Online Appendix for:

To (Rent) Bees or Not to (Rent) Bees? An Examination of the Farmer's Question

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A Theory Model

A.1 Pollination Choice

Farmers of pollination-dependent crops grow much of the world's nutritious and high-value fruits, nuts, and vegetables. They face very complex production decisions, which in many cases involve long-term investments – especially for long-lived tree fruits and nuts – and production is often labor intensive and dependent on migrant farmworkers (Ridley and Devadoss, 2021). Agronomic trends are also evolving away from traditional, low-density, very long-lived plants to high intensity, university-driven plant materials that are selected to tolerate greater density of fruit into smaller area on smaller trees, which are easier to harvest (Robinson et al., 2013).

Pollination choice, and general production strategies that affect pollination resource demand (e.g., planting density), are very important. Although insect pollination is not necessary for all crops, many crops require or benefit greatly from pollination from insects or other organisms.[1] In addition to decisions about general production strategies and other input choices, producers of pollination-dependent crops make decisions about whether and how much to use managed pollination services (e.g., renting honey bees); and whether and how much to invest in wild pollination (e.g., setting aside land for planting wildflower strips, or other natural cover (Cohen, 2022)).[2] Available research suggests that farmer pollination choices are critical as they impact farm-level outcomes like yield and fruit quality (Roubik, 2002; Garibaldi et al., 2013; Park et al., 2016; Russo et al., 2017; Danforth, Minckley, and Neff, 2019), local pollination resources within and beyond the

[1] In many cases crops are sufficiently self-pollinating (e.g., grasses), and in some special cases pollination is carried out with a combination of human labor and motorized or non-motorized farm implements (e.g., paint brushes, compressed air, and possibly drone-based technology in the future). Researchers are also developing self-pollinating plant varieties (Lee, Sumner, and Champetier, 2019). Widely consumed crops that require or greatly benefit from insect pollination include almonds, coffee, apples, avocados, cherries, peaches, blueberries, among many others.

[2] Although reliable global data on variation in pollination practices is not known to exist, available information suggests that farmers of pollination-dependent crops vary widely in the form of pollination they depend upon and in how critical pollination is viewed and valued as a resource. For example, contrast the well-trodden tail of US almond growers' seeming absolute dependence on imported honey bee colonies with reports that for many Northeast US apple growers pollination is almost an afterthought compared to concerns surrounding labor and traditional farm capital (Biltonen, 2020; Kahlke, 2019). Other qualitative variation is documented by Narjes and Lippert (2019) and Narjes and Lippert (2021) who document relationships between beekeepers and longan fruit farmers in Thailand. There are also special cases like vanilla in Madagascar, which is entirely dependent on labor for pollination (Boone, Kaila, and Sahn, 2022).

farm-gate (Kennedy et al., 2013; Park et al., 2015; Grab et al., 2018), and market-level outcomes through shifts in the supply and demand of both pollination resources and agricultural commodities (Rucker, Thurman, and Burgett, 2012; Goodrich, Williams, and Goodhue, 2019).

A.2 Proofs of Propositions 1 through 4

We take our start from the optimal control theory model in the main text:

$$\begin{aligned} \max_{\{I_k(t),\ L(t),\ M(t),\ I_w(t)\}} \ & \int_0^\infty \pi(K(t), L(t), M(t), W(t)) e^{-rt} dt \\ \text{s.t.} \ \ & \dot{K}(t) = \delta_k K(t) + I_k(t) \ \ : \ \lambda_k(t) \\ & \dot{W}(t) = F(W(t)) + I_w(t) - \delta_{mw} M(t) - \delta_{kw} I_k(t) \ \ : \ \lambda_w(t) \\ & K(t),\ L(t),\ M(t),\ W(t) \geq 0 \\ & K(0) = K_o,\ W(0) = W_o, \end{aligned} \tag{A.1}$$

and its current-value Hamiltonian:

$$\begin{aligned} H_c &= \pi(K,\ L,\ M,\ W) \ + \ \lambda_k \left[\delta_k K + I_K\right] + \lambda_w \left[F(W) + I_w - \delta_{mw} M - \delta_{kw} I_k\right] \\ &= p_c \Big(A \left[\gamma_o (\alpha_m M^{-\rho_o} + \alpha_w W^{-\rho_o})^{\frac{\rho}{\rho_o}} + \gamma_{kl} (\alpha_k K^{-\rho_{kl}} + \alpha_l L^{-\rho_{kl}})^{\frac{\rho}{\rho_{kl}}} \right]^{\frac{-1}{\rho}} \Big) - \\ &\quad \Big(p_k I_k + p_l L + p_m M + p_w I_w \Big) + \\ &\quad \lambda_k \left[\delta_k K + I_K\right] + \lambda_w \left[F(W) + I_w - \delta_{mw} M - \delta_{kw} I_k\right]. \end{aligned} \tag{A.2}$$

After applying the Maximum Principle and simplifying expressions we arrive at the following optimality conditions:

[#1L]: $p_c(t) \frac{\partial Q}{\partial L} = p_l(t)$

[#1M]: $p_c(t) \frac{\partial Q}{\partial M} = p_m(t) + p_w(t) \delta_{mw}$

[#1w]: $p_w(t) = \lambda_w(t)$

[#1k]: $p_k(t) = \lambda_k(t) - p_w(t) \delta_{kw}$

[#2w]: $\dot{p}_w = p_w(t)[r - \frac{\partial F(W)}{\partial W}] - p_c(t)\frac{\partial Q}{\partial W}$

[#2k]: $\dot{p}_k = p_k(t)(r - \delta_k) + p_w(t)\delta_{kw}(\frac{\partial F(W)}{\partial W} - \delta_k) + p_c(t)(\delta_{kw}\frac{\partial Q}{\partial W} - \frac{\partial Q}{\partial k})$

[#3w]: $\lim_{t\to\infty} p_w(t)W(t)e^{-rt} = 0$

[#3k]: $\lim_{t\to\infty}(p_k(t) + p_w(t)\delta_{kw})K(t)e^{-rt} = 0$

Per our assumptions stated in the main text, we focus on the respective first-order condition for M, denoted [#1M].

We start with the following Lemma:

Lemma 1:

First, we show that, for most reasonable values of the parameters, the production function is weakly concave in M: $\frac{\partial^2 Q}{\partial M^2} \leq 0$. Since a more explicit expression for this derivative is useful for our results of interest, we can also establish the negativity result analytically.

Given the stated structure of output Q as given by a 2-level CES production (Sato, 1967), we use the following expressions to simplify notation:

$$\text{Let } B = \alpha_m M^{-\rho_o} + \alpha_w W^{-\rho_o}$$

$$\text{Let } C = \alpha_k K^{-\rho_{kl}} + \alpha_l L^{-\rho_{kl}}$$

$$\text{Let } D = \gamma_o(\alpha_m M^{-\rho_o} + \alpha_w W^{-\rho_o})^{\frac{\rho}{\rho_o}} + \gamma_{kl}(\alpha_k K^{-\rho_{kl}} + \alpha_l L^{-\rho_{kl}})^{\frac{\rho}{\rho_{kl}}}$$

$$\Rightarrow Q = A[\gamma_o(B)^{\frac{\rho}{\rho_o}} + \gamma_{kl}(C)^{\frac{\rho}{\rho_{kl}}}]^{\frac{-1}{\rho}} = A[D]^{\frac{-1}{\rho}}$$

Taking this simplified notation as our starting point we see the marginal product with respect to M is as below and that the sign is positive.

$$\frac{\partial Q}{\partial M} = \frac{Q\,(B(M,W))^{\frac{\rho-\rho_o}{\rho_o}}\;\alpha_m\,\gamma_o}{D\,M^{(\rho_o+1)}}$$

$$\Rightarrow\ \text{sign}\left[\frac{\partial Q}{\partial M}\right] \geq 0\ \text{ since all terms are} \geq 0.$$

Taking the above equation as the starting point for the second derivative we have the following expression for the second derivative with respect to M, with many simplifying steps omitted.

$$\frac{\partial^2 Q}{\partial M^2} = \frac{\partial}{\partial M}\left(\frac{QB(M,W)^{\frac{\rho-\rho_o}{\rho_o}}\alpha_m\gamma_o}{DM^{\rho_o+1}}\right)$$

$$= \frac{\alpha_m\gamma_o QB(M,W)^{\frac{\rho-\rho_o}{\rho_o}}}{\left(DM^{\rho_o+1}\right)^2}\left[\alpha_m\gamma_o B(M,W)^{\frac{\rho-\rho_o}{\rho_o}}(1+\rho) - \left(\gamma_o(B(M,W))^{\frac{\rho-\rho_o}{\rho_o}} + \frac{\gamma_{kl}(C(K,L))^{\frac{\rho}{\rho_{kl}}}}{B(M,W)}\right)\left(\alpha_m(\rho-\rho_o)\right) - D(1+\rho_o)M^{\rho_o}\right]$$

Since we know for sure that $\frac{\alpha_m\gamma_o B(M,W)^{\frac{\rho-\rho_o}{\rho_o}}Q}{\left(DM^{\rho_o+1}\right)^2} > 0$, we can resolve the sign of $\frac{\partial^2 Q}{\partial M^2}$ analytically as shown below:

$$\text{sign}\left[\frac{\partial^2 Q}{\partial M^2}\right] =$$
$$\text{sign}\left[\alpha_m\gamma_o B(M,W)^{\frac{\rho-\rho_o}{\rho_o}}(1+\rho) - \left(\gamma_o(B(M,W))^{\frac{\rho-\rho_o}{\rho_o}} + \frac{\gamma_{kl}(C(K,L))^{\frac{\rho}{\rho_{kl}}}}{B(M,W)}\right)\left(\alpha_m(\rho-\rho_o)\right) - D(1+\rho_o)M^{\rho_o}\right]$$

$$\Rightarrow \frac{\partial^2 Q}{\partial M^2} \leq 0 \iff$$
$$\left(\gamma_o(B(M,W))^{\frac{\rho-\rho_o}{\rho_o}} + \frac{\gamma_{kl}(C(K,L))^{\frac{\rho}{\rho_{kl}}}}{B(M,W)}\right)\left(\alpha_m(\rho-\rho_o)\right) + D(1+\rho_o)M^{\rho_o} \geq \alpha_m\gamma_o B(M,W)^{\frac{\rho-\rho_o}{\rho_o}}(1+\rho)$$

From the above we can see that a negative sign is likely analytically. This is because under realistic assumptions, the above inequality is likely to hold given that D, for example, is the majority of what comprises Q. Hence it should hold that $D \geq B(M,W)^{\frac{\rho-\rho_o}{\rho_o}}$.

By this additional work, we assume for the remaining expressions that $\frac{\partial Q}{\partial M} \geq 0$ and $\frac{\partial^2 Q}{\partial M^2} \leq 0$.

Proof of Proposition 1:

Taking [#1M] as the starting point, the respective total derivative and expression for $\frac{dM}{dp_m}$ are as follows:

$$-dp_m + p_c \frac{\partial^2 Q}{\partial M^2} dM = 0$$

$$\Rightarrow \frac{dM}{dp_m} = \frac{1}{p_c \frac{\partial^2 Q}{\partial M^2}}$$

The elasticity η_{M,p_m} of M with respect to managed pollination price p_m is then given by:

$$\eta_{M,p_m} = (\frac{p_m}{M}) \frac{dM}{dp_m} = \frac{p_m}{M p_c \frac{\partial^2 Q}{\partial M^2}}$$

With the intermediate results from Lemma 1, we obtain:

$$\text{sign}\left[\frac{dM}{dp_m}\right] = \text{sign}\left[\frac{1}{p_c \frac{\partial^2 Q}{\partial M^2}}\right] = \frac{(+)}{(+)(-)} \leq 0$$

The remainder of our claims under Proposition 1 follow immediately from the preceding work. Specifically, we see that, *ceteris paribus*, managed pollination use M is decreasing in managed pollination price p_m (since $\frac{dM}{dp_m} \leq 0$), and the own-price elasticity η_{M,p_m} declines in magnitude with with managed pollination use M and with output price p_c.

Under the assumptions from Lemma 1 that Q is concave in M, output Q will exhibit diminishing returns to M. The more production is curved with respect to M (i.e., the greater the diminishing returns to M), the less elastic M will be with respect to managed pollination price (i.e., the less responsive M will be to increases in price).

If production is linear with respect to M (no diminishing returns, hence $\frac{\partial^2 Q}{\partial M^2} = 0$), then demand will be perfectly elastic.

QED.

Proof of Proposition 2:

We establish Proposition 2 in a few steps. First, we establish conditions where $\frac{dM}{dA} > 0$ is likely to hold. Second, we show conditions where $\frac{dM}{dA}$ is likely to be small in magnitude. Third, we show conditions where $\frac{d^2M}{dA^2} < 0$. Finally, we show when all three conditions hold.

Using [#1M] as our starting point, we arrive at the following expression for $\frac{dM}{dA}$,

$$p_c \frac{\partial^2 Q}{\partial A \partial M} dA + p_c \frac{\partial^2 Q}{\partial M^2} dM$$

$$\Rightarrow \frac{dM}{dA} = \frac{-\frac{\partial^2 Q}{\partial A \partial M}}{\frac{\partial^2 Q}{\partial M^2}}$$

By Lemma 1, we established the claim that $\frac{\partial^2 Q}{\partial M^2} \leq 0$. Therefore, we must show that $\frac{\partial^2 Q}{\partial A \partial M} > 0$. Using the earlier expression for $\frac{\partial Q}{\partial M}$ as our starting point we have the following expression, which is positive assuming it is always optimal to use some amount of inputs:

$$\frac{\partial^2 Q}{\partial A \partial M} = \frac{\alpha_m \, \gamma_o (B)^{\frac{\rho - \rho_o}{\rho_o}}}{D^{\frac{\rho+1}{\rho}} \, M^{(\rho_o + 1)}} > 0$$

Thus, $\frac{dM}{dA} > 0$: the use of managed pollination M is increasing in total factor productivity and/or size of farms A.

Moreover, the more production is curved with respect to M (i.e., the greater the diminishing returns to M), the less responsive M is to increases in total factor productivity.

After putting the full result together and simplifying we get the next expression:

$$\frac{dM}{dA} = \frac{-DM^{\rho_o+1}}{A\left[B(M,W)^{\frac{\rho-\rho_o}{\rho_o}}\alpha_m\gamma_o(1+\rho) - D\left(\frac{\alpha_m(\rho-\rho_o)+(\rho_o+1)M^{\rho_o}B(M,W)}{B(M,W)}\right)\right]}.$$

By inspection of the last expression, we can establish conditions where $\frac{dM}{dA}$ is likely to be small in magnitude. We see the denominator term in square brackets is the same term that was used to establish Lemma 1; we showed in our proof of Lemma 1 that this term is likely to be negative.

Combined with conditions such that $\rho > 0$ (i.e., input groups complements) and $-1 < \rho_o < 0$ (i.e., pollination inputs substitutes), or $\rho > \rho_o > 0$ (i.e., input groups being strong complements and pollination inputs being weak complements), the above inequalities ensure the term in square brackets will be negative. These conditions also suggest that the entire term in square brackets may be a comparatively small magnitude.

If the term in square brackets is small in magnitude, then A and M^{ρ_o+1} are likely to play important roles in the magnitude of the effect. This further suggests that for farmers with high total factor productivity A, the change in M with respect to A will be small in magnitude, particularly if $A \geq M^{\rho_o+1}$.

The line of logic above suggests that, although we expect use of managed pollination M to be increasing in farm size, the magnitude of the effect may be comparatively small. This means that other factors may be playing a larger role in determining a farmers' managed pollination use.

Now we need to establish conditions where $\frac{d^2M}{dA^2} < 0$. Using the preceding expression as a starting point, we arrive the following result for this second derivative.

$$\frac{d^2M}{dA^2} = \;\; = \frac{DM^{\rho_o+1}}{A^2\left[B(M,W)^{\frac{\rho-\rho_o}{\rho_o}}\alpha_m\gamma_o(1+\rho) - D\left(\frac{\alpha_m(\rho-\rho_o)+(\rho_o+1)M^{\rho_o}B(M,W)}{B(M,W)}\right)\right]} \leq 0$$

The last inequality will hold because, once again, we see in the denominator term in square brackets is the same term that was used to establish Lemma 1; we showed in our proof of Lemma 1 that this term is likely to be negative. The relationship between A and M^{ρ_o+1} is also similar to that found for $\frac{dM}{dA}$, but now the rate of diminishing returns in M will increase with unit increases in A because A^2 is present.

From the preceding results and Lemma 1, it is apparent that when the conditions below hold, use of M will increase with A; $\frac{dM}{dA}$ will be small in magnitude; and M will be concave in A.

(1) Positive amounts of all inputs are used, especially capital and labor (this will ensure that $D > B^{\frac{\rho-\rho_o}{\rho_o}}$).

(2) Total factor productivity exceeds use of managed pollination: $A > M$.

(3) Input groups are strong complements (i.e., $\rho \geq 1$) and pollination inputs are on the spectrum of substitutes (i.e., $-1 < \rho_o < 0$); or, $\rho > \rho_o > 0$ (i.e. input groups are strong complements and pollination inputs are weak complements). (Either condition will ensure that $\rho - \rho_o > 0$ and $\rho_o + 1 > 0$, which ensures that the term in square brackets will be negative.)

QED.

Proof of Proposition 3:

Finally, we derive the expression for $\frac{dM}{dW}$ and establish plausible scenarios where $\frac{dM}{dW} < 0$.

$$p_c \frac{\partial^2 Q}{\partial W \partial M} dW + p_c \frac{\partial^2 Q}{\partial M^2} dM$$

$$\Rightarrow \frac{dM}{dW} = \frac{-\frac{\partial^2 Q}{\partial W \partial M}}{\frac{\partial^2 Q}{\partial M^2}}$$

To identify possible signing regimes, we solve and simplify the expression for $\frac{\partial^2 Q}{\partial W \partial M}$.

$$\frac{\partial^2 Q}{\partial W \partial M} = \frac{\partial}{\partial W}\left(\frac{QB(M,W)^{\frac{\rho-\rho_o}{\rho}} \alpha_m \gamma_o}{DM^{\rho_o+1}}\right)$$

$$= \left[\frac{-A\alpha_m \alpha_w \gamma_o B(M,W)^{\frac{\rho-2\rho_o}{\rho_o}}}{O_w^{\rho_o+1}\, D^{\frac{2\rho+1}{\rho}}\, M^{\rho_o+1}}\right]\left[(\rho-\rho_o)D \;-\; \gamma_o(\rho+1)B(M,W)^{\frac{\rho}{\rho_o}}\right]$$

Now putting the pieces together, we arrive at a signable expression for $\frac{dM}{dW}$.

$$\frac{dM}{dW} = \frac{-\left(\frac{\partial^2 Q}{\partial W \partial M}\right)}{\frac{\partial^2 Q}{\partial M^2}} = -\frac{\left[\frac{-A\alpha_m \alpha_w \gamma_o B(M,W)^{\frac{\rho-2\rho_o}{\rho_o}}}{O_w^{\rho_o+1}\, D^{\frac{2\rho+1}{\rho}}\, M^{\rho_o+1}}\right]\left[(\rho-\rho_o)D \;-\; \gamma_o(\rho+1)B(M,W)^{\frac{\rho}{\rho_o}}\right]}{\frac{\alpha_m \gamma_o B(M,W)^{\frac{\rho-\rho_o}{\rho_o}} Q}{\left(DM^{\rho_o+1}\right)^2}\left[B(M,W)^{\frac{\rho-\rho_o}{\rho_o}} \alpha_m \gamma_o (1+\rho) - D\left(\frac{\alpha_m(\rho-\rho_o)+(\rho_o+1)M^{\rho_o} B(M,W)}{B(M,W)}\right)\right]}$$

$$= \left[\frac{\alpha_w M^{\rho_o+1}}{B(M,W)O_w^{\rho_o+1}}\right] \frac{\left[(\rho-\rho_o)D \;-\; \gamma_o(\rho+1)B(M,W)^{\frac{\rho}{\rho_o}}\right]}{\left[B(M,W)^{\frac{\rho-\rho_o}{\rho_o}} \alpha_m \gamma_o (1+\rho) - D\left(\frac{\alpha_m(\rho-\rho_o)+(\rho_o+1)I_m^{\rho_o} B(M,W)}{B(M,W)}\right)\right]}$$

$$\Rightarrow \text{ sign}\left[\frac{dM}{dW}\right] = \text{sign}\left[\left[\frac{\alpha_w M^{\rho_o+1}}{B(M,W)O_w^{\rho_o+1}}\right]\frac{\left[(\rho-\rho_o)D \;-\; \gamma_o(\rho+1)B(M,W)^{\frac{\rho}{\rho_o}}\right]}{\left[B(M,W)^{\frac{\rho-\rho_o}{\rho_o}}\alpha_m\gamma_o(1+\rho) - D\left(\frac{\alpha_m(\rho-\rho_o)+(\rho_o+1)M^{\rho_o}B(M,W)}{B(M,W)}\right)\right]}\right]$$

$$= (+)\frac{(?)}{(-)} \quad \text{...by observation, Lemma 1, and preceding work.}$$

$$\Rightarrow \frac{dM}{dW} \leq 0 \iff (\rho-\rho_o)D \;-\; \gamma_o(\rho+1)B(M,W)^{\frac{\rho}{\rho_o}} \geq 0$$
$$\iff (\rho-\rho_o)D \geq \gamma_o(\rho+1)B(M,W)^{\frac{\rho}{\rho_o}}$$

These conditions are likely to hold when:

- $-1 < \rho_o < 0$ and $\rho > 0$ (pollination inputs are substitutes and input groups are complements); or
- $\rho > \rho_o$ (input groups being strong complements and pollination inputs being weak complements).

QED.

Proof of Proposition 4:

Taking [#1M] as the starting point, the respective total derivative and expression for $\frac{dM}{dp_c}$ are as follows:

$$\frac{\partial Q}{\partial M}dp_c + p_c\frac{\partial^2 Q}{\partial M^2}dM = 0$$

$$\Rightarrow \frac{dM}{dp_c} = \frac{\frac{-\partial Q}{\partial M}}{p_c\frac{\partial^2 Q}{\partial M^2}}$$

The elasticity η_{M,p_c} of M with respect to output price p_c is then given by:

$$\eta_{M,p_c} = (\frac{p_c}{M})\frac{dM}{dp_c} = \frac{\frac{-\partial Q}{\partial M}}{M\frac{\partial^2 Q}{\partial M^2}}$$

With the intermediate results in Lemma 1, we obtain:

$$\text{sign}\left[\frac{dM}{dp_c}\right] = \text{sign}\left[\frac{\frac{-\partial Q}{\partial M}}{p_c\frac{\partial^2 Q}{\partial M^2}}\right] = \frac{(-)(+)}{(+)(-)} \geq 0$$

Thus, we see that, *ceteris paribus*, managed pollination use M is increasing in output price p_c (since $\frac{dM}{dp_c} \geq 0$), while the elasticity of M with respect to output price p_c does not depend on p_c.

QED.

B Data

B.1 Background on Apple Production

Apples are a useful crop to study farmer pollination behavior. Apples are a widely produced and consumed commodity around the world[3] with high cultural value. From a pollination perspective, apples are also unique in the sense that wild pollinators have been shown to be much more effective at inducing fruit set[4] than honey bees are (Blitzer et al., 2016; Russo et al., 2017), with important implications for fruit quality and price received. This may be particularly important for farmers as high quality fruit receives a much better price on average compared to lower quality fruit which is often sold for processing (e.g., apple sauce and other products). A complexity in mapping pollination efficacy to yield, at least with modern approaches to apple production, is that farmers commonly engage in thinning (typically with a chemical agent) immediately after fruit set to encourage the plant to drop poorly pollinated fruit early and thus increase investment in remaining fruit. Another interesting aspect of pollination with apples is that apples are not considered a honey-producing crop (Rucker, Thurman, and Burgett, 2012), as apple blossoms yield little or no honey (Cheung, 1973), and this translates into higher pollination rental fees for apple farmers to mitigate against the fact that beekeepers do not gain forage resources to produce palatable honey from pollinating apples (Rucker, Thurman, and Burgett, 2012).

From a production perspective, apples have traditionally been grown in orchards with tall (6-8 meters), widely spaced (80-100 trees per hectare), and very long-lived trees (30-50 years or more). In recent decades, production strategies have started shifting towards more modern approaches where apples are grown in high density plantings on trellis systems, with shorter trees and very small spacings between rows and individual trees (Robinson et al., 2007, 2013). These high density systems bear little resemblance to the orchards of the past, with hopes of increasing yields and

[3]Today, China leads the world in global apple production with the US a fairly distant second (authors' calculations, FAOSTAT). Among states in the US, apple production is highest in Washington followed by New York.

[4]Fruit set is the biological process in which flowers become fruit and potential fruit size is determined (Mid Valley Agricultural Services, 2006). When seed formation is complete and well-distributed, the fruit is considered to be more appealing (e.g., consistent shape and fruit quantity/quality), which generally means a higher price is received by the farmer.

lowering labor costs. Some recommendations put optimal tree height at around 3-4 meters, orchard rows at 3-4 meters apart, and trees spaced within rows at as little as 0.7 meters, resulting in tree densities of 2-3,000 trees per hectare or more at the high end (Robinson et al., 2013).

B.2 Data and Data Sources

For our empirical analysis, we leverage rich, farm-level microdata from the 2007 USDA Agricultural Resource Management Survey (USDA-ARMS), which is designed to be nationally representative as well as representative at the level of a state. The USDA National Agricultural Statistics Service (USDA-NASS) imposes stringent conditions and restrictions on the use of its USDA-ARMS data, including strict security measures, data confidentiality, and the required use of provided replication weights. Qualified researchers at US universities or Government agencies can submit a formal request to the USDA Economic Research Service (ERS) and USDA-NASS to have access granted to USDA-ARMS data for specific research projects (USDA Economic Research Service (ERS), 2022). We access the USDA-ARMS data via the NORC Data Enclave.

The 2007 USDA-ARMS provides rich farm-level data from apple farmers in seven US states: California (CA), Michigan (MI), New York (NY), North Carolina (NC), Oregon (OR), Pennsylvania (PA), and Washington (WA). Useful data comes from the Phase III and Phase II surveys. Phase III covers operation-level data on land, production, and financial information. Phase II provides rich production data for a random operation and a random block of apples within the selected operation. Data at the random apple block level covers all the main aspects of production, including input use, costs and yield, for the 2007 production year, as well as honey bee rental data for the years 2006-2007. Although data on costs and on the binary choice to rent bees are available for 2006-2007, the quantity of honey bee colonies rented is only available for 2007. There are 1057 farmers who have sufficient responses for our research, which comprises the vast majority of the farmers sampled. In Figure C.1 in Appendix C, we provide a barplot showing the distribution by state for the responses that comprise our base sample. Our observations span 7 states, 207 counties, and 466 zip codes.

To operationalize and enhance our research objectives, we also merge a variety of other data with the 2007 ARMS. We use data on almond production in California from USDA-NASS.

The 2007 USDA-ARMS did not request information on output prices. Thus, for apple output price, we use the state-level total utilized production price from USDA-NASS, which is a weighted average of fresh market and processed prices.

For distance measures, we compute Euclidean distances using R and we also employ the Google Distance Matrix API to derive road distances as alternative "share" variables in our instrument construction.

To derive relevant data on weather covariates that might affect yield, and collect credible proxy measures for landscape influence and local pollinator habitat (the closest proxy available for wild pollinator stocks), we use the closest[5] and most reliable coverage year from the USDA Cropland Data Layer (CDL) (Boryan et al. (2011)) for each state to construct a county-level mask of apple and tree-crop producing regions within each county. Using the resulting boundaries within each county for apple-specific and/or tree-crop-specific regions, as well as the county boundaries themselves, we further use the CDL to construct a variety of variables to characterize land cover heterogeneity, and also credible measures of pollinator habitat quality (Martins, Gonzalez, and Lechowicz, 2015; Park et al., 2015), including the proportion of land area in natural forest cover and the proportion of land area in natural open cover. We define natural open cover as the proportion of apple-specific and/or tree-crop-specific areas within a county in any of the following cover types: clover, wildflowers, shrubland, herbaceous wetlands, developed open space, and wetlands. We also

[5]Apples are difficult to identify with high accuracy, as are tree crops, therefore classification error in annual CDL layers induce potential for measurement error. Since tree crops are long-lived, there are unlikely to be large year-to-year changes in cover. Therefore we adopted the following rule to construct apple- and tree-crop specific spatial masks and gather other land cover information within county domains, and county-specific apple and tree-crop spatial domains: use the CDL crop mask data for the timepoint closest to 2007 as possible, but if the closest year to 2007 had low cover for apples and tree-crops, use the next closest year of the CDL that had substantially higher cover for apples and/or tree crops. The logic here is that if ARMS data imply that apple growers are present within a county, yet the CDL does not pick up apples or tree-crops, the closest year to 2007 that shows at least some spatial footprint for these crops is likely a more accurate spatial mapping of this agricultural activity than another year that might be closer to 2007. Since we cannot resolve sampled farm locations in space, these boundaries are designed to reflect that average conditions that apple growers face in their respective counties. Crops that are included in our tree crop definition include: apples, cherries, peaches, other tree crops, pears, prunes, plums, nectarines, and apricots; citrus and nut crops were excluded.

employ the tree-crop-specific regions and county boundaries to gather monthly precipitation and temperature data from PRISM spanning January-November of the 2007 production (Daly et al., 2008).

The West Coast states in our data set are California (CA), Oregon (OR), and Washington (WA). The Midwest and East Coast states in our data set (which we refer to collectively as the 'Eastern' states) are Michigan (MI), New York (NY), North Carolina (NC), and Pennsylvania (PA).

Although the 2007 USDA-ARMS collected data on the binary choice to rent honey bees over 2006-2007, the costs to rent honey bees per colony over 2006-2007, and the quantity of honey bees rented in 2007, data on the quantity of honey bees rented in 2006 is not available except in the instance a farmer reported not renting bees (in which case we know quantity rented is zero). We therefore use four different subsamples for our analyses of managed pollination demand.

In the first subsample, we use data from 2007 only. Since the 2007 USDA-ARMS collected data on the quantity of honey bees demanded in 2007, this subsample does not require any quantity imputation.

The second subsample employs an unbalanced panel over 2006-2007 that includes all observations from 2007, as well as the 430 growers who reported not renting bees in 2006, for whom we know the number of colonies rented in 2006 is zero (thereby eliminating the need for quantity imputation). Thus, this subsample does not require any quantity imputation for missing 2006 quantity.

The third subsample is a balanced panel that includes all growers in the data for both 2006 and 2007. We impute missing 2006 quantity as follows. For the 578 growers who rented bees in both years, we impute the number of colonies rented in 2006 to be the number of colonies rented in 2007. For the 49 growers who rented bees in 2006 but not in 2007, we impute the quantity rented in 2006 using regression-based imputation.

The fourth subsample is a balanced panel that includes all growers in the data for both 2006 and 2007. We impute missing 2006 quantity using regression-based imputation for all 627 growers who rented bees in 2006 and therefore do not have data on 2006 quantity.

For the regression-based quantity imputation, we use data from 2007 to regress the number of honey bee colonies rented on a dummy for renting bees that year, block fresh market dummy, block bearing apple acres, block number of apple trees, block average age of trees, and state fixed effects. To impute the 2006 quantity using the 2007 quantity imputation regression, we evaluate the quantity imputation regression using the 2006 values of the regressors.

For growers who rented honey bees in a given year, we use the grower's rental fee for the price. For growers who did not rent in a given year and therefore did not report a bee rental fee for that year, we impute the missing price for that grower-year using regression-based imputation. For the regression-based price imputation, we regress the honey bee rental bee on a dummy for the block being deliberately scouted for insects, weeds, disease; a dummy for the operator attending pest management training; a dummy for the block orchard floor system being a grass alley way; a dummy for the apple trees on the block being predominantly semi-dwarf; a block fresh market dummy; a dummy for the year 2007; and state fixed effects.

C Supplementary Tables and Figures

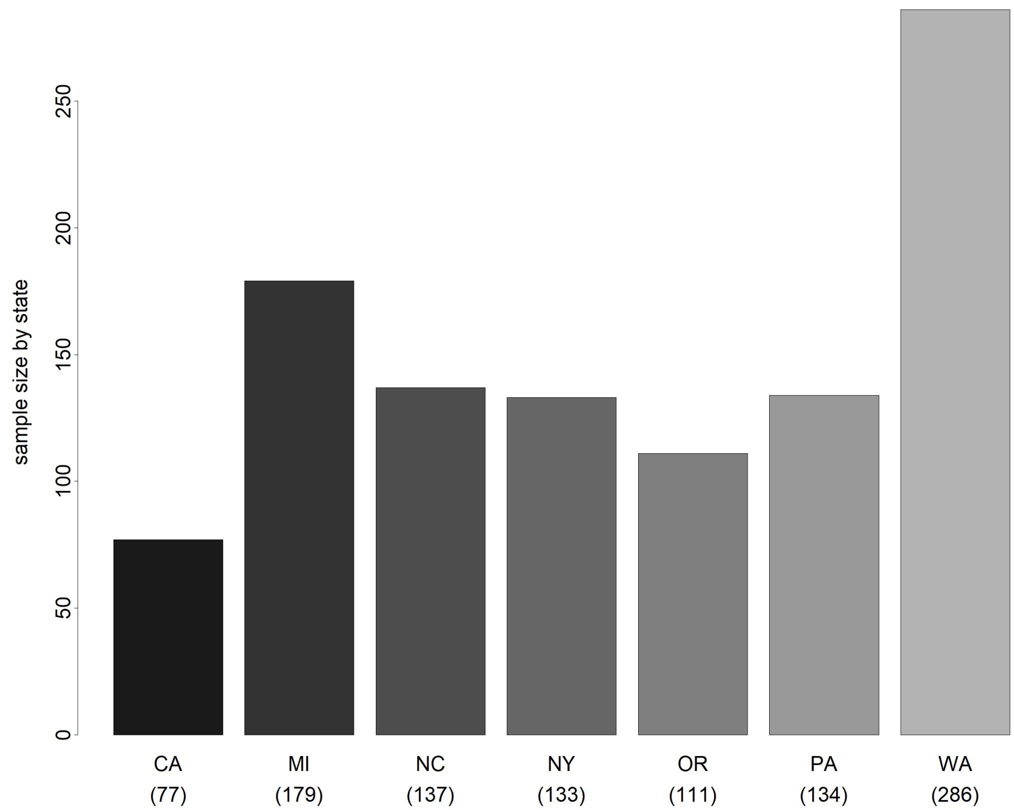

Figure C.1: Distribution of the sample apple farmers from 2007 USDA-ARMS that we employ in our analysis.

Table C.1: Weighted summary statistics.

	Weighted Mean	Standard Deviation	# Observations
Operation-level variables			
total bearing apple blocks	15.08	20.55	1,057
attended recent pest management training (dummy)	0.54	0.5	1,057
Block-level variables			
rented bees in 2007 (dummy)	0.74	0.44	1,057
rented bees in 2006 (dummy)	0.74	0.44	1,057
did not rent bees in 2006-2007 (dummy)	0.25	0.43	1,057
number of honey bee colonies rented (conditional on renting) in 2007	17.37	30.13	601
number of honey bee colonies rented per acre (conditional on renting) in 2007	1.87	2.26	601
honey bee rental fee ($/colony) in 2007	47.66	13.33	1,057
honey bee rental fee ($/colony) in 2006	44.71	12.63	1,057
apple bearing acres	10.6	21.88	1,057
trees per acre	283.13	257.16	1,039
average age of trees	18.94	12.71	1,042
has federal crop insurance in 2007 (dummy)	0.62	0.48	1,057
yield (bushels/acre)	589.78	422.3	1,057
approximate profit ($) per acre	5746.59	7467.6	1,057
number apple trees	3512.68	12248.46	1,039
production for fresh market (dummy)	0.84	0.37	1,057
deliberately scouts for pests (dummy)	0.85	0.36	1,057
grass valley floor system (dummy)	0.88	0.33	1,056
semi dwarf tree type (dummy)	0.55	0.5	1,057
Zip code-level variables			
zip code distance to Fresno County, CA (km)	2490.48	1313.74	466
zip code distance (Euclidean) to Fresno County, CA (km) X total almond acres in CA	1892765217	998006436.5	932
State-level variables			
total utilized production price ($/lb) in 2007	0.25	0.01	7
total utilized production price ($/lb) in 2006-2007	0.24	0.08	14
County-level variables			
natural forest cover (county proportion)	0.50	0.22	207
natural open cover (county proportion)	0.17	0.16	207
mean temperature (C), winter 2006-2007	1.86	4.64	414
mean precipitation (mm), winter 2006-2007	2.84	1.98	414
mean temperature (C), spring 2006-2007	13.47	2.51	414
mean precipitation (mm), spring 2006-2007	2.31	0.97	414
mean temperature (C), summer 2006-2007	20.83	2.59	414
mean precipitation (mm), summer 2006-2007	2.41	1.81	414
mean temperature (C), fall 2006-2007	10.07	2.77	414
mean precipitation (mm), fall 2006-2007	3.10	1.89	414

Notes: Sample sizes may differ from respective full sample sizes because a farmer did not answer the question, or the question was not applicable. There are 7 states, 207 counties, and 466 zip codes.

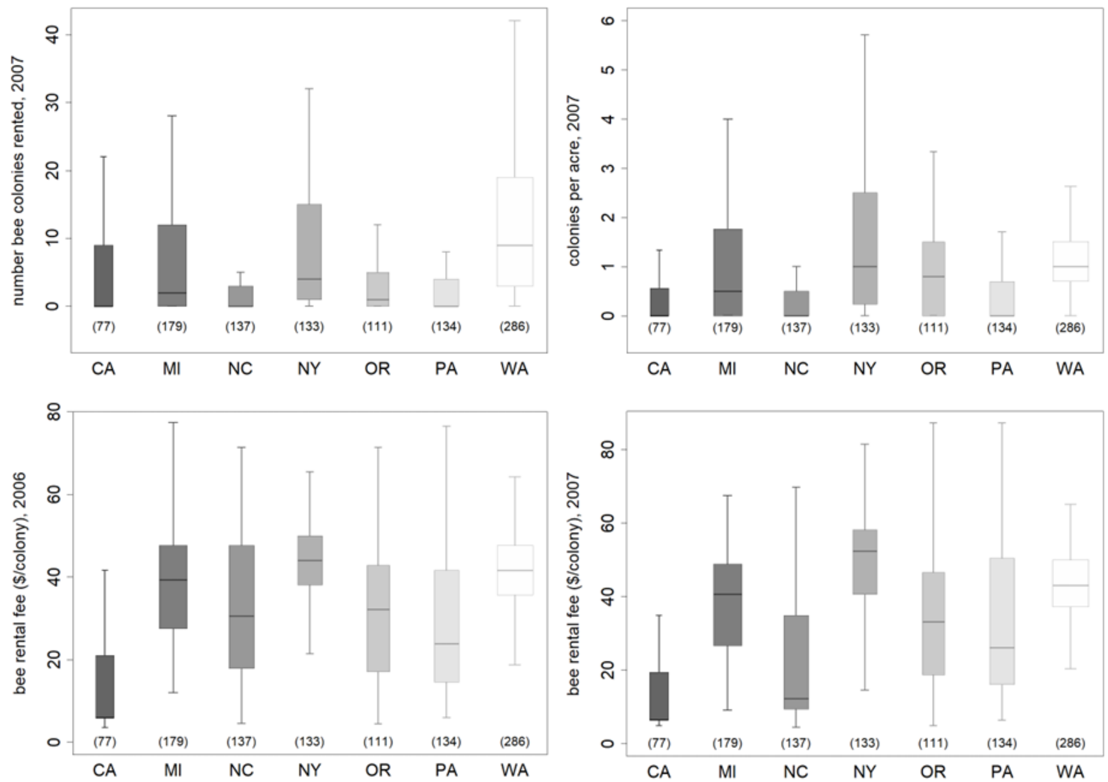

Figure C.2: Weighted boxplots by state capturing: the number of honey bee colonies rented in 2007; the number of honey bee colonies rented per acre in 2007; honey bee rental fee ($/colony) in 2006; and honey bee rental fee ($/colony) in 2007. All variables are comprised of random block-level variation. Numbers in parentheses next to state abbreviations indicate the respective sample size for that boxplot.

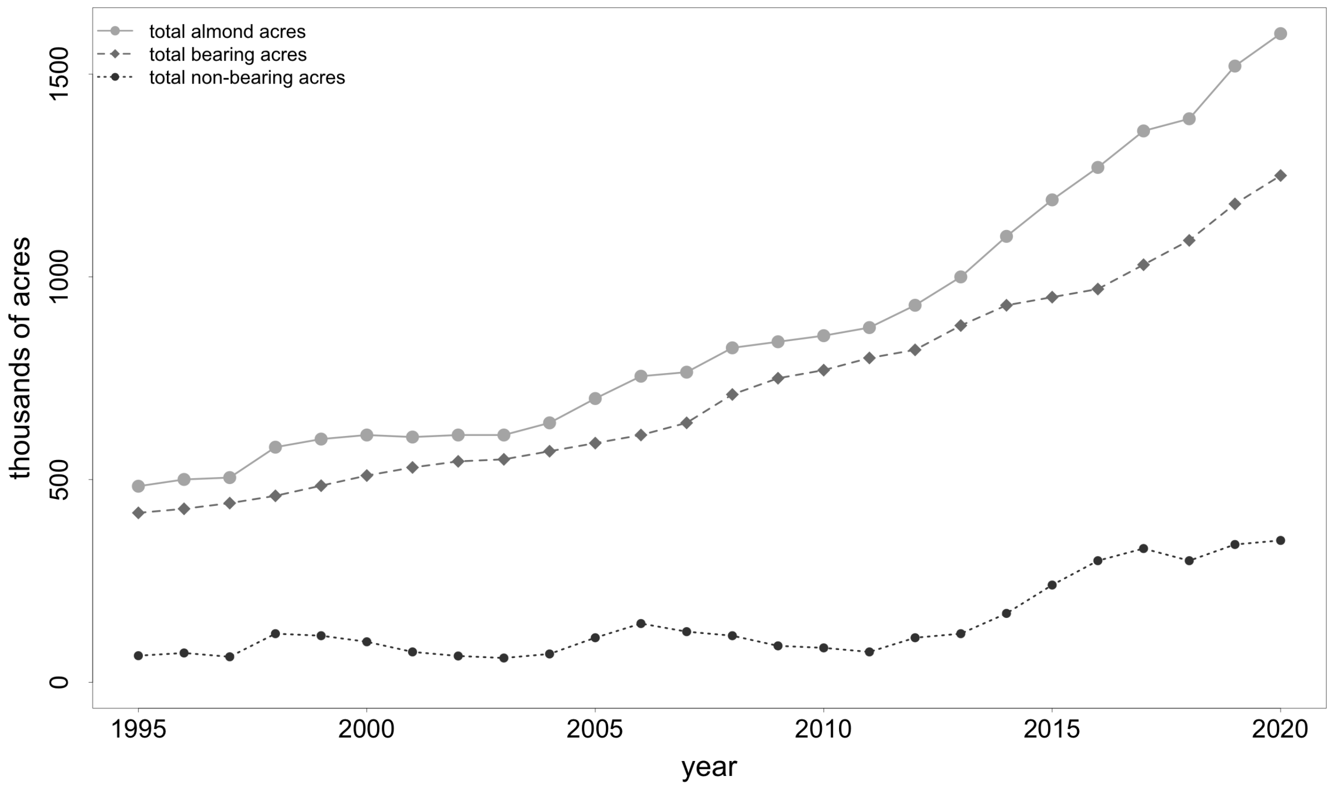

Figure C.3: Almond acreage in California, 1995-2020
Data source: USDA-NASS 2020 California Almond Acreage Report.

Table C.2: First-stage results for honey bee demand own-price elasticity estimation, 2SLS (weighted).

Dependent variable is the honey bee rental fee ($/colony)	(1)	(2)	(3)
IV: zip code distance to Fresno County, CA (km)	0.00811***		
	(0.00165)		
IV: zip code distance to Fresno County, CA (km) X total almond acres in CA		0.000000009***	0.000000010***
		(0.000000002)	(0.000000002)
apple bearing acres	-0.024	-0.015	-0.014
	(0.033)	(0.027)	(0.023)
apple bearing acres, squared	0.000076	0.000056	0.000048
	(0.000090)	(0.000074)	(0.000063)
total bearing apple blocks	-0.0594	-0.0460	-0.0404
	(0.0534)	(0.0427)	(0.0369)
total bearing apple blocks, squared	0.00034	0.00028	0.00035
	(0.00054)	(0.00044)	(0.00037)
trees per acre	0.0148***	0.0121***	0.0137***
	(0.0049)	(0.0037)	(0.0034)
trees per acre, squared	-0.0000083**	-0.0000068**	-0.0000085***
	(0.0000041)	(0.0000033)	(0.0000028)
average age of trees	0.116	0.091	0.049
	(0.079)	(0.057)	(0.055)
average age of trees, squared	-0.0016	-0.0010	-0.0009
	(0.0011)	(0.0008)	(0.0008)
natural forest cover	-11.45**	-9.17**	-12.47***
	(5.55)	(4.35)	(3.86)
natural forest cover, squared	22.57***	16.40***	25.85***
	(7.06)	(5.31)	(4.90)
natural open cover	35.98**	23.34**	42.79***
	(13.96)	(9.81)	(9.69)
natural open cover, squared	-32.78**	-23.67**	-39.42***
	(15.72)	(10.85)	(10.91)
total utilized production price ($/pound)	56.74***	41.83***	26.31***
	(13.70)	(9.70)	(7.93)
has federal crop insurance in 2007 (dummy)	1.54*	1.47**	1.41**
	(0.82)	(0.63)	(0.57)
CA (dummy)	-3.27	-3.80	-1.31
	(5.90)	(4.27)	(3.97)
OR (dummy)	-3.29	-0.33	-0.28
	(5.27)	(3.69)	(3.36)
WA (dummy)	-6.44	-2.33	-0.09
	(5.40)	(3.78)	(3.27)
year 2007 (dummy)		1.59*	1.29*
		(0.83)	(0.66)
constant	6.15	12.44***	11.43***
	(6.26)	(4.46)	(4.29)
Data included in sample:			
All observations from 2007	Y	Y	Y
Growers who did not rent in 2006	N	Y	Y
Growers who rented bees in 2006	N	N	Y
First-stage F-statistic, F_{kp}	9.83	13.17	14.9
Adjusted R^2	0.243	0.313	0.238
# Observations	1,020	1,438	2,056

Notes: Table presents first-stage results for honey bee demand IV estimation (weighted). Specification (1) uses data from 2007 only; this is the first stage for specification (1) in Table 1. Specification (2) employs an unbalanced panel over 2006-2007 that includes all observations from 2007, as well as growers who reported not renting bees in 2006; this is the first stage for specification (2) in Table 1. Specification (3) is a balanced panel that includes all growers in the data for both 2006 and 2007; this is the first stage for both specifications (3) and (4) in Table 1. For specification (1), the instrument Z_{sct} is the Euclidean distance from the centroids of zip code units of farm locations to the centroid of Fresno County, California. For specifications (2) and (3), the instrument Z_{sct} is the interaction between the distance from zip code centroids where farms are located to the centroid of Fresno County, California and the total almond acres in California in year t. Huber-White robust standard errors are in parentheses. Significance codes: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Table C.3: Honey bee demand own-price elasticity estimation, OLS results (weighted).

Dependent variable is the number of honey bee colonies rented	(1)	(2)	(3)	(4)
honey bee rental fee ($/colony)	-0.054	-0.054	-0.028	-0.036
	(0.050)	(0.042)	(0.035)	(0.027)
apple bearing acres	1.117***	0.992***	1.117***	0.891***
	(0.053)	(0.044)	(0.037)	(0.029)
apple bearing acres, squared	-0.00080***	-0.00051***	-0.00080***	-0.00011
	(0.00014)	(0.00012)	(0.00010)	(0.00008)
total bearing apple blocks	0.139	0.122*	0.139**	0.137***
	(0.085)	(0.069)	(0.059)	(0.045)
total bearing apple blocks, squared	-0.00161*	-0.00161**	-0.00156***	-0.00143***
	(0.00086)	(0.00070)	(0.00060)	(0.00046)
trees per acre	0.019**	0.018***	0.020***	0.015***
	(0.008)	(0.006)	(0.005)	(0.004)
trees per acre, squared	-0.00002**	-0.00002***	-0.00002***	-0.00001***
	(0.00001)	(0.00001)	(0.000005)	(0.000004)
average age of trees	-0.080	-0.038	-0.048	-0.046
	(0.125)	(0.091)	(0.088)	(0.067)
average age of trees, squared	-0.00037	-0.00029	-0.00061	-0.00046
	(0.00182)	(0.00124)	(0.00128)	(0.00098)
natural forest cover	-1.80	-1.08	2.35	-1.49
	(8.83)	(7.04)	(6.20)	(4.75)
natural forest cover, squared	5.03	2.62	-0.56	3.15
	(11.25)	(8.59)	(7.89)	(6.05)
natural open cover	16.27	8.16	11.79	20.97*
	(21.66)	(15.49)	(15.09)	(11.57)
natural open cover, squared	-12.60	-5.57	-7.69	-20.09
	(24.41)	(17.17)	(17.03)	(13.06)
total utilized production price ($/pound)	57.01***	36.96**	26.51**	20.50**
	(21.26)	(15.24)	(12.37)	(9.48)
has federal crop insurance in 2007 (dummy)	-1.281	-2.006*	-1.124	0.201
	(1.308)	(1.026)	(0.917)	(0.703)
CA (dummy)	-10.43***	-7.30**	-6.44**	-5.38***
	(4.01)	(2.87)	(2.60)	(1.99)
OR (dummy)	-10.95**	-5.89*	-5.08*	-4.11*
	(4.97)	(3.31)	(3.03)	(2.32)
WA (dummy)	-12.58**	-6.65*	-5.09	-4.47*
	(5.91)	(3.95)	(3.33)	(2.56)
year 2007 (dummy)		6.36***	-1.33	-1.07
		(1.33)	(1.05)	(0.80)
constant	-11.25*	-11.83***	-6.33*	
	(5.86)	(3.98)	(3.59)	
Elasticity at mean	-0.200	-0.246	-0.102	-0.130
Data included in sample:				
All observations from 2007	Y	Y	Y	Y
Growers who did not rent in 2006	N	Y	Y	Y
Growers who rented bees in 2006	N	N	Y	Y
Adjusted R^2	0.544	0.537	0.546	0.665
# Observations	1,020	1,438	2,056	2,056

Notes: Table presents OLS results for honey bee demand (weighted). Specification (1) uses data from 2007 only. Specification (2) employs an unbalanced panel over 2006-2007 that includes all observations from 2007, as well as growers who reported not renting bees in 2006, for whom we know the number of colonies rented in 2006 is zero (thereby eliminating the need for quantity imputation). Specification (3) is a balanced panel that includes all growers in the data for both 2006 and 2007: if the grower rented bees in both years, we impute the number of colonies rented in 2006 to be the number of colonies rented in 2007; if the grower rented bees in 2006 but not in 2007, we impute the quantity rented in 2006 using regression-based imputation. Specification (4) is a balanced panel that includes all growers in the data for both 2006 and 2007: we impute missing quantity using regression-based imputation. Elasticity is evaluated at the mean price and quantity in the data for the respective sample of data. Huber-White robust standard errors are in parentheses. Significance codes: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Table C.4: Honey bee demand own-price elasticity estimation, IV-tobit results (weighted).

	Dependent variable is the number of honey bee colonies rented			
	(1)	(2)	(3)	(4)
honey bee rental fee ($/colony)	-1.269	-1.978**	-1.002*	-0.730*
	(0.784)	(0.981)	(0.538)	(0.394)
apple bearing acres	1.175***	1.124***	1.179***	0.937***
	(0.153)	(0.159)	(0.105)	(0.090)
apple bearing acres, squared	-0.00091***	-0.00078**	-0.00093***	-0.00020
	(0.00033)	(0.00034)	(0.00022)	(0.00026)
total bearing apple blocks	0.330*	0.402*	0.386***	0.322***
	(0.189)	(0.228)	(0.130)	(0.104)
total bearing apple blocks, squared	-0.00345**	-0.00446*	-0.00363***	-0.00298***
	(0.00198)	(0.00240)	(0.00134)	(0.00111)
trees per acre	0.042*	0.050**	0.0396***	0.0302***
	(0.020)	(0.023)	(0.0132)	(0.0100)
trees per acre, squared	-0.000030**	-0.000032*	-0.000029***	-0.000018**
	(0.000015)	(0.000017)	(0.000010)	(0.000007)
average age of trees	0.117	0.238	0.105	0.0625
	(0.263)	(0.277)	(0.165)	(0.130)
average age of trees, squared	-0.00531	-0.00733*	-0.00481*	-0.00348*
	(0.00411)	(0.00431)	(0.00268)	(0.00205)
natural forest cover	-16.92	-15.40	-7.179	-8.564
	(17.72)	(19.18)	(12.15)	(9.411)
natural forest cover, squared	39.20	33.57	25.41	21.96
	(29.46)	(28.44)	(20.41)	(15.44)
natural open cover	74.69	95.53**	63.76**	61.71***
	(45.85)	(45.06)	(30.36)	(23.50)
natural open cover, squared	-67.39	-97.59**	-56.76*	-59.93**
	(45.07)	(43.63)	(29.95)	(23.30)
total utilized production price ($/pound)	236.7***	393.1***	110.8***	81.75***
	(71.70)	(83.30)	(29.71)	(20.49)
has federal crop insurance in 2007 (dummy)	4.205*	6.127**	4.059**	4.101***
	(2.409)	(2.697)	(1.722)	(1.412)
CA (dummy)	-61.94**	-92.95***	-42.43***	-31.28***
	(25.32)	(29.82)	(15.15)	(10.98)
OR (dummy)	-53.90**	-73.16***	-29.37***	-21.59***
	(21.13)	(21.50)	(11.10)	(7.975)
WA (dummy)	-60.17**	-89.54***	-27.39***	-20.72***
	(23.40)	(23.90)	(10.77)	(7.559)
year 2007 (dummy)			-3.396	-2.608
			(2.163)	(1.627)
constant	-8.813	-16.22	4.068	2.454
	(26.75)	(32.80)	(20.35)	(15.14)
Elasticity at conditional mean	-3.52	-5.49**	-2.72*	-1.98*
	Data included in sample:			
All observations from 2007	Y	Y	Y	Y
Growers who did not rent in 2006	N	Y	Y	Y
Growers who rented bees in 2006	N	N	Y	Y
# Observations	1,020	1,438	2,056	2,056

Notes: Table presents IV-tobit results for honey bee demand (weighted). Specification (1) uses data from 2007 only. Specification (2) employs an unbalanced panel over 2006-2007 that includes all observations from 2007, as well as growers who reported not renting bees in 2006, for whom we know the number of colonies rented in 2006 is zero (thereby eliminating the need for quantity imputation). Specification (3) is a balanced panel that includes all growers in the data for both 2006 and 2007: if the grower rented bees in both years, we impute the number of colonies rented in 2006 to be the number of colonies rented in 2007; if the grower rented bees in 2006 but not in 2007, we impute the quantity rented in 2006 using regression-based imputation. Specification (4) is a balanced panel that includes all growers in the data for both 2006 and 2007: we impute missing quantity using regression-based imputation. For specification (1), the instrument for price (honey bee rental fee) is the Euclidean distance from the centroids of zip code units of farm locations to the centroid of Fresno County, California. For specifications (2), (3), and (4), the instrument for price (honey bee rental fee) is the interaction between the distance from zip code centroids where farms are located to the centroid of Fresno County, California and the total almond acres in California in year t. Elasticity at conditional mean is evaluated at the mean price and quantity among grower-years with positive quantity in the respective sample of data. Huber-White robust standard errors are in parentheses. Significance codes: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Table C.5: Honey bee demand own-price elasticity estimation using honey bee colonies rented per acre, 2sls results (weighted).

	(1)	(2)	(3)	(4)
Dependent variable is the number of honey bee colonies rented per acre.				
honey bee rental fee ($/colony)	-0.152***	-0.135***	-0.140***	-0.151*
	(0.048)	(0.038)	(0.035)	(0.080)
total bearing apple blocks	0.014	0.014	0.020**	0.071***
	(0.013)	(0.010)	(0.009)	(0.020)
total bearing apple blocks, squared	-0.00018	-0.00017*	-0.00020**	-0.00073***
	(0.00013)	(0.00010)	(0.00009)	(0.00020)
trees per acre	0.0025*	0.0021**	0.0023**	-0.0058***
	(0.0013)	(0.0010)	(0.0009)	(0.0021)
trees per acre, squared	-0.000002**	-0.000002**	-0.000002***	0.000003*
	(0.000001)	(0.000001)	(0.000001)	(0.000002)
average age of trees	-0.044**	-0.037***	-0.049***	-0.189***
	(0.019)	(0.013)	(0.013)	(0.030)
average age of trees, squared	0.00028	0.00029*	0.00034*	0.00171***
	(0.00027)	(0.00017)	(0.00019)	(0.00043)
natural forest cover	-1.29	-0.62	-0.92	3.42
	(1.42)	(1.03)	(1.00)	(2.32)
natural forest cover, squared	2.40	1.05	2.18	-6.38*
	(2.05)	(1.37)	(1.49)	(3.46)
natural open cover	6.83**	3.44	6.89***	-2.78
	(3.37)	(2.19)	(2.39)	(5.54)
natural open cover, squared	-8.78**	-5.23**	-8.75***	-5.99
	(3.71)	(2.42)	(2.60)	(6.03)
total utilized production price ($/pound)	19.15***	13.78***	9.08***	2.52
	(4.78)	(3.03)	(2.26)	(5.24)
has federal crop insurance in 2007 (dummy)	0.023	-0.001	0.047	-0.826**
	(0.201)	(0.148)	(0.138)	(0.321)
CA (dummy)	-5.88***	-4.57***	-4.52***	-2.85
	(1.54)	(1.09)	(0.97)	(2.25)
OR (dummy)	-5.17***	-3.50***	-3.41***	-0.04
	(1.37)	(0.84)	(0.791)	(1.83)
WA (dummy)	-5.38***	-3.57***	-2.88***	2.30
	(1.52)	(0.92)	(0.77)	(1.78)
year 2007 (dummy)		1.20***	-0.100	-1.10***
		(0.19)	(0.155)	(0.360)
constant	5.24***	4.39***	6.50***	13.44***
	(1.73)	(1.43)	(1.36)	(3.15)
Elasticity at mean	-5.05***	-5.57***	-4.49***	-3.25*
Data included in sample:				
All observations from 2007	Y	Y	Y	Y
Growers who did not rent in 2006	N	Y	Y	Y
Growers who rented bees in 2006	N	N	Y	Y
First-stage F-statistic, F_{kp}	9.79	13.03	14.78	14.78
DWH t-statistic	2.45	2.58	3.13	2.51
Adjusted R^2	-0.623	-0.386	-0.537	-0.005
# Observations	1,020	1,438	2,056	2,056

Notes: Table presents IV results for honey bee demand (weighted). Specification (1) uses data from 2007 only. Specification (2) employs an unbalanced panel over 2006-2007 that includes all observations from 2007, as well as growers who reported not renting bees in 2006, for whom we know the number of colonies rented per acre in 2006 is zero (thereby eliminating the need for quantity imputation). Specification (3) is a balanced panel that includes all growers in the data for both 2006 and 2007: if the grower rented bees in both years, we impute the number of colonies rented per acre in 2006 to be the number of colonies rented per acre in 2007; if the grower rented bees in 2006 but not in 2007, we impute the quantity rented in 2006 using regression-based imputation. Specification (4) is a balanced panel that includes all growers in the data for both 2006 and 2007: we impute missing quantity using regression-based imputation. For specification (1), the instrument for price (honey bee rental fee) is the Euclidean distance from the centroids of zip code units of farm locations to the centroid of Fresno County, California. For specifications (2), (3), and (4), the instrument for price (honey bee rental fee) is the interaction between the distance from zip code centroids where farms are located to the centroid of Fresno County, California and the total almond acres in California in year t. Elasticity is evaluated at the mean price and quantity in the data for the respective sample of data. Huber-White robust standard errors are in parentheses. Significance codes: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Table C.6: Honey bee demand own-price elasticity estimation using honey bee colonies rented per acre, IV-tobit results (weighted).

	Dependent variable is the number of honey bee colonies rented per acre			
	(1)	(2)	(3)	(4)
honey bee rental fee (\$/colony)	-0.202*	-0.293**	-0.169**	-0.223*
	(0.104)	(0.128)	(0.074)	(0.123)
total bearing apple blocks	0.037	0.047	0.047***	0.155**
	(0.026)	(0.0304)	(0.017)	(0.076)
total bearing apple blocks, squared	-0.00039	-0.00050	-0.00043**	-0.00146**
	(0.00026)	(0.00031)	(0.00018)	(0.00074)
trees per acre	0.0036	0.00446	0.00317	-0.00414
	(0.0038)	(0.00391)	(0.00257)	(0.00984)
trees per acre, squared	-0.000003	-0.000003	-0.000003	0.000003
	(0.000003)	(0.000003)	(0.000002)	(0.000006)
average age of trees	-0.041	-0.029	-0.044	-0.193
	(0.050)	(0.048)	(0.033)	(0.171)
average age of trees, squared	0.000054	-0.00014	0.00011	0.00138
	(0.00057)	(0.00055)	(0.00039)	(0.00170)
natural forest cover	-2.383	-2.250	-1.370	2.397
	(2.283)	(2.514)	(1.550)	(4.046)
natural forest cover, squared	4.256	3.682	3.047	-5.101
	(3.933)	(3.719)	(2.721)	(9.893)
natural open cover	12.80*	15.03**	11.76**	10.77
	(7.487)	(6.937)	(5.072)	(13.01)
natural open cover, squared	-15.92**	-19.28***	-14.79***	-24.75**
	(7.234)	(7.163)	(4.823)	(10.32)
total utilized production price (\$/pound)	32.11***	52.05***	14.88***	19.22***
	(8.655)	(10.05)	(4.092)	(7.310)
has federal crop insurance in 2007 (dummy)	0.462	0.794**	0.473*	0.452
	(0.372)	(0.387)	(0.255)	(0.618)
CA (dummy)	-9.133***	-12.97***	-6.522***	-8.374**
	(3.198)	(3.717)	(2.018)	(3.589)
OR (dummy)	-7.742***	-10.11***	-4.501***	-2.336
	(2.725)	(2.656)	(1.569)	(4.548)
WA (dummy)	-8.308**	-11.96***	-3.893***	0.142
	(3.232)	(3.000)	(1.784)	(7.089)
year 2007 (dummy)			-0.364	-2.020**
			(0.309)	(0.888)
constant	3.411	2.411	5.194*	9.384
	(4,067)	(4.655)	(3.047)	(6.348)
Elasticity at conditional mean	-5.08*	-7.37**	-4.10**	-3.65*
Data included in sample:				
All observations from 2007	Y	Y	Y	Y
Growers who did not rent in 2006	N	Y	Y	Y
Growers who rented bees in 2006	N	N	Y	Y
# Observations	1,020	1,438	2,056	2,056

Notes: Table presents IV-tobit results for honey bee demand (weighted). Specification (1) uses data from 2007 only. Specification (2) employs an unbalanced panel over 2006-2007 that includes all observations from 2007, as well as growers who reported not renting bees in 2006, for whom we know the number of colonies rented per acre in 2006 is zero (thereby eliminating the need for quantity imputation). Specification (3) is a balanced panel that includes all growers in the data for both 2006 and 2007: if the grower rented bees in both years, we impute the number of colonies rented per acre in 2006 to be the number of colonies rented per acre in 2007; if the grower rented bees in 2006 but not in 2007, we impute the quantity rented in 2006 using regression-based imputation. Specification (4) is a balanced panel that includes all growers in the data for both 2006 and 2007: we impute missing quantity using regression-based imputation. For specification (1), the instrument for price (honey bee rental fee) is the Euclidean distance from the centroids of zip code units of farm locations to the centroid of Fresno County, California. For specifications (2), (3), and (4), the instrument for price (honey bee rental fee) is the interaction between the distance from zip code centroids where farms are located to the centroid of Fresno County, California and the total almond acres in California in year t. Elasticity at conditional mean is evaluated at the mean price and quantity among grower-years with positive quantity in the respective sample of data. Huber-White robust standard errors are in parentheses. Significance codes: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Table C.7: Binary choice to never rent bees, probit and IV-probit results (weighted).

	Dependent variable is probability of never renting honey bees			
	(1)	(2)	(3)	(4)
	probit	probit	IV-probit	IV-probit
honey bee rental fee in 2006 ($/colony)			0.015	
			(0.045)	
honey bee rental fee in 2007 ($/colony)				0.010
				(0.032)
apple bearing acres	-0.017*	-0.017*	-0.018*	-0.017*
	(0.009)	(0.009)	(0.009)	(0.009)
apple bearing acres, squared	0.000037*	0.000037*	0.000037*	0.000036*
	(0.000021)	(0.000021)	(0.000021)	(0.000021)
total bearing apple blocks	-0.068***	-0.070***	-0.068***	-0.067***
	(0.014)	(0.014)	(0.014)	(0.014)
total bearing apple blocks, squared	0.00059***	0.00061***	0.00058***	0.00058***
	(0.00016)	(0.00016)	(0.00016)	(000016)
trees per acre	0.0005	0.0004	0.0003	0.0003
	(0.0012)	(0.0012)	(0.0013)	(0.0013)
trees per acre, squared	-0.000002	-0.000002	-0.000002	-0.0000019
	(0.000001)	(0.000001)	(0.000002)	(0.0000015)
average age of trees	-0.0036	-0.0053	-0.0024	-0.0041
	(0.0172)	(0.0173)	(0.0167)	(0.0175)
average age of trees, squared	0.00021	0.00024	0.00020	0.00021
	(0.00026)	(0.00026)	(0.00025)	(0.00026)
natural forest cover	1.370	1.235	1.553	1.479
	(1.313)	(1.304)	(1.498)	(1.370)
natural forest cover, squared	-2.039	-1.711	-2.473	-2.281
	(1.492)	(1.508)	(2.072)	(1.681)
natural open cover	-6.896***	-6.374***	-7.531**	-7.063***
	(2.366)	(2.521)	(2.997)	(2.417)
natural open cover, squared	6.243***	5.776**	6.848**	6.360***
	(2.352)	(2.449)	(2.955)	(2.406)
total utilized production price ($/pound)	-7.196***	-8.002**	-8.061***	-7.872***
	(2.180)	(4.057)	(2.981)	(2.689)
has federal crop insurance in 2007 (dummy)	-0.553***	-0.525***	-0.567***	-0.563***
	(0.152)	(0.151)	(0.154)	(0.154)
CA (dummy)	1.524***	1.557***	1.942	1.817*
	(0.410)	(0.495)	(1.274)	(0.943)
OR (dummy)	1.232**	1.250**	1.590	1.472*
	(0.497)	(0.625)	(1.129)	(0.815)
WA (dummy)		1.420	1.677	1.593*
		(0.982)	(1.182)	(0.968)
PA (dummy)	1.340*	0.116		
	(0.723)	(0.305)		
NC (dummy)		-0.474		
		(0.454)		
NY (dummy)		[dropped]		
constant	2.639***	2.773***	2.183	2.286*
		(1.020)	(1.647)	(1.345)
	Average partial effects			
apple bearing acres	-0.00217*	-0.00211*	-0.0167*	-0.0163*
total bearing apple blocks	-0.00656***	-0.00656***	-0.0499***	-0.0496***
trees per acre	-0.0000898	-0.0000940	-0.000798	-0.000785
average age of trees	0.000569	0.000468	0.00513	0.00394
natural forest cover	-0.0172	-0.00319	-0.268	-0.201
natural open cover	-0.431**	-0.390**	-3.585**	-3.397***
# Observations	1,020	1,020	1,020	1,020

Notes: Table presents results (weighted) from probit and IV-probit regressions of the binary choice to never rent honey bees. For the IV-probit regessions in specifications (3) and (4), the instrument for price (honey bee rental fee) is the Euclidean distance from the centroids of zip code units of farm locations to the centroid of Fresno County, California. Huber-White robust standard errors are in parentheses. Significance codes: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

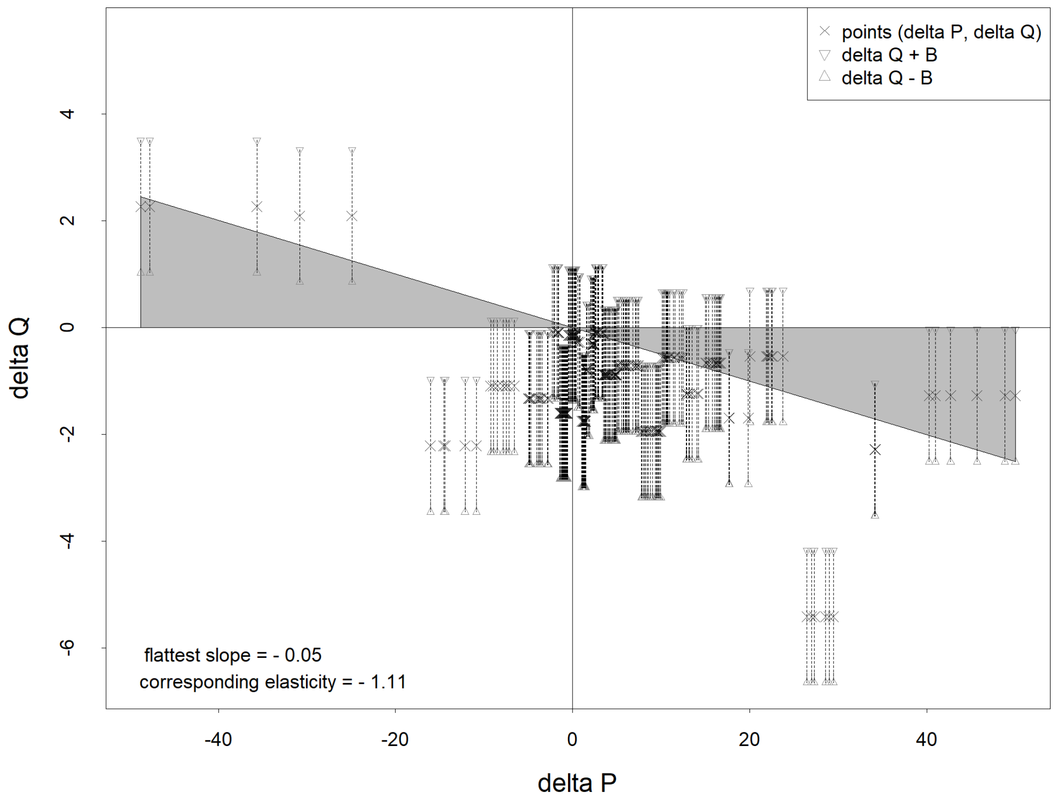

Figure C.4: Figure illustrates the construction of bounds on the honey bee demand elasticity from using the absolute value of the differenced quantity for observations for which the differenced price is equal to zero as our demand shock, the number of colonies rented per acre (rather than the number of colonies rented) as our measure of quantity, and a demand shock bound B of 1.24, which is twice the maximum absolute value of the differenced quantity for observations for which the differenced price is equal to zero. The subsample is the same balanced panel of 1,028 farmers that we use in specification (4) in Table 1 and specification (4) in Table C.5. The cross-hatches depict a scatterplot of the first differenced price on the x-axis and smoothed first differenced quantity on the y-axis. The dotted interval around each cross-hatch as radius of $B = 1.24$. The shaded region depicts all demand functions consistent with an upper bound of $B = 1.24$ on the maximum absolute value of the demand shock. These are the downward-sloping lines that pass through the origin and through all of the dotted intervals. The implied bound on the slope is -0.05 and the corresponding bound on demand elasticity (when evaluated at mean price and quantity) is -1.11.

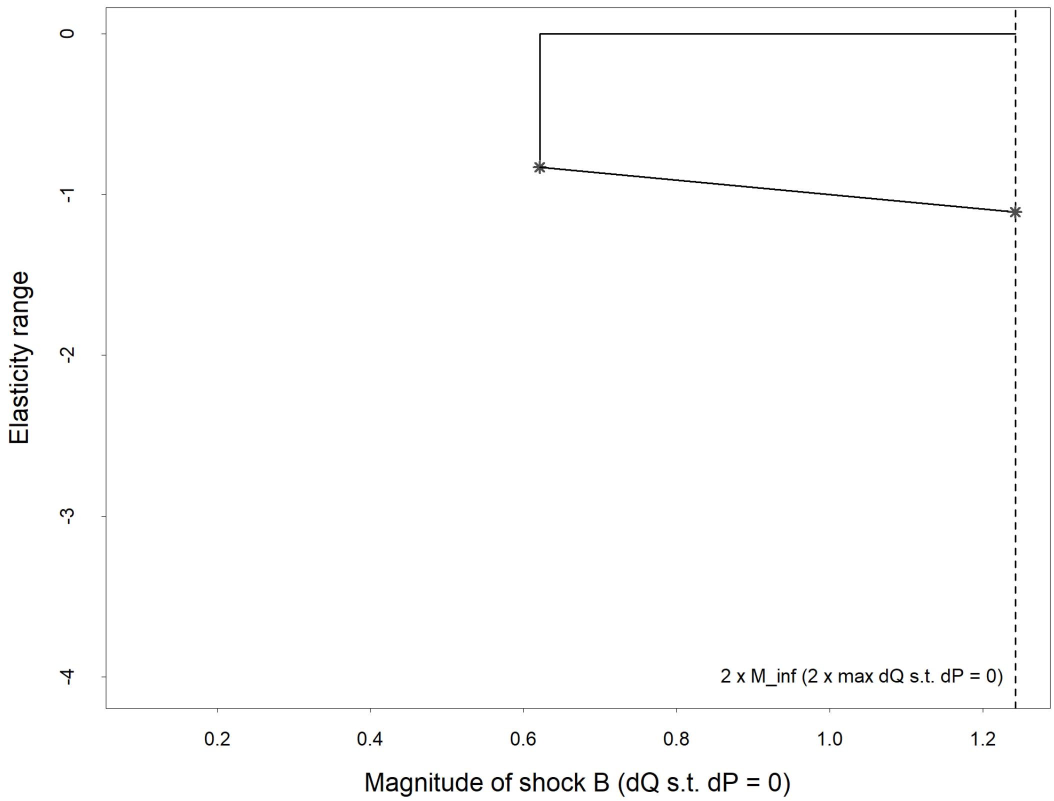

Figure C.5: Figure plots the range of honey bee elasticities (when evaluated at mean price and quantity) that are consistent with bounds on the plausible size of shocks to demand ranging from the mean absolute value of the differenced quantity for observations for which the differenced price is equal to zero, to twice the maximum absolute value of the differenced quantity for observations for which the differenced price is equal to zero, when using the number of colonies rented per acre (rather than the number of colonies rented) as our measure of quantity. The subsample is the same balanced panel of 1,028 farmers that we use in specification (4) in Table 1 and specification (4) in Table C.5. The dashed vertical line is at twice the maximum absolute value of the differenced quantity for observations for which the differenced price is equal to zero.

Table C.8: Weighted fixed effects regression of yield on honey bee colonies per acre.

	Dependent variable is block-level apple yield (bushels/acre)
	(1)
honey bee colonies per acre	113.827***
	(19.814)
honey bee colonies per acre, squared	-11.412***
	(3.166)
Production scale variables	Y
Land cover variables	Y
Labor input variables	Y
Weather variables	Y
State FE	Y
Adjusted R^2	0.311
# Observations	998

Notes: Table presents results from weighted fixed effects regression of block-level yield in bushels per acre regressed on honey bee colonies per acre. Regression controls for measures of production scale (trees per acre, trees per acre squared, average age of trees, and average age of trees squared), remotely sensed land cover measures to proxy for wild bee habitat and landscape heterogeneity (natural forest cover, natural forest cover squared, natural open cover, natural open cover squared), labor inputs (pruning/thinning hours, harvesting hours, land prep and machine hours, pest scouting hours, part-time and seasonal hours, and full-time hours), weather variables (monthly average temperature and precipitation over January-September, the months leading into the main harvest period), and state fixed effects. Huber-White robust standard errors are in parentheses. Significance codes: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

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