Pricing and Welfare Impacts of New Crop Traits: The Role of IPRs and Coase's Conjecture Revisited

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Crop traits are durable when embedded in varieties, and thus they may be subject to Coase's conjecture that monopolists who sell durables may be unable to earn normal monopoly rents, or in the extreme case, not any rents at all. To determine the potential relevance of this conjecture for the crop traits market, we analyze the theoretical time path of trait prices under three systems of intellectual property rights (utility patents, plant breeders' rights, and none), alternative assumptions about sellers' ability to commit to future action, and alternative assumptions that buyers are either myopic or far-sighted with respect to expectations about the future price of the durable. Under only one of these stylized circumstances does the Coase conjecture have traction, but it is a plausible circumstance in much of the world—owners with plant breeders' rights, buyers with foresight. sellers unable to commit to future price paths. In this circumstance, this theory suggests that sellers holding only plant breeders rights would realize only 11% of potential social welfare benefits from the trait, while farmers and/or downstream consumers would realize about 85%. On the other hand, with myopic buyers under any system of intellectual property rights, temporal price discrimination is feasible, resulting in above-normal monopolist welfare (about 70% of maximum social welfare benefits) and little damage to consumers relative to normal monopoly pricing.

Key words: crop traits, Coase, durable monopoly, time-inconsistency, IPRs.

Individual crop traits at one time were inextricably packaged in the germplasm matrix of individual varieties or hybrids that farmers planted. That has changed. Scientists are now able to use genetic modification (GM) techniques to transfer traits previously unknown in a crop species into existing crop varieties and hybrids with desirable agronomic and product traits. An early example is the toxin-producing trait known as Bt, which was transferred from a bacterium into corn and cotton to provide protection from insects. The biotechnology firms that specialize in identifying new traits and methods of transfer are not necessarily the same firms that specialize in producing varieties and hybrids for sale to farmers. Consequently, many crop traits are now marketed by biotechnology firms to seed companies, who in turn incorporate them into their existing lines for sale to farmers. It is this market for crop traits that is the subject of analysis in this study.

A crop trait of this type is a durable input if it is introduced into an open pollinated variety (OPV) of a crop, because the farmer can use the harvested crop as seed for subsequent crops that will in turn exhibit the trait. Furthermore, if the biotechnology firms can pro-

tect these traits with intellectual property rights (IPRs), this market has the peculiarities of the monopolist selling a durable (dubbed a "durapolist" by Orbach, 2004). The durapolist has an incentive to price discriminate through time, setting a high price for the durable in the first period to "skim" off the buyers willing to pay the highest price, then lowering the price in each subsequent period so as to capture a large fraction of consumers' surplus. However, according to Coase's (1972) original conjecture, it seems likely that potential buyers will be aware of this incentive and simply wait for the price to fall, with the result in the extreme case that the durapolist will be quickly forced to sell the durable at marginal cost and realize no monopoly profits at all. There have been numerous extensions and applications of Coase's original insight allowing an understanding of, for example, unlawful reproductions of patented technology. These include copying (or 'pirating') of different types of media, print, and software. Waldman (2003) presents a complete and useful review of this literature.

In the agricultural economics literature, a number of papers address the issue of pricing of GM technology,

but only three address the time-related issues associated with the pricing of seeds that embody IPR-protected traits. Perrin and Fulginiti (2004) described multi-year equilibrium time paths for prices, implied by a Coasian model that in retrospect appears inappropriate to the seed market. Burton, Love, Ozertan, and Taylor (2005) developed a two-period model to examine the implications of genetic use restricted technologies (GURTs), which eliminate the trait after the first crop, versus short- or long-term contracts for use of seed. Ambec, Langinier, and Lemarie (2008) develop a two-period model to examine the incentives for the seed firm to produce a non-durable seed, such as a hybrid, rather than a durable seed. In contrast to these other papers, the role of this article is to re-examine the time-inconsistency issue in multiple-year equilibrium price paths relevant to seed markets in countries that enforce plant breeders rights, but lack the patent protection for seeds, which in most industrialized countries allows seed firms to price their seeds as non-durables. In this article we will then examine the market structure for crop traits to consider when it is likely that crop trait owners are limited in their ability to extract normal monopoly profits by the time inconsistency problem. We will see that, in addition to alternative institutional regimes, outcomes are sensitive to farmers' expectations regarding future trait price and whether or not the seller is able to credibly commit to future price announcements. We will further consider the welfare implications of these outcomes.

Market Structure for Traits

Characteristics of the market that are important in determining the theoretical time path of trait prices are (1) the durability of the trait, (2) the nature of intellectual property rights available to the trait owner, (3) the foresight of buyers with respect to future trait prices, and (4) the ability of the monopolist to credibly commit to future actions. Trait durability does vary depending on the kind of seed into which the trait is incorporated; property rights regimes in seed markets also vary around the world, and while firms in general cannot credibly commit to future behavior, it is conceivable. We now describe these characteristics of trait markets in more detail.

Durability of a Crop Trait

A crop trait will be a durable good only if it is transferred into a traditional open pollinated variety (OPV), as opposed to a hybrid. Hybrid seed, as the term is nor-

mally used in the seed market, does not "breed true," that is, the seeds of the harvested crop will produce a polyglot of plant types of little or no commercial value. This is because the production technique crosses two inbred lines, each of a homogeneous genotype but distinct from one another, in such a way that the hybrid plants themselves are very uniform, but that uniformity is lost with the genetic heterogeneity in the seeds produced by the hybrid plant. Hence, if a trait is transferred to a hybrid, the trait is generally not a durable, the durapoly issue does not arise, and the analysis of this study is not relevant.

In contrast to a hybrid, the seeds and plants of OPVs are self-replicating. Varieties are developed by the recurrent selection, over several generations, of plants conforming to a set of desired characteristics. The plants in the population that emerge from this process in general are virtually identical, both in appearance and in genetic structure, so the harvested seeds can be saved and planted for subsequent crops with little deterioration of traits over several generations. Therefore, if a trait is introduced into an OPV, it will generally be a durable good. If genetic drift and contamination is substantial, it would alter the durability properties of the trait. This does not materially affect the comparisons in our analysis.

The above discussion of the durability of traits is subject to modification by some emerging technologies, namely GURTS and apomixes. GURTs (also known more colorfully as "terminator technology" or "suicide seeds") either turn off the trait in seeds of the farm-produced harvest or make those seeds infertile, eliminating the durability of a trait embodied in a variety. Apomixes technology allows hybrid plants to produce clone-like seeds that duplicate the genotype of the hybrid seed, thus imparting durability to traits embodied in hybrids (Vielle Calsada, Crane, & Stelly, 1996). GURT technology is available, but is not presently being used, apparently because of political reasons. Apomixes has not yet been commercialized, apparently because of technical problems.

A substantial fraction of the world's crops are planted as OPVs, and it is anticipated that the number of GM traits available for them will increase rapidly in the next few years. Wheat, soybeans, cotton, and subsistence crops are commonly produced as OPVs, whereas crops such as maize and sorghum are produced commercially as hybrids in most areas of the world. James (2007) estimates that as of 2007, about 60% of the world soybean acreage and 18% of world cotton acreage was planted to varieties that incorporated patented traits. The

potential for even more widespread use of GM traits in varieties suggests that the durapoly issue is relevant and worth examining.

IPRs for Crop Traits

Crop traits are subject to two systems of intellectual property rights (IPRs) that convey different sets of monopoly rights to crop trait owners (see Perrin, 1994, for a static analysis of how these IPRs might affect agriculture in developing countries). The first of these is plant breeders' rights (PBRs), an intellectual property rights convention developed in the 1960's and now subscribed to by 46 countries, coordinated under the Union for the Protection of Varieties, or UPOV. PBRs were established in the United States with the 1970 Plant Variety Protection Act. The second IPR system is the standard utility patent system, which first became available for biological innovations such as crop traits in the United States, the European Union, and a few other countries beginning in the 1980's.

The rights conveyed to the owner differ between the two systems (Tripp, Louwaars, & Eaton, 2007). Under plant breeders' rights, the farmer who buys a variety can replant seed from his harvest for most crops but does not have the right to convey his harvest to others for use as seed. Given that traits embodied in the seeds of varieties are durable, this situation would seem to conform to the durapolist market structure: a monopolist selling a durable good to a group of competitive buyers. However, once the buyers' harvest enters the market, it provides a near-perfect substitute for traits offered for sale by the trait owner, posing a threat to the monopoly status of the trait owner after the first year of sales. Because of this glut of potential competitors, the ability of the trait owner to enforce his property rights, and the cost of that enforcement, play a crucial role in pricing of a trait embodied in a PBR-protected variety. With a very weak property rights system (or none at all), the monopolist is no longer a monopolist after the first year of sales because the crop marketed by every first-year adopter carries the trait and is available to other producers at essentially zero cost by simply purchasing the seed in the commodity market channel at the common commodity price. A collapse of the trait price due to such a property rights failure is of course a different phenomenon from a collapse associated with the time-inconsistency of Coase's conjecture.

On the other hand, if a crop trait is protected by a utility patent, the trait owner has the additional right to exclude even the buyer from replanting the seed containing the trait. To implement this exclusion, sellers often require buyers of varieties with patented traits to sign a technology agreement in which they agree to not replant the seed. Under US law it is illegal for the farmer to replant such seeds even in the absence of an explicit technology agreement. The trait in this case is no longer a durable, or at least not a legal durable. A trait owner who obtains a utility patent thus avoids the durapoly dilemma by eliminating the durability of the trait. The trait owner is then essentially in the position of offering one-year leases of the trait, a situation similar to that of placing the trait in a hybrid. Again, however, the feasibility and cost of enforcing the no-replant restriction determines whether the seller can avoid the Coase outcome.

While utility patents are clearly the stronger form of property rights, they are not available everywhere for crop traits, and they are more expensive to obtain than breeders' rights, so both systems persist.

Buyer Foresight and Seller Commitment

The heart of the difficulty faced by a durapoly is a timeinconsistency problem, in that its optimal behavior in the future will be inconsistent with its optimal plan for the present and the future together. For example, the initial optimal sales strategy may be to offer seed for sale just once, at the profit-maximizing price in the first period, with no further sales in the future. Yet when the future arrives, willing buyers remain in the market and it is then optimal for the firm to sell again at a new monopoly price appropriate for the remaining demand curve. Recognizing that possibility in advance however, buyers in the first period will hold out for the lower future price, and first-period sales won't match the seller's expectations. If the durapolist lowers the initial price in response, this may reinforce buyers' hold-out strategy, forcing the price downward toward marginal cost, perhaps even "in the twinkling of an eye," as Coase conjectured.

If however the firm can credibly commit to its exante optimal future behavior despite the time-inconsistency of its incentives, buyers' incentives to wait will be altered, and the seller could implement the ex-ante optimal strategy. Firms in many industries do find ways

Waldman, in a survey article on pricing of durables, notes
that the time-inconsistency problem arises with respect to any
subsequent firm behavior affecting the market value of units
previously sold (such as new product development), not just
future price and quantity decisions.

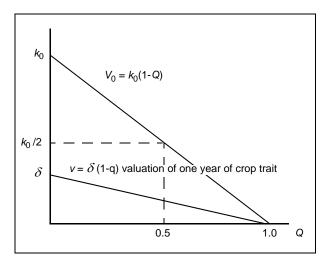


Figure 1. User evaluations of the benefit of a trait.

to commit to future sales or price behavior, through buyback programs, destruction of molds or templates, establishing a record of persistent behavior, etc. In fact, Waldman suggests that the main value of Coase's conjecture is to help us understand a variety of observed contractual strategies intended to avoid the Coase result, which are otherwise inexplicable.

But if buyers are myopic and therefore base their purchase decision solely on today's price, giving no thought to the possible future price, the firm can engage in intertemporal price discrimination, achieving more than normal monopoly rents. While this is not a very plausible model of buyer behavior, it is useful to identify the implications for equilibrium price paths for comparison with alternative assumptions.

We now turn to an analysis of the equilibrium trait pricing paths under these stylized market structures and the associated distributions of welfare benefits.

The Maximum Social Welfare Benefit (MSWB) of a Crop Trait

Welfare is measured here in terms of traditional consumer and producer surplus—areas between the price line and the demand curve and supply curve, respectively. The consumer benefits may accrue to downstream market participants as well as farmers. The demand curve for the current services of a crop trait is derived from the harvest-time payoffs of the trait on heterogeneous plots of land. This payoff can be due either to a reduction of unit production cost or to added crop value, or both. Without loss of generality, we can consider plots to vary continuously with respect to potential payoff from the trait, and we can scale the range of these

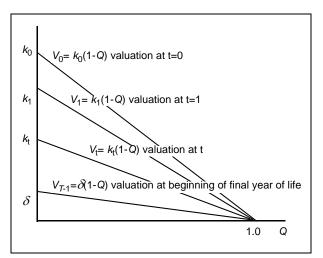


Figure 2. User evaluations decline as years pass.

payoffs, realized at the end of the crop season, from zero to one. If the density of plot valuations is uniform, the market demand curve at the beginning of the season for a single year will be linear, $v = \delta(1-Q)$, where the discount factor is $\delta = 1/(1+i)$, and Q indexes the units on which the valuation is made (lower line in Figure 1). This is a plausible approximation of annual demand for such GM crop traits as insect and herbicide resistance, as both pest pressures and the efficiency of alternative pest-control technologies will vary across parcels.

We suppose the trait to be a durable in the sense that it has a calendar life of T calendar years from the date of its introduction, after which its value becomes nil, due to the emergence of superior technologies after T years (obsolescence) or due to lost efficacy (depreciation). The present value of the flow of services from a durable trait when it is introduced is thus $V_0 = k_0(1-Q)$, where $k_0 = [1-(1+i)^{-T}]/i$, the present value of a unit annuity starting at time t = 1, one year from release, and continuing through time t = T. The durable will decline in value as the end of the T-year calendar period approaches, as illustrated in Figure 2, with the schedule of buyers' valuations of the durable t years after it is introduced being $V_t = k_t(1-Q)$, where $k_t = [1-(1+i)^{-(T-t)}]/i$.

It is a reasonable approximation for our purposes to assume that the marginal cost of incorporating the trait into additional seed stocks is zero, so that all revenues from the trait represent the trait owner's rent or producer surplus. Consumers' surplus is measured as the area under the valuation curve and above the price line, though we note that this surplus will not necessarily be realized by farmers, as it may be passed along in part or in whole to downstream consumers via lower product prices. The maximum harvest-time social surplus from

0.97*

0.06*

0.91*

0.97*

(as above)

0.93*

0.50

0.25

0.75

0.50

0.25

0.75

Table 1. Theoretical social welfare achieved, relative to the maximum social welfare benefit achievable from a trait.

the trait (area below the valuation curve out to the level of adoption) is thus 0.5. If the trait is a durable that will repeat these benefits for T years, the maximum social welfare benefit from the trait (present value of social surplus) is

Total social welfare

Total social welfare

Trait owners

Consumers

Trait owners

Consumers Total social welfare

$$MSWB = \frac{k_0}{2}$$
 (1)

As another benchmark, we refer to "normal monopoly profit" as the area $(k_0/2)/2 = k_0/4$. This corresponds to the maximum revenue a monopolist could obtain for a good with zero marginal cost, obtainable by charging $P = k_0/2$ and selling $Q_0 = 1/2$ units. For this solution, the present value of producer surplus (owner revenue) is $k_0/4 = (1/2)$ MSWB, the present value of consumer surplus is $k_0/8 = (1/4)$ MSWB, and (1/4)MSWB is lost because of the restricted use of the trait—inefficiency due to market power.

In what follows, we contrast the welfare distribution of various expected market outcomes relative to this potential welfare standard.

Pricing and Welfare Outcomes Under Stylized Market Structures

With No IPRs

Foresight w/

commitment

Foresight w/o

commitment

If no effective property rights exist, the trait owner loses all market power the year following introduction, because grain in the commodity markets consists of viable seeds carrying the trait, and this seed can be had for little or no premium over the common market price of the crop. If buyers have foresight, they will anticipate this price collapse, and the demand curve facing the trait owner at time t=0 is that for just one year of benefits,

or $P = \delta(1-Q)$. The optimal price is $P_0 = \delta/2$, $Q_0 = 1/2$, and adoption will reach 100% in the second year when the price is zero. Note that this price equals half of the benefit the highest beneficiary expects to receive the first year, as plotted on Figure 3.

0.93*

0.50

0.25

0.75

0.11*

0.84*

0.95*

Producer surplus (trait owner revenue) amounts to $\delta/4$, which for T=10 and i=0.05, equals 0.06 MSWB. The present value of consumer surplus consists of that for first-year buyers $((k_0/2 - \delta/2)/2 + k_0/8)$ plus the discounted value of that for second-year buyers $\delta(k_1/8)$ for a total of 0.91 MSWB, for a total social welfare benefit of 97% of the maximum available from the trait (Table 1, last column). These values are a function of time horizon, T, and interest rate, i. For combinations of T from 5 to 20 years and i from 0.01 to 0.20, owner benefits range from 0.03 to 0.14 MSWB (for T = 20, i = 0.01; and T =5, i = 0.20, respectively). Consumer benefits range from 0.96 to 0.79 MSWB and total social benefits are above 93% in all cases. Social welfare benefits are high because nearly complete adoption occurs immediately—time horizon and discount rate have their primary effect on the distribution of these maximum benefits, rather than the total social benefits realized.

In the unlikely event that all buyers are myopic with respect to future prices of the trait, the trait owner can charge the higher monopoly price $P_0 = k_0/2$ the first year, and half the potential customers will purchase because future trait price is irrelevant to myopic buyers. As shown in Figure 3, for a 10-year trait and i = 0.05, this price amounts to about four times the annual benefit the highest beneficiary expects, and eight times the price that could be charged in the foresight case above. A year later the price collapses and the remaining half of potential buyers adopt the trait. Owner benefits are 50% MSWB, normal monopoly profit. Consumer benefits equal $k_0/8$ the first year and $k_1/8$ the second, or 0.47

^{*}These fractions will vary with trait life, T, and interest rate, i, here 10 years and .05, respectively.

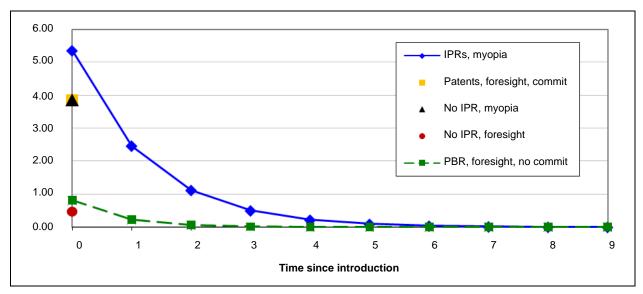


Figure 3. Equilibrium time paths of trait price, P_t , for T = 10, i = 0.05.

MSWB given T = 10 and i = 0.05. For the range of T and i mentioned above, present value of consumer surplus ranges from 0.43 to 0.46 MSWB, while owner benefits remain at 0.50 MSWB.

IPRs with Myopic Buyers: Intertemporal Price Discrimination

Myopic buyers will purchase the durable whenever its price is at or below the buyer's valuation, disregarding what the price of the durable might be next year.

If the trait is protected by either a strong patent or PBR system, the owner may choose to sell the trait as a durable. (By "strong" IPR's, we mean that enforcement is perfect and costless). Because myopic buyers ignore future prices, the owner is free to seek higher-than-normal monopoly profits by charging a higher price the first year than in subsequent years—price discrimination through time. Here, we determine the optimal time path of prices by backward induction (see Stokey, 1979, for a generalized continuous-time solution to similar intertemporal price discrimination problems). At any given time t, given P_{t-1} and Q_{t-1} such that $P_{t-1} = k_{t-1}(1-Q_{t-1})$, the owner chooses P_t to maximize current revenue, i.e.,

$$\max_{P_{t}} \left\{ P_{t}(Q_{t} - Q_{t-1}) = P_{t} \left(\frac{P_{t-1}}{k_{t-1}} - \frac{P_{t}}{k_{t}} \right) \right\}, \tag{2}$$

which yields the solution $P_t = (k_t / 2k_{t-1})P_{t-1}$, and by recursive substitution we determine that for t > 0, $P_t = (k_t / 2^t k_0)P_0$, thus establishing the optimal path of

intertemporal price discrimination. The initial price is more than five times the highest annual benefit, and falls slowly (see the example in Figure 3, labeled "IPRs, myopia"). At time t = 0, the pricing problem and its solution are (*Note: PVR=Present Value of Revenue*)

$$\max_{P_0} \left\{ PVR = P_0(Q_0) + \sum_{t=1}^{T-1} \delta^t P_t(Q_t - Q_{t-1}) \\ = P_0(1 - \frac{P_0}{k_0}) + \sum_{t=1}^{T-1} \delta^t (\frac{k_t}{2^t} \frac{P_0}{k_0}) (\frac{1}{2^t} \frac{P_0}{k_0}) \right\},$$

which solves for the optimal price:

$$P_0^* = \frac{k_0}{2} \frac{1}{(1 - \sigma k_0)},\tag{3}$$

where
$$\sigma = \frac{1}{k_0^2} \sum_{t=1}^{T-1} \left(\frac{\delta}{4}\right)^t k_t$$
.

Under this pattern of intertemporal price discrimination, welfare distribution is determined by examination of welfare rectangles and triangles each year. For the case of a 10-year trait and 5% discount rate, these benefits are as follows (these results and those for other cases are summarized in Table 1):

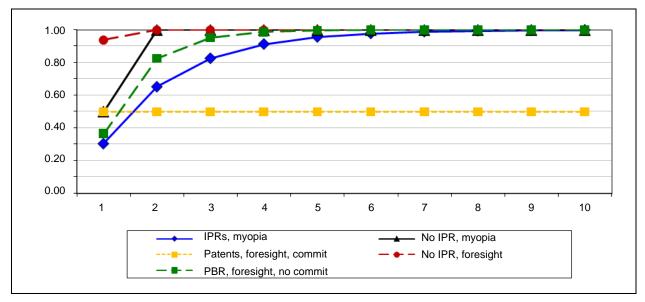


Figure 4. Cumulative diffusion of Trait Q_t , for T = 10.

Owner welfare:

$$PVR = \frac{k_0}{4} \frac{1}{(1 - \sigma k_0)} = \frac{1}{2} \frac{1}{(1 - \sigma k_0)} MSWB \Big|_{\substack{i = .05 \\ T = 10}} = .69 MSWB$$

Present Value of Cons. Surplus (PVCS) $|_{\substack{i=.05\\T=10}}=.24$ MSWB

Total social welfare
$$\Big|_{\substack{i=.05\\T=10}} = .93$$
 MSWB.

Under price discrimination, 93% of the potential social welfare from the trait is realized, although trait owners capture 69% compared to only 24% by consumers. Optimal prices under this market structure follow a declining fraction of the previous year's price that approaches zero (Figure 3), while adoption approaches 100% (Figure 4).

It is obvious that MSWB will vary greatly with T and i. However, we have found that again in this case the share distribution of those benefits is quite insensitive to T and i. For a 5-year trait at 20% discount rate, owner-consumer-total shares of MSWB are 65%-22%-87%, while for a 20-year trait at zero discount, those numbers are 73%-25%-98%. All combinations of 5 < T < 20 and 0 < i < 0.30 resulted in distributions within these bounds.

IPRs with Far-sighted Buyers (Coase)

If buyers are far-sighted, Coase noted that they will not purchase the durable today, even though it is profitable, if it will be even more profitable to wait until next year. Their behavior depends upon what they expect the selling price to be in coming years. Because of the time-inconsistency problem, sellers may prefer a different future price than the one they initially announce, so their ability to credibly commit to such announcements is an important determinant of the equilibrium time path of prices.

With No Seller Commitment. If the seller is unable to commit to a future pricing scheme, he must choose a time path for prices that is consistent with far-sighted buyers' strategy. To be explicit, for buyers at time t < (T-1) to be willing to buy at time t rather than wait, the present value of buying now must be equal to or greater than the present value of waiting until the following year. For the marginal buyer at time t, who is indexed by Q_t , the present values of buying now and waiting must be equal, or

$$V_{t}(Q_{t}) - P_{t} = \delta[V_{t+1}(Q_{t}) - P_{t+1}], \text{ or }$$

$$k_{t}(1 - Q_{t}) - P_{t} = \delta[k_{t+1}(1 - Q_{t}) - P_{t+1}], \text{ or,}$$
given that $(k_{t} - \delta k_{t+1}) = \delta$, (5)
$$Q_{t} = 1 - \frac{1}{\delta} P_{t} + P_{t+1}.$$

To determine the optimal recursive path for prices, we again use backward induction. At the time of final trait sales, t = (T-1), the owner's problem is

$$\max_{P_{T-1}} \left\{ P_{T-1} \left(Q_{T-1} - Q_{T-2} \right) = P_{T-1} \left(\frac{P_{T-2}}{\delta} - \frac{1+\delta}{\delta} P_{T-1} \right) \right\} ,$$
 which solves as
$$P_{T-1} = P_{T-2} / 2 \big(1 + \delta \big).$$
 (6)

For t < (T-1), price is constrained by the relationship in Equation 5, and the problem each of those years is

$$\max_{P_{t}} \left\{ P_{t}q_{t} = P_{t} \left(Q_{t} - Q_{t} \right) = P_{t} \left(\frac{P_{t-1}}{\delta} - \frac{1+\delta}{\delta} P_{t} + P_{t+1} \right) \right\},$$
which solves as
$$(7)$$

$$P_{t} = \left(P_{t-1} + \delta P_{t+1} \right) / 2(1+\delta) \text{ which can be written}$$

$$P_{t} = 2(1+\delta) P_{t+1} - \delta P_{t+2}.$$

In principle, one can use Equations 6 and 7 recursively to express every P_t in terms of P_{T-1} , so that one could then choose P_{T-1} to maximize the present value of revenues, similar to the procedure in Equation 3 above. However, this analytical approach proved to be too cumbersome for us to solve for traits with lives longer than about 5 years, so we use a search procedure. Using Equation 6 and the last expression in Equation 7, we could numerically evaluate every P_t in terms of the next two later prices (one later price in the case of P_{T-2}), and we then obtained the optimum value of P_{T-1} by numerical search.

The optimal price path for T = 10 and i = 0.05 begins with $P_0 = 0.82$, or 82% of the highest annual benefit, and declines rapidly to less than 0.01 by t = 4, as shown by the dashed line in Figure 3. These levels were again not very sensitive to choice of T and i. Here the implications of the Coase conjecture are evident: while the price of the durable is not forced to zero (because prices are not updated continuously, but rather annually), the price path is very low, and trait owner welfare is only 11% of MSWB. Farmers, on the other hand, very quickly come to full adoption (Figure 4), and achieve a welfare gain equal to 84% MSWB.

While owners holding either patent rights or PBRs have the option of selling the trait as a durable with this result, those with patent rights can do much better by leasing the trait. Trait leases commonly prohibit farmerbuyers from replanting the seed, either through an explicit purchase "technology agreement" or by implicit threat of lawsuit. This option not permitted under PBR's. The optimal annual lease rate is $\delta/2$, resulting in sales to one-half the market every year. With the lease option, patent owners realize a normal monopoly rent from the trait, achieving a welfare gain of 0.5 MSWB, while consumers achieve a welfare gain of 0.25 MSWB, the usual consumer gain under monopoly. Thus, when sellers are unable to commit to a future course of action, patent holders can achieve normal monopoly rents via the leasing option, while PBR holders suffer the consequences of the Coase conjecture, and realize welfare benefits in the vicinity of one-fifth of normal monopoly rents.

Tirole (1988) examined the Coase conjecture for the case of a durable with an infinite stream of non-declining benefits, rather than the constant but finite stream of benefits that we consider here. Perrin and Fulginiti (2004) previously applied the Tirole model to trait pricing. The set-up posed by Tirole involves a number of assumptions that are less appropriate to trait pricing than are market structures we have considered above. His model assumes that buyers collude in jointly selecting a limit price, a completely implausible characterization of farmer-buyers. It considers a durable with infinite, rather than limited, life. And he imposes the condition that the price the seller chooses in each period must be a constant fraction of the marginal buyer's valuation, which in general is not the optimal time path for a durable of finite life. We conclude that the results from Tirole's model, as developed by Perrin and Fulginiti, are far less likely to represent alternative trait pricing outcomes than the results of the model developed just above.

With Seller Commitment. If sellers are able to commit to a future course of action, trait owners can achieve normal monopoly profits, regardless of the type of IPR. They simply announce that the trait will be sold only on the release date, t = 0, for the normal monopoly price, $P_0 = k_0/2$, and that no further sales will be made. Since the trait owner can prohibit producers from adopting the trait unless they purchase at the initial offering, even far-sighted buyers will be willing to buy as long as the price is lower than their own valuation, thus insuring sales of $Q_0 = 1/2$. Thus if sellers are able to commit to future

^{2.} For T = 5, i = 0.05: $P_0 = 0.81$ and price fell below 0.01 at T = 4. For T = 10, i = 0.20: $P_0 = 0.70$ and price fell below 0.01 at T = 4. For T = 5, i = 0.20: $P_0 = 0.70$ and price fell below 0.01 at T = 4.

action, the welfare distribution is the normal monopoly distribution, with sellers achieving 0.5 MSWB and consumers realizing 0.25 MSWB. This scenario has seldom been found to be plausible, and certainly it is not in the case of crop traits, where farmers typically require years of observation and testing before adoption occurs.

Summary of Pricing Outcomes

In Table 1 we summarize the welfare results from the six environments considered. The corresponding price paths and adoption paths, for a trait with a 10-year life and a real discount rate of i = 0.05, are shown in Figures 3 and 4. Trait owners are clearly better off if buyers are myopic, but that does not seem very likely. Otherwise, the best the owners can do is obtain normal monopoly profits, but they will do much worse in the case of PBR ownership without owner commitment, in which the implications of the Coase conjecture are felt. This particular circumstance, PBR's with buyer foresight but no owner commitment, is relevant to many countries of the world where patents on traits are not permitted but PBR's are. Trait owners have relatively small incentives to enter these markets, because the Coase conjecture limits them to only about 11% of MSWB, and if the PBR's are not costlessly enforceable (as seems likely), even less.

Consumers will of course benefit most from the trait in the absence of any IPRs, but it is surprising that they would do almost that well in the case of PBRs with sellers unable to commit. Total social welfare is maximized with no property rights in the short run, but returns to owners are so low that long-run welfare may be damaged due to lack of new inventions. Of the circumstances considered, buyer myopia is virtually a Paretobest circumstance regardless of IPR regime, but it is hard to imagine a country in which this is a plausible representation of reality.

Compared to the model considered by Burton et al. (2005), this article examines multiple-year rather than two-year horizons, but also considers results when farmers do not have perfect expectations with respect to future prices, and when trait owners can commit to future pricing. Under the assumptions common to these two studies (farmers have foresight and firms lack commitment), our welfare conclusions are consistent with theirs, i.e., PBRs (essentially equivalent to their long-term contracts) yield higher farmer and social welfare, but lower trait owner benefits as compared to patents (essentially equivalent to their TPS option which allows annual pricing without need for monitoring). And of

course our conclusions are consistent with those of the very different model of Ambec et al. (2008), who find that trait owners prefer nondurables (hybrids) to durables (inbred lines), while farmers and society prefer the opposite.

Some Empirical Observations

Recent studies of the world commercialization of the Monsanto-owned Bt insect-resistance trait in cotton provide some idea of the empirical relevance of these scenarios. In India, where no IPRs for varieties or traits had been available prior to 2005, Bt cotton was introduced in hybrid cotton and Qaim (2003) found that in 2001 the Bt hybrid seed cost farmers 287% more than a non-Bt counterpart. As a hybrid, there would have been little incentive for farmers to save seed, so this premium is essentially a lease rate on the trait, allowing the seed company to reap normal monopoly rents equal to about half the potential social benefits. But Tripp et al. (2007) report that by 2004, the monopoly was substantially eroded by clandestine breeding to incorporate the Bt gene. New seed laws may reduce this "piracy," but without enforcement of such laws, it seems evident that in most countries even hybrids will not provide a safe monopoly for long.

In China, on the other hand, Bt cotton was introduced by transferring US cotton varieties to be sold through state and private seed companies. Pray, Huang, Hu, and Rozelle (2002) found that the first-year (1999) price carried no premium, in 2000 it was 181% higher for the Bt variety, and by 2001 it was 333% higher. While this would seem to reflect a "get-acquainted" pricing scheme for a well-protected trait, there was apparently no effective enforcement of IPRs, because Tripp et al. (2007) report that by 2006, illicit seed marketing had spread to the extent that the legitimate varieties hardly command any price premium.

Traxler, Godoy-Avila, Falck-Zepeda, and Espinoza-Arellan (2001) and Thirtle, Beyers, Ismail, and Piesse (2003) report that prices of seed for Bt cotton varieties in Mexico and South Africa were about two-thirds more than non-Bt varieties, for at least two successive years in each case. Both countries have fairly strong IPRs for seeds, and in both cases the seed companies prohibited farmers' own replanting and used marketing restrictions to help enforce it. In the enforcement environment of these two countries, the companies were able to lease the trait as a non-durable—at least for the two years of the study.

Bt cotton in Argentina represents an instructive empirical case. Qaim and de Janvry (2003) documented that official adopters paid a seed premium of 617% during the 1999-2000 season, and 463% the following season, which resulted in official adoption rates of only 5.4%. They calculated that the optimum seed price in a static framework should have been about half the price actually charged, and concluded that global marketing considerations must have led the seed company to overprice the seed. However, they also report a black market price of the Bt variety at one-third the official price. This and the earlier total loss of control of the Roundup-Ready soybean trait (Qaim & Traxler, 2005) make it pretty clear that enforcement of IPRs in Argentina was totally ineffective at that time. This closely corresponds to the non-IPR scenario with myopic buyers, in which the trait owner charges a very high price the first year (years in this case), then plans on little or no subsequent sales, as had been the case for RR soybeans.

Conclusions

We have set about to examine theoretically plausible intertemporal pricing patterns for, and welfare outcomes from, the emerging markets for crop traits. Given the potential durability of these traits, we were especially interested in the circumstances under which the Coase conjecture might deprive owners of crop traits the opportunity to earn rents. To do this, we derived equilibrium intertemporal price paths for each of six stylized market structures, consisting of two alternative assumptions about farmers' expectations regarding future trait price (myopia versus foresight), three IPR systems (strong patents, strong plant breeders rights [PBRs], no property rights), and whether or not the seller is able to credibly commit to future price announcements.

We found that the Coase conjecture (durables sold at or near marginal cost) is relevant to one market structure that would appear to be relevant in many countries of the world: the case of Plant Breeder's Rights with farsighted buyers but sellers who are unable to credibly commit to future price announcements. If sellers could commit to a one-time-sale strategy, they could earn normal monopoly profit, but it would be difficult to convince far-sighted buyers that there would be no future sales, given that the owner would clearly benefit from them (the time-inconsistency problem). Patent holders, on the other hand, can avoid this Coasian pitfall by leasing the trait for annual use only (a common practice among patent holders, not available to PBR holders), thereby achieving normal monopoly rents from the trait.

While it does not seem that buyers could be totally myopic about future trait prices, social welfare benefits from the traits would be nearly maximized if they were, regardless of the status of property rights. In that circumstance, monopoly trait owners could practice intertemporal price discrimination, whether property rights are held as patents or PBRs. In so doing, they would earn more than normal monopoly profits, while at the same time buyers are not significantly worse off than for the case of standard monopoly pricing (under plausible discount rates and time horizons). This is because nearly all potential buyers benefit to some degree under price discrimination, whereas only half benefit (though to a greater extent each) under standard monopoly pricing.

Total social welfare from a trait is maximized when there are no effective property rights, because full adoption at low or zero cost occurs. However, trait owners can realize virtually none of that benefit, unless buyers are myopic, and the incentive for creating new traits is lost. This is completely consistent with standard theory that patents create allocative inefficiency in order to increase overall social efficiency with a larger number of inventions.

The assumptions of the analysis here are highly stylized. Not all buyers are myopic, and not all have good foresight, and our analysis does not account for markets in which a mix of these types exists. IPRs are not costless nor are they costlessly enforceable, nor are there many jurisdictions where no IPRs at all exist. The real world is somewhere in between, but the results derived here nonetheless provide insights as to the important issues and tendencies. Traits are not characterized by abrupt obsolescence as characterized here, but introducing a standard depreciation rate into the model used here would not change the general nature of the results. Hence we believe that the above conclusions are relevant to policy debates regarding the value of the different types of IPRs, and to the academic discussions of the potential relevance of Coase's conjecture.

The most logical extension of the work here would be a test of whether the general results are consistent with empirical price paths observed under alternative IPR systems. To date, we have not been able to put together a sufficient amount of data to allow any meaningful tests of these results, though we have provided some evidence from other studies. Extension of the models here to the case of oligopoly in the trait market might well add further understanding of trait price trajectories, as might incorporation of tie-in sales with nondurable goods such as pesticides.

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