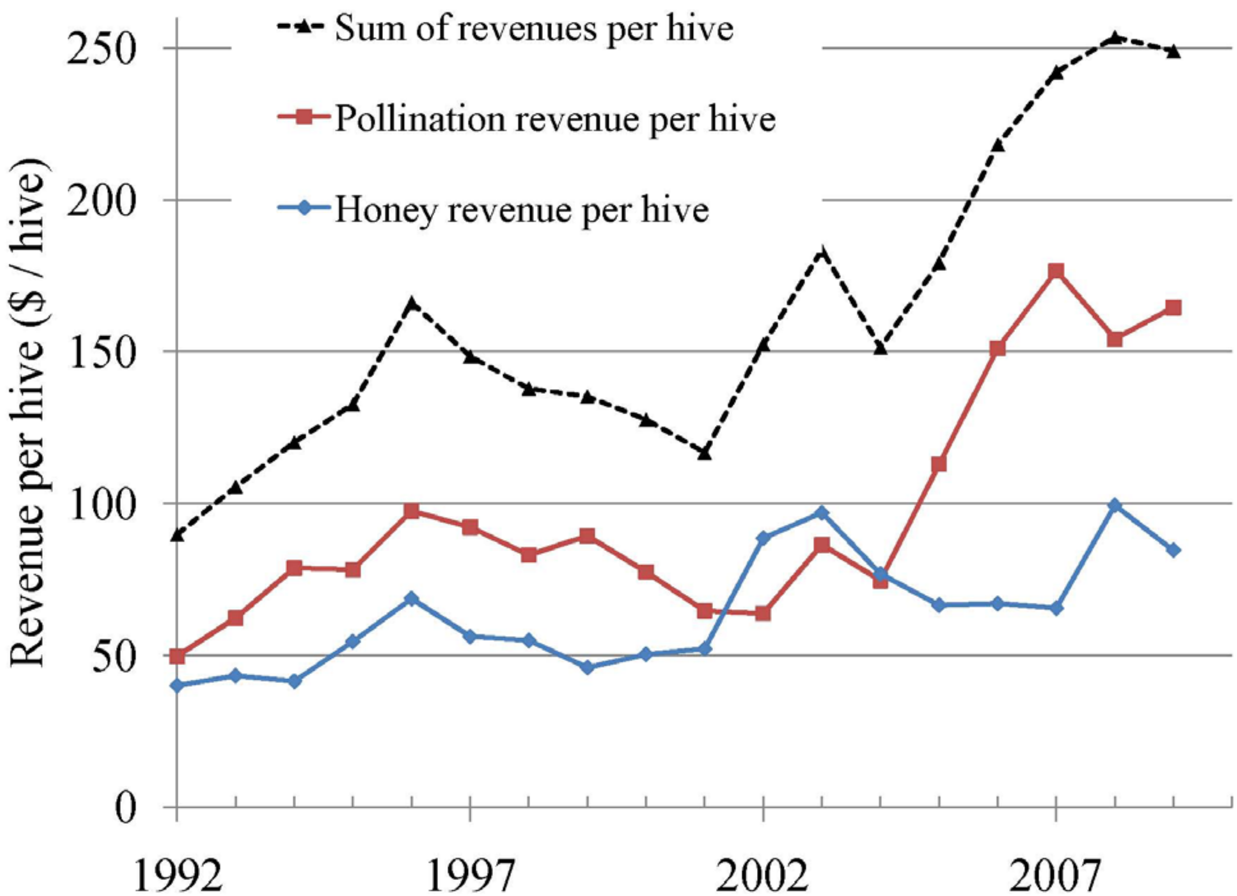


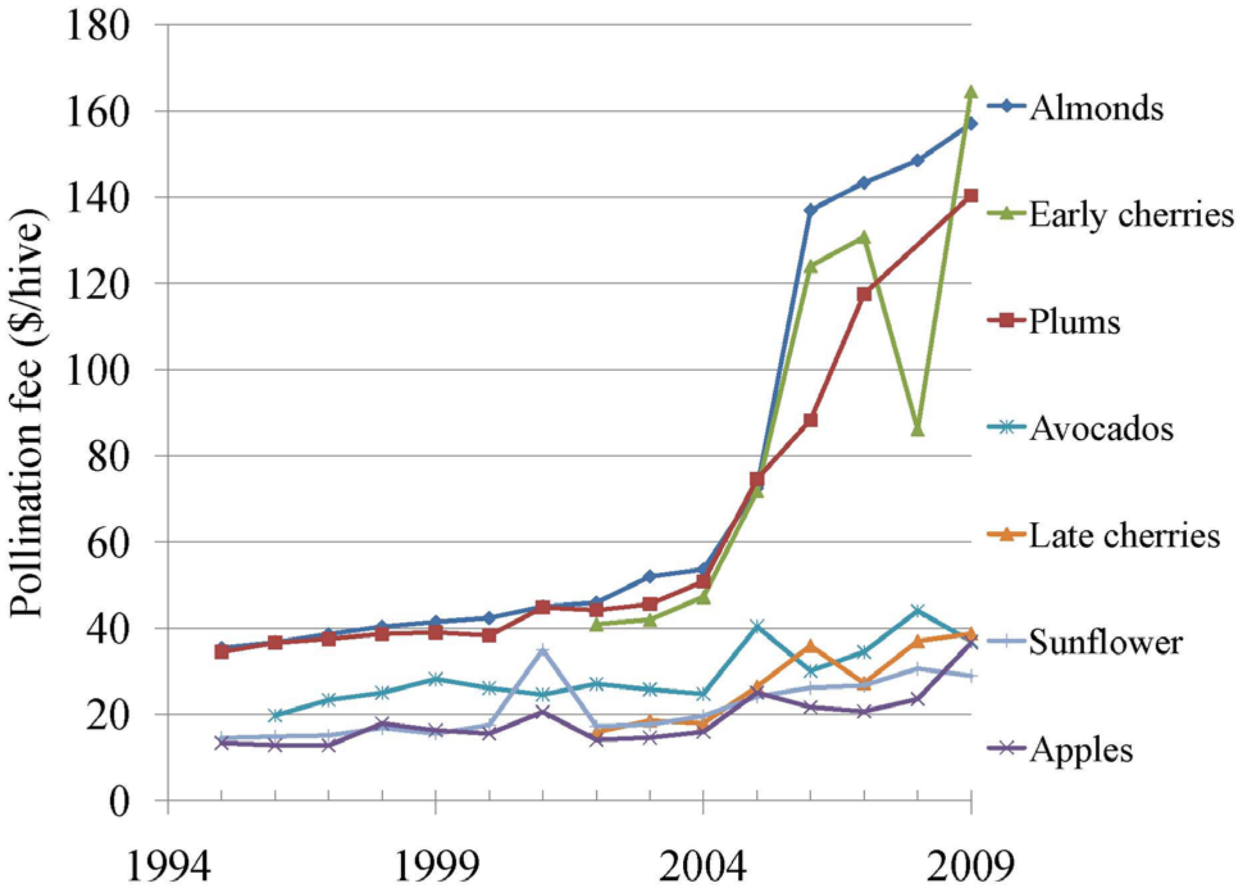
Source: USDA Honey reports, U.S. Census of Agriculture.

Figure 1. Hive numbers in the United States from 1945 to 2009



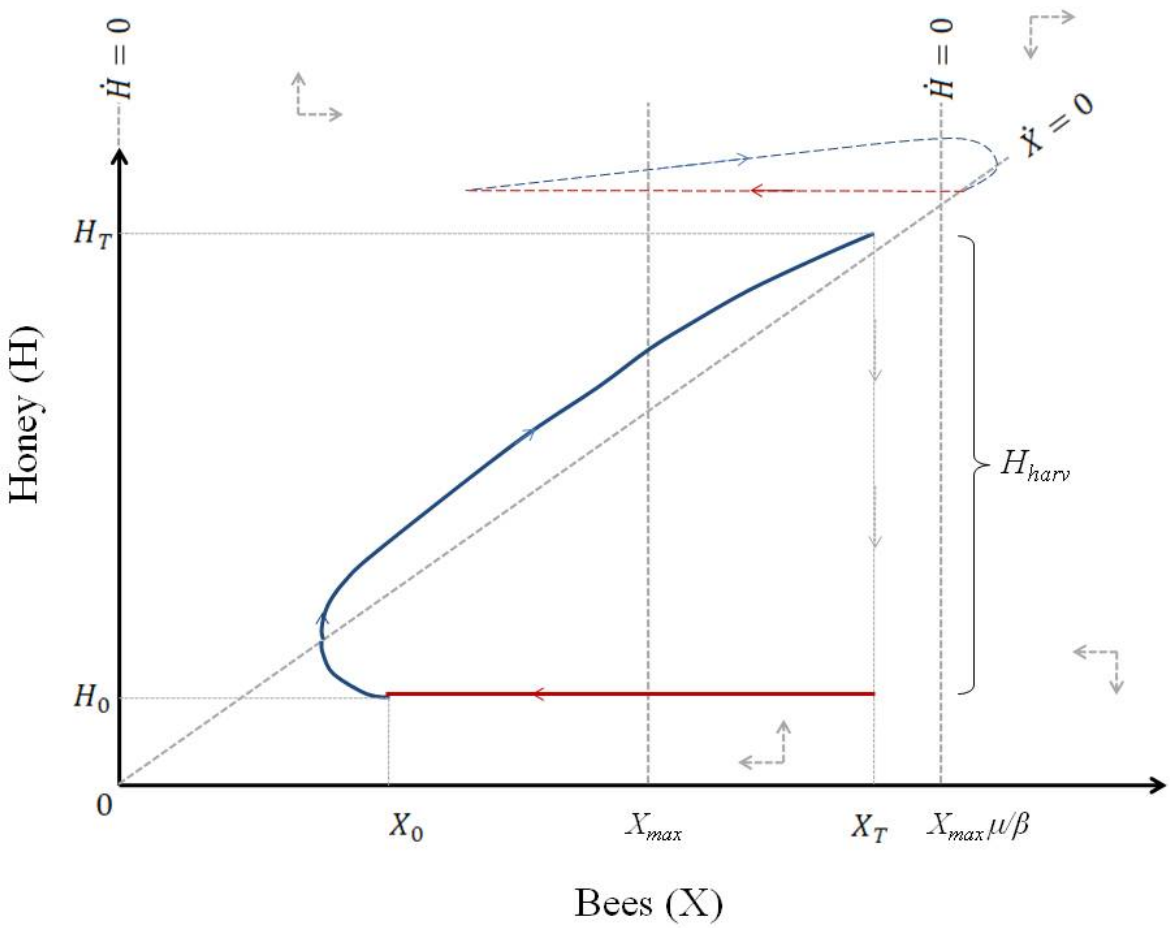
Source: The pollination revenues come from the average pollination revenues per hive reported in the “Pacific Northwest Honey Bee Pollination Economics Surveys” 1999, 2006, 2007 and 2009 from M. Burgett at the Department of Horticulture, Oregon State University. The honey yield in pounds per hive and honey prices 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



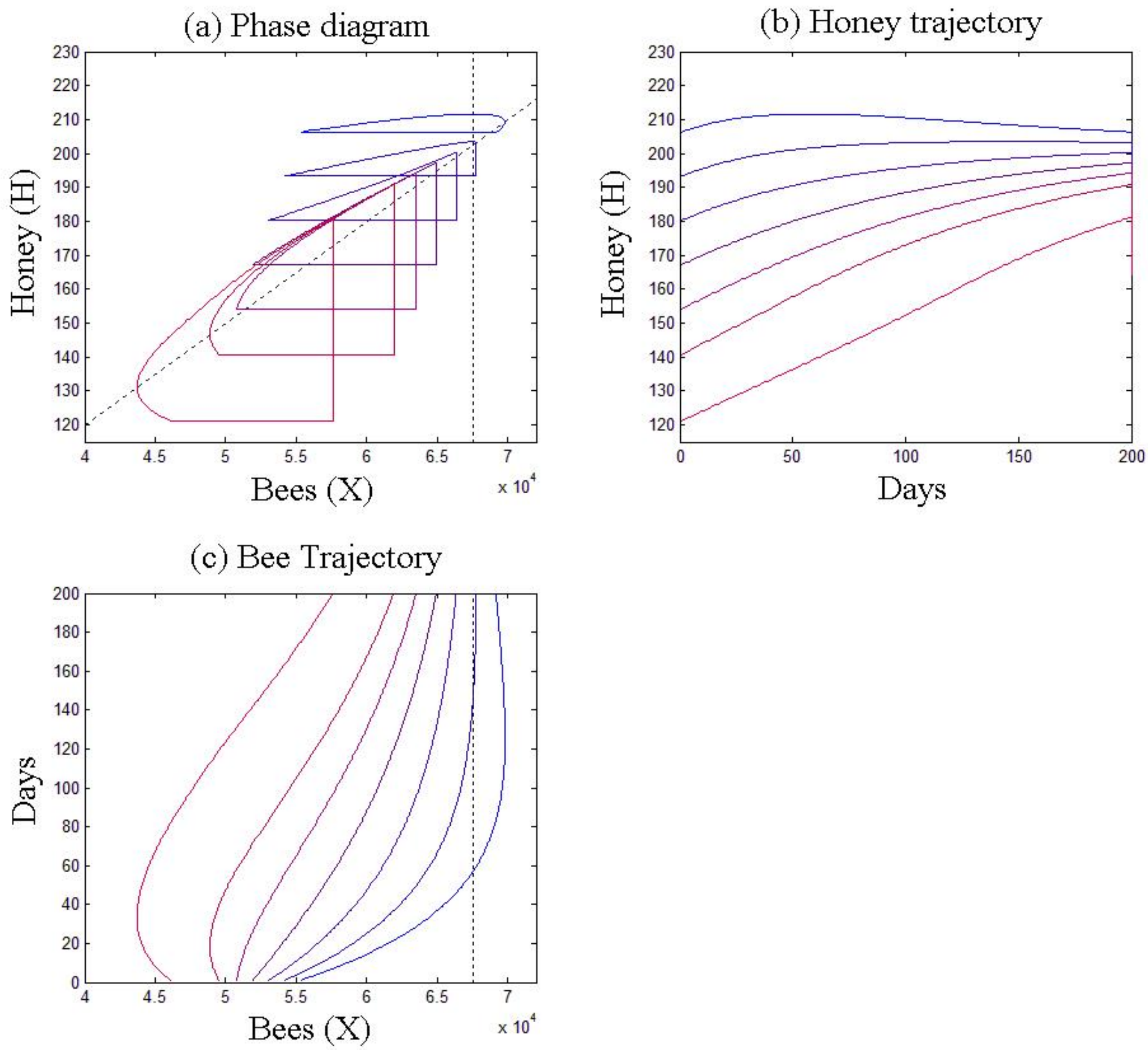
Source: California State Beekeeping Association Pollination Surveys. The figure does not show the pollination fee for plums in 2008 because only two observations are available for that year and crop.
Note: Almonds, plums, early blooming varieties of cherries, and avocado bloom in February and March whereas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

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



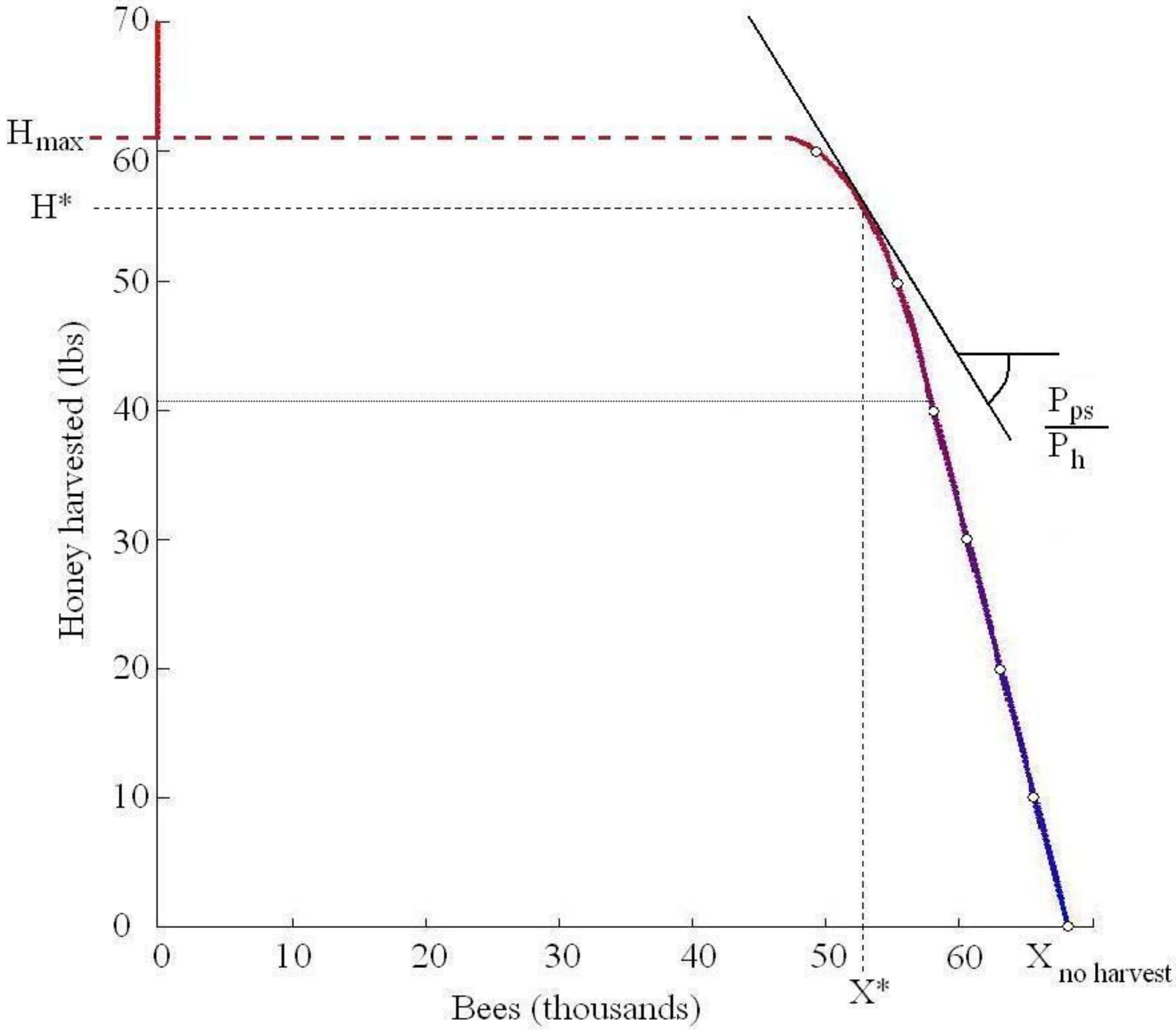
Note: The cycle in dashed line in the top right corner of the diagram corresponds to the trajectory in the absence of honey harvest, whereas for the solid line, $H_{harv} = H_T - H_0$ is extracted at time T. The curved section of each of the two cycles corresponds to the active period whereas the straight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

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



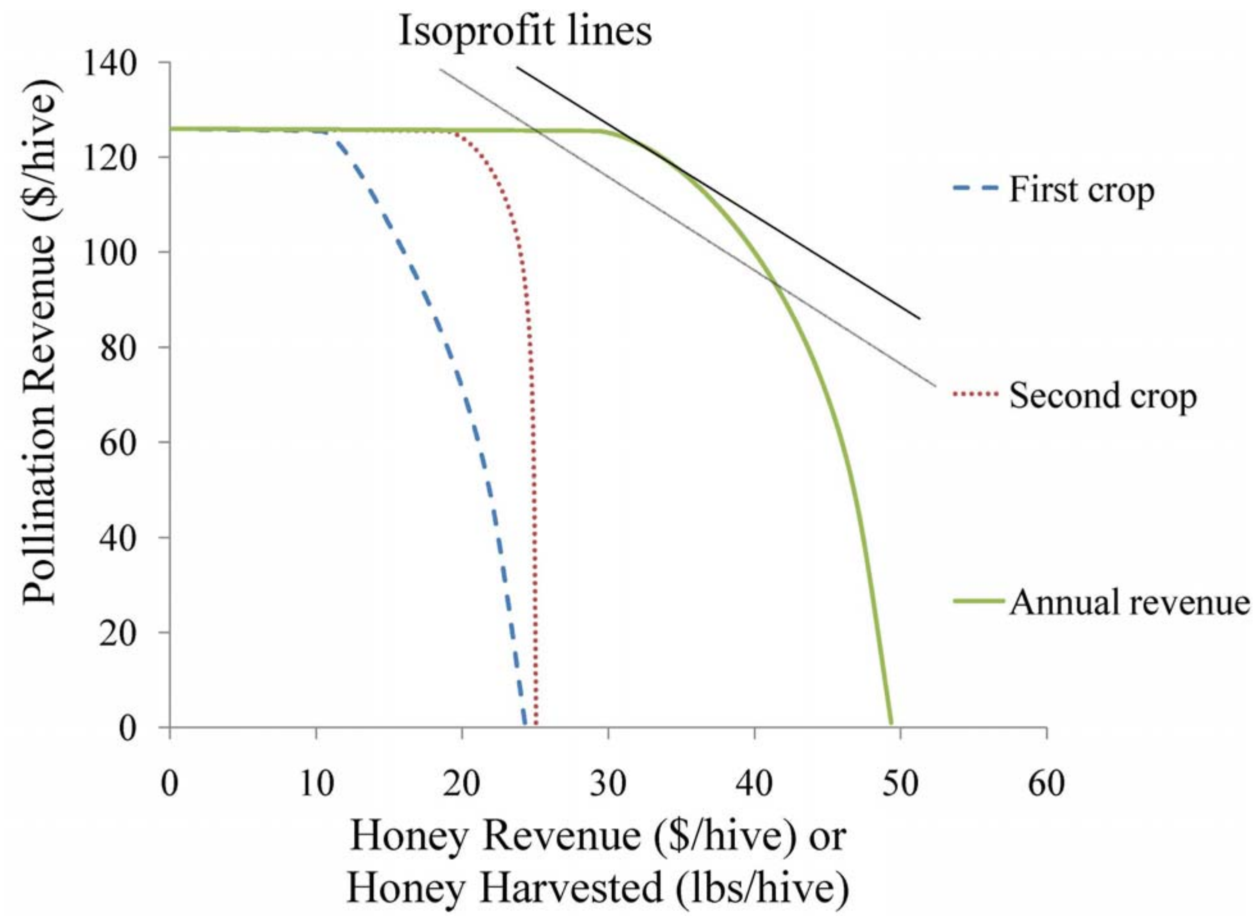
Note: Values of simulation parameters: T = 200 days; X_{max} = 50,000 bees; $\mu = 2.7 \text{x} 10^{-5}$; $\beta = 2.0 \text{x} 10^{-5}$; $\delta = 0.02$; $\gamma = 1{,}000$; $\alpha = 0.01$; $\omega = 0.2$;H_{harv} = {0, 10, 20, 30, 40, 50, 60} lbs.

Figure 5. Phase diagram and bee and honey trajectories for different honey harvests



Note: Values of simulation parameters: T = 200 days; X_{max} = 50,000 bees; μ = 2.7x10^{-5}; β = 2.0x10^{-5}; δ = 0.02; γ = 1,000; α = 0.01; ω = 0.2; H_{harv} = {0, 10, 20, 30, 40, 50, 60} lbs. H* and X* represent the optimal honey harvest and average bee population. The ratio P_h/P_{ps} is the honey to pollination services price ratio. The horizontal dotted line at H=41.9 lbs marks the point where the production possibility frontier switches from linear to non-linear.

Figure 6. Production possibility frontier along honey and bee population dimensions



Note: The annual 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 $1.00/lbs. The average honey price for 1999-2009 from USDA Honey reports was $1.05/lbs.

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

Footnotes

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

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. A hive generally refers to the wooden box whereas a colony refers to the group of bees that live in it. Healthy colonies include a single egg-laying queen.

3 To the best of our knowledge, there is no published economic analysis of the decline in hive numbers. For instance, the list of possible causes of decline for managed pollinators provided by National Research Council (2007, p. 75) does includes the term “market forces” along with mites, pathogens, pesticides, and Africanized honey bees. However, no further reference to economic analysis is made.

4 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 as a single fee the entire bee wage to beekeepers.

5 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.

6 To the best of our knowledge, the pollination survey data from the California State Beekeepers Association are not available online but can be obtained from the authors or by directly contacting the association (http://www.californiastatebeekeepers.com/).

7 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.

8 See Schmickl and Crailsheim (2007) for details about the dynamics and feedbacks of bee population. We 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.

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

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

11 See the note in figure 5 for parameter and honey harvest values.

12 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. For a more thorough discussion of this issue see Seeley (1995) and Danka, Sylvester, and Boykin (2006).

13 It is in principle possible for the bee population size to be higher on average during an earlier period than in subsequent ones if the carrying capacity of the early crop is high relative to the second crop and bees remain long enough on that first crop.

14 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 in terms of bee health and for honey production.

15 The heterogeneity of beekeepers has also been documented, for instance by Daberkow, Korb, and Hoff (2009) but the relationship between the characteristics of beekeeping operations and the characteristics of hives has been less studied.

16 Almond growers demand relatively high-strength hives. Contracts between growers and beekeepers that specify the strength of hives, which is a measure of the number of bees in hives, are common in the almond industry.