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An Equilibrium Analysis of Antibiotics Use and Replanting Decisions in Apple Production

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Antibiotics are used in fruit production to control fire blight, a bacterial disease of fruit trees that causes yield losses and eventually tree death. Fearing the development of widespread antibiotic resistance, scientists and public health officials are becoming increasingly concerned about antibiotics use in agriculture. A framework is developed for assessing the impacts of changes in tree damage risk following a ban on antibiotics use in the apple industry. Allowing for entry and exit, a long-run analysis of replanting dates and equilibrium prices is provided, as well as an estimate of the welfare impacts of a ban on antibiotics.

Key words: antibiotics, apple orchard, dynamics, equilibrium, replanting, resistance

Introduction

Antibiotics are used in fruit production to control fire blight, an economically important bacterial disease of apples, pears, and other plants of the rose family (*rosacea*) caused by the bacterium *Erwinia amylovora*. Fire blight differs from other common plant diseases in that it not only affects yield and quality of the current crop, but also leads to significantly lower tree productivity for several years. Severe infections can lead to tree death, especially in younger trees (van der Zwet and Beer). Outbreaks of fire blight are sporadic, but losses can be severe if the disease diffuses in a given production area.

Currently, 35.8% of U.S. apple acreage is planted to fire blight-susceptible varieties (Rosenberger). This percentage continues to increase because many of the new varieties, such as Fuji and Pink Lady, are much more susceptible than the common older varieties, such as Red or Golden Delicious. Furthermore, a similar trend toward planting rootstocks with high susceptibility to fire blight has been observed (van der Zwet and Beer). Plant pathologists have consistently reported fire blight as a disease of high importance in apple and pear orchards (van der Zwet and Beer).

In 1991, a severe fire blight outbreak in Michigan caused losses estimated at \$3.8 million. If antibiotics are unavailable for fire blight control, experts predict apple acreage would decrease by 13% in the next five years, and annual yield would decrease by 8%

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(Rosenberger). The principal antibiotics in a fire blight control program are streptomycin and oxytetracycline. Copper compounds are available as an alternative means of control; however, they are much less effective and more phytotoxic than antibiotics.

There is a possibility of losing access to antibiotics as a means of disease control in agriculture. This practice is currently a controversial issue due to public health concerns over the risk of resistance development (Witte; Grady). The increase in antibiotic resistance has triggered policy makers' concern, and policies to reduce the nontherapeutic use of antibiotics have been proposed. Bacteria can store their resistance genes in plasmoids, a cell structure which can be transferred between bacteria, thereby also transferring the resistance genes.¹ It has been shown that people who are frequently exposed to antibiotics are at higher risk for contracting antibiotic-resistant bacteria (Levy 1998). When applying antibiotics in aerosols to fruit trees, bacteria on the trees are killed, but lingering antibiotic residues can encourage the development of resistance.²

These public health concerns seriously challenge the future use of antibiotics for disease control in fruit production. In fact, in Italy antibiotics may no longer be used for fire blight control. Moreover, because of developments in apple production systems themselves, a study of the implications of losing control over fire blight is of particular interest. Specifically, the fire blight bacterium has developed resistance to streptomycin in the Pacific Northwest (Smith). Growers have to rely on access to oxytetracycline, for which an exceptional permission must be obtained from the Environmental Protection Agency. Continued permission is not assured. This problem is aggravated by the fact that unusually warm spring weather conditions during the late 1990s in the Northwest have led to an increase in fire blight prevalence.

The objective of this analysis is to estimate the importance of antibiotics in apple production systems. To this end, a model of orchard replanting is developed which can incorporate the changes in orchard survival probabilities. Here we are not interested in developing management programs to control the resistance dynamics of the fire blight bacterium, but rather we examine the direct effects of antibiotic cancellations on the structure of the orchard industry. Existing models developed to estimate economic impacts resulting from a regulation of pesticide use are not suitable for our context because these models are annual in nature and focus on changes in annual costs of production or changes in yield (Lichtenberg, Parker, and Zilberman; Sunding). They do not incorporate the risk that a tree might be destroyed before it reaches its planned replanting time, and so do not offer a way to accommodate changes in survival probabilities. Our analysis uses a concept of industry equilibrium similar to Silberberg's to capture market-level impacts, and embeds choices of individual investors in a partial-equilibrium model. In an empirical application, we estimate the welfare impacts of a ban on antibiotics in U.S. apple production.

¹ Especially if bacteria are of common families, resistance features likely can be transferred. *Erwinia*, for instance, belongs to the family of Enterobacteriaceae, the family that includes *Escherichia coli*, *Salmonella*, and *Shigella*, all of which are well-known causes of foodborne diseases. Bacteria in this family can exchange genes among themselves. Although streptomycin, the antibiotic most frequently used in fruit production, is no longer widely used in human health treatment, streptomycin resistance is often found in conjunction with other resistance determinants. Some *Erwinia amylovora* displaying multidrug resistance have been isolated, and so the use of streptomycin increases the development of multidrug resistance (Levy 1992, p. 163).

² People can then acquire resistant bacteria through food consumption. Corpet showed that when humans are restricted to a diet of bacteria-free foods, the number of resistant bacteria in their feces decreases 1,000 fold. Levy (1992, p. 165) isolated 20,000 to 100,000 antibiotic-resistant bacteria per gram of vegetable in a study conducted in Boston. The amount of resistant bacteria on food does not appear to be trivial.

The Model

There exists a sizable literature on the estimation of perennial crop supply dealing with the question of industrywide acreage adjustments (Akiyama and Trivedi; Elnagheeb and Florkowski; French, King, and Minami; Hartley, Nerlove, and Peters; Knapp and Konyar). Microeconomic models of the replanting decision have been formulated as recursive dynamic programming problems (see, for example, Gunter and Bender), but they do not allow for a general analysis of the solution properties in equilibrium. Dorfman and Heien present an analysis of the effects of revenue uncertainty and adjustment costs on investment and perennial crop planting. However, our concern is not with annual revenue uncertainty, but with changes in survival probability of the orchard. We develop a model that analyzes the role of disease survival probability on the replanting decision for an individual orchard. Our model builds on the existing literature in forestry economics (Englin, Boxall, and Hauer; Hartman; Reed). Parts of the model, described below, are a generalization of Reed's study of harvesting policies for forests at risk to destruction by fire.

Site Value

In this section, we develop a Faustmann-type model (Clark, chapters 9.1 and 11.2) to analyze the decision to replant an existing orchard, where we explicitly model the probability that an orchard is destroyed at any given time. The Faustmann framework accommodates the opportunity cost of waiting to replant an orchard. Any research seeking to study, among other things, the impact of policies on orchard age would be ill-posed if it did not formally model this opportunity cost. The decision concerns when to replant a standing disease-susceptible orchard, where lower revenue flows accrue to orchards that survive past maturity.³ We model the occurrence of fire blight at the orchard level. If the technology exhibits constant returns to scale, translating the model to a less aggregated unit of analysis would not change the results.

Our model concerns the decision to replant an existing orchard at lump-sum cost I . An orchard once planted can remain in production for several decades. At replanting time, the basic orchard technology is chosen, including aspects such as variety, root-stock, irrigation, and planting density, and subsequently the production function has a very low elasticity of substitution with respect to variable input choices. To focus on the long-term planting decision, we model production using a revenue function depending on orchard age t . The net revenue flow can be described by:

$$(1) \quad r(t) = p(t)y(t) - c(t),$$

where $p(t)$ is the price paid for the crop at time t , $y(t)$ is yield at time t , and $c(t)$ represents the cost of running the existing orchard.⁴

³ An alternative problem would be whether to invest in the first place. The distinction between these problems will become apparent when we formally pose the model. We chose to study the former, i.e., the reconsideration of an ongoing investment, because a ban on antibiotics will likely lead existing growers to reconsider whether to replant or not.

⁴ In this specification, marginal harvest costs can be accommodated by adjusting the price function.

Times between successive orchard destructions are denoted as $\{X_1, X_2, \dots\}$, and can occur either because the orchard has been destroyed by disease or other adverse events, or because management has made the removal decision. Each period from planting to cutting of the orchard is described as an orchard cycle, and the duration of the n th orchard cycle is X_n . Discounting forward the net returns of the orchard over its life cycle at rate δ , the cumulative net return is:

$$(2) \quad R_n = \int_0^{X_n} r(t)e^{\delta(X_n-t)} dt = e^{\delta X_n} \int_0^{X_n} r(t)e^{-\delta t} dt.$$

The occurrence of destruction by fire blight or any other adverse event is modeled as a Poisson process with the intensity rate λ , so that the probability distribution of the random variables $\{X_n\}$ is:

$$(3) \quad F_{X_n}(t) = \begin{cases} 1 - e^{-\lambda t} & \text{if } t < T, \\ 1 & \text{if } t \geq T, \end{cases}$$

where $F_{X_n}(t)$ is the cumulative density function; i.e., for $\{n = 1, 2, \dots\}$, $F_{X_n}(t) = \text{Prob}(X_n \leq t)$. The parameter λ measures the intensity of the likelihood of destruction by disease, and henceforth we refer to it as the risk parameter. Note that λ does not affect the instantaneous revenue, $r(t)$, within a given cycle of stochastic length, but rather the expectation and all other moments of X_n . It therefore captures the probability of a deadly fire blight event. In (3), T is the time of planned replanting so that the planned replanting time T is the upper bound on orchard age. The destruction times are independent of each other and thus form a renewal process (Taylor and Karlin).⁵

To calculate the complete site value, we compute the discounted infinite horizon return to the land, applying the discount rate δ , so that the expected discounted return is designated by:

$$(4) \quad J(T) = E \left[\sum_{n=1}^{\infty} e^{-\delta(X_1+X_2+\dots+X_n)} (R_n - I) \right].$$

Note that the modeled decision maker is an incumbent, and so lump-sum cost I first materializes at stochastic time X_1 rather than at time zero. The orchard manager's problem as presented in (3) and (4) is similar to Reed's analysis, but uses the more general cumulative net return function (2).

From Reed's observation, we employ the independence of the identically drawn X_i to write $J(T)$ as:⁶

$$(5) \quad J(T) = \frac{E[e^{-\delta X}(R - I)]}{[1 - E(e^{-\delta X})]},$$

where X represents the process that generates the sequence $\{X_1, X_2, \dots\}$. We can calculate $E[e^{-\delta X}] = (\lambda + \delta e^{-(\lambda+\delta)T})/(\lambda + \delta)$ and, carrying out the expectations in the numerator, we obtain the following expression for the total site value:

⁵ The independence assumption is not very restrictive for our problem because disease outbreaks are not expected to be correlated between years.

⁶ See equation (11) in Reed.

$$(6) \quad J(T) = \frac{(\lambda + \delta)\lambda \int_0^T \int_0^\tau r(t)e^{-\delta t} dt e^{-\lambda\tau} d\tau}{\phi} + \frac{(\lambda + \delta)e^{-\lambda T} \int_0^T r(t)e^{-\delta t} dt}{\phi} - \frac{I[\lambda + \delta e^{-(\lambda+\delta)T}]}{\phi},$$

where $\phi = \delta[1 - e^{-(\lambda+\delta)T}]$. As expressed in equation (6), the total return to the site is equal to the appropriately weighted expected revenue in the event of involuntary destruction plus the survival probability times the appropriately discounted expected revenue conditional on survival until planned replanting less the appropriately discounted cost of replanting in either event.

Replanting Decision

Differentiating $J(T)$ with respect to T and setting the derivative equal to zero gives implicitly the optimal lifetime of an orchard. Note that $d\phi/dT = \delta(\lambda + \delta)e^{-(\lambda+\delta)T}$, and so

$$(7) \quad \frac{dJ}{dT} = \frac{1}{\phi} \left[(\lambda + \delta)\lambda \int_0^T r(t)e^{-\delta t} dt e^{-\lambda T} - \lambda(\lambda + \delta)e^{-\lambda T} \int_0^T r(t)e^{-\delta t} dt + (\lambda + \delta)e^{-\lambda T} r(T)e^{-\delta T} + I\delta(\lambda + \delta)e^{-(\lambda+\delta)T} - \delta(\lambda + \delta)e^{-(\lambda+\delta)T} J(T) \right] = \kappa [r(T) + \delta I - \delta J(T)],$$

where $\kappa = (\lambda + \delta)e^{-(\lambda+\delta)T}/\phi \neq 0$. Letting T^* denote the optimizing value, the first-order condition can be written as:

$$(8) \quad r(T^*) = \delta J(T^*) - \delta I.$$

The optimal orchard replanting time T^* depends on the discount rate δ , on the risk parameter for orchard destruction by disease λ , and on the shapes of the price function $p(t)$, yield function $y(t)$, and cost function $c(t)$. The first-order condition states that the incremental return of keeping the orchard, $r(T^*)$, must equal the rent from starting over, $\delta[J(T^*) - I]$, so that the instantaneous return at T^* , $r(T^*)$, must be smaller than the average return $\delta J(T^*)$. Net revenue at the replanting date must be exactly equal to the average return net of the discounted replanting cost.

The second-order condition requires that $r_T(T^*) \leq 0$, i.e., $p_T(T^*)y(T^*) + p(T^*)y_T(T^*) - c_T(T^*) \leq 0$, where the subscripted T denotes a derivative with respect to T , and where we use the first-order condition to assert that $J_T(T^*) = 0$. If $r(t)$ increases, peaks, and then falls substantially, then a global maximum is likely. Henceforth we assume such a maximum.

Impact of λ on Site Value

We can observe that the size of λ has two opposing effects on total site value. This is easiest to ascertain from equation (5). As the risk parameter λ increases, the expected lifetime decreases, lowering the denominator and increasing the annualized cost of

investment. Therefore, $E[e^{-\delta X}I]/\{1 - E[e^{-\delta X}]\}$ as a whole increases. On the receipts side, expected revenue may increase or decrease. In the case of an increase in λ , the expected return for the event $X = T$ decreases, but the probability-weighted return for the case $X < T$ can increase or decrease given T . If the overall expected return per cycle decreases, then both the numerator $E[e^{-\delta X}R]$ and the denominator $1 - E[e^{-\delta X}]$ decrease, so that the condition of decreasing expected lifetime return is not sufficient to sign $J_\lambda(\cdot)$. If the denominator $1 - E[e^{-\delta X}]$ decreases by proportionately less than the proportional change in the expected lifetime return $E[e^{-\delta X}R]$, then $J(\cdot)$ would decrease as λ increases. However, this depends on the particular form of $r(t)$ and the size of δ and T . Despite difficulty in signing the derivative, $J_\lambda(\cdot)$ seems most likely to be negative. This condition holds true for the function we study in our empirical application later in the article. A brief explanation as to why $J_\lambda(\cdot)$ cannot be signed without further restrictions is available from the authors upon request.⁷

Equilibrium

Equation (8) implicitly defines the optimal cycle length for one orchard. For the equilibrium analysis, we assume there exists a sufficiently large acreage which is equally fit for apple production and, in the long run, that acres switch to or from apple production according to the opportunity cost of production.⁸ Each acre remains in apple production as long as the average return $\delta J(T^*)$ meets or exceeds the opportunity cost of land use and management, which is denoted by π_0 . If $\delta J(T^*)$ decreases below π_0 , then growers choose to leave apple production and employ the land in alternative activities such as cherry or pear production. If prices do not adjust, production is reduced to zero. Similarly, if $\delta J(T^*)$ increases but prices remain fixed, then resources from other industries enter apple production and supply increases. Orchards are held to be homogeneous, and the supply of apples is assumed to be perfectly elastic. This assumption allows us to apply an extended version of Silberberg's long-run equilibrium model.

However, a supply shift due to changes in average returns or opportunity costs affects market prices, and an equilibrium analysis requires us to study the effect on prices and T^* simultaneously. To do so, we must further characterize the dynamic structure of the industry. It is assumed that in a steady-state equilibrium, an equal number of acres is planted each year. The price trajectory $p(t)$ is a function of the orchard age, and it is necessary to precisely define a shift in the trajectory. We develop the price function as $p(t) = a + s(t)$, and let $s(t)$ evolve according to orchard age. Explicitly, we set $s(0) = 0$ so that $p(0) = a$. Changes in $s(t)$ reflect decreases in quality which occur with orchard age (Funt et al.) and changes in the marketability of a variety. A change in the price schedule is then defined as a shift in the parameter $a > 0$. The equilibrium price schedule is thus determined to satisfy

$$(9) \quad \pi_0 = \delta J(T^*).$$

⁷ The problem is related to that of capital budgeting problems, where there may be multiple internal rate-of-return solutions to a given problem, and where present value is not monotonic in the rate of return.

⁸ Most commercial U.S. apple orchards are on irrigated land where a variety of alternative crops, such as pears, peaches, and row crops, are feasible.

The optimal replanting date T^* is chosen according to (8) but conditional on parameter α , and parameter α adjusts to ensure adherence to condition (9).

To close the model explicitly for a subsequent equilibrium and welfare analysis, we introduce the aggregate demand equation $Q^D(P)$ and a net import equation $M(P, Q^P)$, where P is the prevailing market price and Q^P is the aggregate amount of U.S. apples produced.⁹ The partial market equilibrium then results as:

$$(10.1) \quad Q^D(P) = Q^D,$$

$$(10.2) \quad M(P, Q^P) = M,$$

$$(10.3) \quad Q^P + M = Q^D.$$

Q^P is modeled as residual supply equating aggregate demand with aggregate supply from U.S. production and net imports. And we assume for our equilibrium analysis that, locally at least, the supply function is perfectly elastic.

The equilibrium stated in equation system (10) is a long-run equilibrium, because only then does the assumption of a locally, perfectly elastic supply curve seem suitable. To link equations (8) and (9) to system (10), the age distribution of orchards must be made explicit; production is subject to stochastic shocks, the occurrence of which is determined by λ . Aggregate U.S. production is specified as:

$$(11) \quad Q^P = \int_0^{T^*} y(\tau)A(\tau) d\tau,$$

where $A(\tau)$, $\tau \in [0, T^*]$ is the current age distribution of orchards, i.e., the number of acres of age τ , and $y(\tau)$ is the yield for each age. A similar equation can be constructed for the prevailing weighted average market price:

$$(12) \quad P = \frac{\left[\int_0^{T^*} p(\tau)y(\tau)A(\tau) d\tau \right]}{Q^P}.$$

For our long-run U.S.-wide analysis, we assume the overall age distribution $A(\tau)$ is stable, as fire blight events are local events which depend on local disease pressure and local weather conditions. Given that we are interested in the long-run development over a large area of different growing regions (i.e., the entire U.S.), we assume $A(\tau)$ in the long run is uniform over $[0, T^*]$ so that an equal share of trees of every age exists. The assumption of a uniform age distribution was made to facilitate a subsequent simulation analysis.¹⁰

Equations (11) and (12) aggregate the variables of individual decisions, as described in equations (8) and (9), to the equilibrium model in (10). So equipped, we can assess the impact of a shift in technology on equilibrium. To reestablish a finite and positive supply after a shift in technology, price adjusts according to equations (8) and (9). This shift in

⁹ We recognize there may be aggregation bias arising from the fact that we aggregate one market per year for each of the T^* years into a single price statistic. However, we aggregate to render the model tractable.

¹⁰ We do not model convergence to equilibrium in the aftermath of a parameter shock, and we have not established the conditions under which long-run convergence to a uniform age distribution is assured. Further, the adjustment in the short-run and perhaps in the long-run price path $p(t)$ may not accord with the assumptions on the nature of endogenous adjustments. Clearly, the information environment and the technical ease with which firms can adjust will be important. For our purposes, the inclusion of these and other factors would render the model too unwieldy to provide useful policy suggestions.

the price trajectory, $p(t)$, is modeled through a shift in the parameter a , denoted by Δa . We can derive the resulting changes in quantities demanded and supplied by totally differentiating (10) and so obtain:

$$(13.1) \quad \left(\frac{\partial Q^D}{\partial P} \frac{P}{Q^D} \right) \frac{Q^D}{P} \Delta a = \Delta Q^D,$$

$$(13.2) \quad \left(\frac{\partial M}{\partial P} \frac{P}{M} \right) \frac{M}{P} \Delta a + \left(\frac{\partial M}{\partial Q^P} \frac{Q^P}{M} \right) \frac{M}{Q^P} \Delta Q^P = \Delta M,$$

$$(13.3) \quad \Delta Q^P + \Delta M = \Delta Q^D.$$

System (13) is linear in the changes ΔQ^D , ΔM , and ΔQ^P , and thus can easily be solved for these quantities given the appropriate elasticity estimates and data on current quantities and prices.

Having identified a long-run equilibrium, it is possible to analyze the impact of changing fire blight prevalence on the system. Such a change can be decomposed into three effects: (a) a change in the cost trajectory for increased costs of pruning and orchard hygiene, (b) a change in yield trajectory (temporary loss of productivity), and (c) a change in the survival probability (terminal loss of productivity). Impacts (a) and (b) will hence lead to changes of the net revenue function.

Analyzing the responses in market price Δa and replanting time T^* using conditions (8) and (9), we find the equilibrium price increases with rising costs and decreases with an upward shift in the yield function. If $J_\lambda \leq 0$, we derive $dT^*/d\lambda \geq 0$ and $da/d\lambda \geq 0$. Optimal replanting is delayed and the equilibrium price schedule shifts upward. This result contrasts with that obtained in Reed's analysis, where an increase in risk of forest fire was shown to shorten the optimum rotation length.¹¹

To understand why optimal rotation length would likely increase with mortality risk, we must consider the form of instantaneous revenue functions that satisfy our assumption of a unique maximum. The function will increase, achieve a maximum, and later decrease substantially. If the risk of fire blight increases, replanting the orchard will incur the risk of losing the investment before recovering it. The delay of the decision to replant illustrates the irreversibility involved in the orchard manager's decision to replant. The "sunk" cost incurred at replanting makes the orchard owner more averse to incurring the investment at the increased risk of losing it. (Detailed analytical derivations of the comparative statics results are available from the authors upon request.)

Simulation Analysis of the Economic Impact of Antibiotics Use Removal

In order to assess the welfare impacts of a ban on antibiotics, U.S. apple production data are collected and analyzed to establish an empirical revenue function. Biological impact estimates are then implemented from a U.S. Department of Agriculture/National Pesticide Impact Assessment Program (USDA/NAPIAP) project assessing the production

¹¹ Consider the simple case where price parameter a is fixed. Using equation (8), together with the envelope theorem, we have $dT^*/d\lambda = \delta J_\lambda / r_T(T)$, where $r_T(T) < 0$ from the second-order condition.

Table 1. U.S. Apple Production Data, 1994-96

Item	Unit	Average	Item	Unit	Average
Acreage	000 acres	449.6	Net Imports	mil. lbs.	1,763.10
Yield	lbs./acre	23,500.0	Average Price	¢/lb.	15.31
Production	mil. lbs.	10,654.1	Price for Processed Apples	¢/lb.	7.54

Source: USDA, *Noncitrus Fruits and Nuts: Annual Summary*.

impacts of pesticide bans in apple production (Rosenberger) in order to estimate the economic impacts of a ban on antibiotics. Since apple trees yield fruit once a year, we conduct the simulation analysis using the discrete analog of the analytical model.

Yield Function

For the yield function, we use data from O'Rourke, who estimates the yield for a representative orchard in the state of Washington.¹² This yield function gives data for 41 years of orchard age and forms an S-shaped function which levels off after achieving its maximum in year 24. For the welfare analysis, we normalize the yield function so the average yield will equal the U.S. 1994-96 average yield of 23,500 pounds/acre (table 1) under the assumption that an equal number of acres of each maturity are in production. This normalization will depend on the estimated optimal cycle length resulting from the optimization of $J(T)$, and will therefore depend on the cost, investment, and price data.

Price Function

Limited data are available to estimate the price function. Discussions with many industry specialists indicated to us that price decreases for the orchard crop are a major reason for replanting an orchard. For a particular variety, prices may decrease because of supply increases and changes in demand. In addition to price changes by variety, the value of crop from a particular genetic material may change according to details such as coloring or storage quality of the apples. The data to estimate these effects are sparse and ignore many quality and demand effects.

Price data by variety were obtained from the Washington Growers Clearing House "Apple Price Summary" annual bulletin to estimate a price function by variety. For the newer varieties of Gala, Fuji, Braeburn, and Jonagold, we have annual data for the production years 1992/93 through 1997/98. This data panel of four varieties over six years is used to estimate price as a function of time employing an exponential function with a positive intercept as a lower limit for price. The lower limit is chosen to be the average price received for apples in the processed sector (7.54¢/pound). We impose this restriction on the intercept in the estimation procedure. The function is estimated as:

$$(14) \quad p_t = 0.0754 + (0.737 + 0.221D_1 - 0.183D_2 - 0.102D_3)\exp(-0.134t),$$

(0.799) (0.087) (0.087) (0.086) (0.026)

¹² O'Rourke estimates the yield curve by employing available data from fruit censi in the state of Washington, and also additional evidence from the industry.

where D_1 , D_2 , and D_3 represent dummy variables distinguishing the different varieties.¹³ The numbers in parentheses report standard errors, and all estimated parameters except the D_3 coefficient are significant. The regression R^2 equals 0.72. The F -test statistic to the restriction on the intercept is $F(1, 18) = 11.6$, and is rejected at the 1% significance level. The hypothesis is nevertheless maintained for the simulation analysis, because processing prices are a lower bound on eating variety apples. For the estimation of welfare impacts, the price function is calibrated to yield the U.S. average price of 15.31¢/pound by adjusting the multiplicative term to the exponential function.

Cost Function

A specification for the cost function was chosen using evidence from enterprise budgets for apple orchards (Bechtel et al.; Carkner, Havens, and MacConnell; Dickrell, Hinman, and Tvergyak; Funt et al.; Hinman et al. (1993a, b); Hinman, Williams, and Faubion; Marshall et al.; Parker et al.; Seavert and Burkhart). It is specified as a discrete step function; $(c_1; c_2) = (\$1,700; \$2,500)$, where c_1 denotes the lower annual fixed costs in early production years ($t \leq 5$), and c_2 denotes the higher annual fixed costs in later production years ($t \geq 6$). Evidence from these budget estimates also motivated our choice for I at \$6,000/acre.

Replanting Time and Price Adjustments

We analyze the impacts of changes in the production environment on the long-run equilibrium of the apple industry. Some general production statistics for the U.S. apple industry are given in table 1 (USDA 1995–97). For the simulation analysis, data from O'Rourke are used to evaluate tree survival probabilities. Consistent with this data set, the baseline parameter value of λ is set at $\lambda_0 = 0.01$. The discount rate δ is set approximately at the real rate of return on long-term securities at 0.04. Based on expert surveys, Rosenberger estimates a loss of antibiotics for fire blight management will lead to an 8% decrease in yield and a 13% acreage reduction in the subsequent five years. Under the assumption of a Poisson process, the acreage loss is equivalent to a value of $\lambda_1 = 0.027$. Based on the data provided in Rosenberger, the increase in cost of production is almost negligible at \$2.6/acre.

We employ these data to estimate the impact of an antibiotics ban using the yield, price, cost, and investment function specifications. For this estimation, $J(T)$ is calculated in discrete form using the annual return data for the functional specifications. We calculate the optimal replanting time under our baseline assumptions (T_0) together with the base return (π_0). Increasing λ to $\lambda_1 = 0.027$, increasing the cost function by \$2.6/acre, and decreasing yield by 8%, we vary a and calculate the new $T^* = T_1$ such that $\delta J(T_1, a_1) = \delta J(T_0, a_0)$. We calculate $\Delta a = a_1 - a_0$.

To obtain estimates of welfare impacts resulting from a ban on antibiotics, the equilibrium model presented in equations (13) is implemented. Elasticity estimates for this model were obtained from Roosen, who estimates the demand elasticity as -0.55,

¹³ A random-effects model was also implemented for the estimation of the price function. However, the Hausman test rejected the hypothesis that the random effects are uncorrelated with the explanatory variables. Therefore the fixed-effects specification was preferred.

Table 2. Impacts of a Ban on Antibiotic Use on U.S. Apple Production

Parameter ^a	Unit	Simulation Result	Parameter ^a	Unit	Simulation Result
π_0	\$/acre	871.8	ΔQ^P	mil. lbs.	-1,616.8
T_0	years	28.0	$\Delta Acre$	000 acres	-60.3
T_1	years	33.0	ΔCS	\$ mil.	-266.2
$\Delta\alpha$	¢/lb.	2.6	ΔPS	\$ mil.	-52.6
ΔQ^D	mil. lbs.	-961.0			

Note: A ban on antibiotic use produces the following results: yield decreases by 8%, cost increases by \$2.6/acre, and λ increases to $\lambda_1 = 0.027$.

^a Parameters are defined as follows: π_0 presents the baseline profit per acre, T_0 is the optimal replanting time under baseline assumptions, and T_1 is the optimal replanting time after a ban on antibiotics; $\Delta\alpha$ is the shift in the price schedule necessary to restore equilibrium. T_0 , T_1 , and $\Delta\alpha$ are calculated according to equations (8) and (9). ΔQ^D and ΔQ^P are the changes in quantity of apples demanded and domestically supplied, respectively, and follow from the equilibrium model (10). $\Delta Acre$ denotes the change in acreage, ΔCS the change in consumer surplus, and ΔPS the change in producer surplus.

the elasticity of imports with respect to prices as -0.76 , and the elasticity of imports with respect to home production as -3.3 . Given production and yield changes, we can now calculate the change in acreage ($\Delta Acre$), and the change in producer surplus ($\Delta PS = \Delta Acre \times \pi_0$).¹⁴ Consumer surplus change is calculated as $\Delta CS = -(Q^D + \Delta Q^D/2)\Delta\alpha$.

As reported in table 2, the simulation result for baseline profit, π_0 , is \$872/acre, and the replanting age is $T_0 = 28$ years. As expected, the optimal replanting date lies in the decreasing part of the yield function.¹⁵ After a ban on antibiotics, the optimal replanting age increases to $T_1 = 33$ years, a result consistent with $J_\lambda \leq 0$. A price increase of $\Delta\alpha = 2.6$ ¢/pound is necessary to restore equilibrium. The estimated change in domestic supply is $\Delta Q^P = -1.617$ billion pounds, and the change in quantity demanded is $\Delta Q^D = -961$ million pounds. The difference is met by a change in net imports. Estimated welfare changes, ΔPS and ΔCS , sum to \$319 million.¹⁶ Table 2 also reports the estimated change in acreage, $\Delta Acre$, because the producer surplus estimate will not only depend on production impacts but also on the imputed opportunity cost of apple production, π_0 . U.S. apple acreage decreases by 60,300 acres (13%).

The magnitude of the welfare impacts is largely determined by the price increase necessary to restore equilibrium. This price increase gives rise to a reduction in demand, and consequently a reduction in consumer surplus. Changes in net imports and in U.S. production restore market equilibrium. Given the perfectly elastic supply curve, in the long run the welfare impacts are borne by consumers.

¹⁴ The change in producer surplus ΔPS in this long-run model does not strictly adhere to the definition of producer surplus as given by revenue less total variable cost. Here, we measure the change in long-run grower income. In the long run, the grower remains as well off regardless of the decision to enter or exit apple production, and ΔPS measures the change in industry income.

¹⁵ If price declines rapidly over time and/or if replanting would be costless, then T^* could be smaller than the T that maximizes $y(T)$.

¹⁶ These estimates of welfare change are bound to overcount true welfare changes. ΔPS measures change in profit in the apple industry. Growers leaving the industry find alternative uses for their resources so that their opportunity cost would not be zero. Also, the measure of consumer surplus change in this study (ΔCS) counts only change due to own price. A stricter regulation of antibiotic use in agriculture is motivated by the adverse effects on resistance management in the human health sector. These benefits are not accounted for in this study.

Table 3. Sensitivity Analysis with Respect to Changes in λ and to Changes in Yield

λ_1	Average Yield in Pounds/Acre				
	22,900	22,300	21,700	21,100	20,500
0.014	$\Delta a = 0.7$ $T_1 = 30$	$\Delta a = 1.2$ $T_1 = 30$	$\Delta a = 1.7$ $T_1 = 31$	$\Delta a = 2.2$ $T_1 = 32$	$\Delta a = 2.8$ $T_1 = 32$
0.018	$\Delta a = 0.9$ $T_1 = 30$	$\Delta a = 1.4$ $T_1 = 31$	$\Delta a = 1.9$ $T_1 = 32$	$\Delta a = 2.5$ $T_1 = 32$	$\Delta a = 3.0$ $T_1 = 33$
0.022	$\Delta a = 1.1$ $T_1 = 31$	$\Delta a = 1.6$ $T_1 = 31$	$\Delta a = 2.2$ $T_1 = 32$	$\Delta a = 2.7$ $T_1 = 33$	$\Delta a = 3.3$ $T_1 = 33$
0.026	$\Delta a = 1.4$ $T_1 = 31$	$\Delta a = 1.9$ $T_1 = 32$	$\Delta a = 2.4$ $T_1 = 33$	$\Delta a = 3.0$ $T_1 = 33$	$\Delta a = 3.6$ $T_1 = 34$
0.030	$\Delta a = 1.6$ $T_1 = 32$	$\Delta a = 2.2$ $T_1 = 33$	$\Delta a = 2.7$ $T_1 = 33$	$\Delta a = 3.3$ $T_1 = 34$	$\Delta a = 3.9$ $T_1 = 35$

Note: Change in prices (Δa) is measured in $\text{\$/pound}$, and post-impact optimal replanting time (T_1) is measured in years.

Sensitivity Analysis

To gain a better understanding of how different values for λ and changes in average yield would impact the equilibrium conditions, a sensitivity analysis is performed varying the post-impact value of λ and the change in yield. The parameter changes range from their baseline level ($\lambda = 0.01$ and no change in yield) beyond the estimated changes supplied by the experts. We report several results where λ assumes values between 0.014 and 0.030 and where average yields are reduced by values between 600 (2.6%) and 3,000 pounds/acre/year (13%). The resulting optimal adjustments in price parameter Δa and replanting time T_1 are shown in table 3. It can be observed that Δa , the post-impact price adjustment, is positive, and that T_1 , the post-impact replanting time, increases as the impacts become stronger, a result consistent with J_λ being negative. Thus, as the risk of mortality increases, growers defer replanting because the probability of recovering the investment in replanting is lower.

Experts are often thought to include a risk premium in their impact estimates (Roosen and Hennessy) and to overestimate the negative impacts of pesticide cancellations. We therefore repeated the simulation recorded in table 2 under reduced impact estimates at 50% of the originally estimated impacts—i.e., a reduction in yield by 4%, an increase in cost by $\$1.3/\text{acre}$, and a change in λ to $\lambda_1 = 0.0185$. This alternate simulation leads, for example, to a reduction in welfare changes by approximately 50%.¹⁷

To interpret the results of this simulation, we have to remind ourselves of the assumptions underlying the derivation of these estimates. We treat all growers alike and shift

¹⁷ Our simulation analysis is constrained by the limited data on apple production systems available in the literature. To assess the robustness of the conclusions we draw from the simulations presented in tables 2 and 3, we also employed different data on the yield function, the price function, the cost function, and the replanting costs. To arrive at our alternative yield functions, we used data collected by Funt. The results are similar to those presented in tables 2 and 3. This analysis of robustness is available from the senior author upon request.

the perfectly elastic supply curve in a parallel way. Price increases would be smaller if we used an increasing supply curve; in addition, some grower groups might be less affected by a ban on antibiotics. We ignore any changes in yield in response to an increase in prices, and in particular our model does not include technological change. If antibiotics are banned, it is most likely that the value of fire blight resistance in a variety would increase and growers would change the current trend of planting susceptible varieties. This, in turn, would reduce the change in λ . Our overall estimates should be interpreted as an upper bound on welfare impacts.

Conclusion

We have developed an equilibrium model of the decision to replant fruit orchards incorporating the risk that an orchard could be destroyed by disease or other adverse events. Optimal replanting time depends on the determinants of the stochastic revenue trajectory, e.g., the yield and fixed cost trajectories as well as the mortality parameter. The model facilitates thinking about long-term issues in pest control for perennial crops and about the decision to replant. It could be used to analyze the impact of changes in the survival probabilities of any kind of long-term investment project.

Our approach is more flexible than Reed's model, which analyzes the decision to cut and replant a forest at risk to forest fire, because in our case revenue is not restricted to accrue at a single point in time. We employ the model to simulate losses resulting from a ban on antibiotics in U.S. apple production, and we project that optimal replanting would be delayed by about five years. This delay is perhaps counterintuitive, and contrasts with the result obtained by Reed for the forest rotation problem under risk of fire. It arises mainly because the nature of the stakes in the gamble of deferring replanting are inherently different. In our model, what is at stake is additional revenue, whereas in the standard model what is at stake is total revenue. The price increase to restore equilibrium is estimated by employing the long-run equilibrium notion of Silberberg, and we arrive at an estimate of 2.6¢/pound. We estimate upper-bound losses to the apple industry of about \$320 million.

About 50% of all antibiotics used in the United States are used as agricultural inputs, the vast majority as growth enhancers in animal production. Still, 30% of U.S. apple acreage is treated with antibiotics (USDA 1998), and the most common application of the broad-spectrum antibiotic streptomycin is for treatment of fire blight in apple and pear production. Given the recent critical attention to antibiotics use in agriculture, an analysis of the welfare impact following an antibiotic removal in fruit production is urgently needed.

With this study, we attempt to initiate a discussion of the importance of antibiotics in fruit production. A complete investigation of the economic impact would additionally require a precise analysis of the risk posed to humans through exposure to resistant pathogens by antibiotic use in orchards. Experts agree that antibiotics use in food production encourages the development of antibiotic-resistant human pathogens. But the importance of this link is an open scientific issue. If the link between resistance development in plant and human pathogens is strong, then the impact of increasing the prevalence of antibiotic-resistant bacteria on human welfare is likely to have large consequences for welfare. The cost of increased antibiotic resistance is not negligible.

Sawert estimates that treatment cost alone would increase from \$20,000 to \$180,000 for tuberculosis patients with resistant *Mycobacterium tuberculosis*. Drawing the link between human health impacts and antibiotic use in agriculture would require an integrative analysis of disease epidemics, resistance dynamics, and economic effects.

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