Journal of Agricultural and Resource Economics 28(1):1–14

State-Contingent Demand for Herbicide-Tolerance Seed Trait

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Suppose a farmer had to apply a herbicide pre-emergence or not at all. The advent of a herbicide-tolerance trait innovation then provides the option to wait for more information before making a state-contingent post-emergence application. This option to wait can increase or decrease average herbicide use. For heterogeneous acre types, trait royalties increase with the level of uncertainty about the extent of weed damage. Royalties are largest when acre infestation susceptibility types are bunched around the type indifferent to applying the herbicide in the absence of the trait. The trait complements (substitutes for) information technologies that facilitate informed post-emergence (pre-emergence) decisions.

Key words: genetics, information inputs, patent value, post-emergence, real option

Introduction

Agriculture in North and South America has seen rapid adoption of genetically engineered crop varieties. While demand-side concerns remain as serious impediments to the development of markets for these varieties, cost, yield, and risk considerations have provided the supply side with strong incentives to adopt (Kalaitzandonakes). This analysis is concerned with developing an economic framework to study the advent of a patented genetic trait for crops vulnerable to a pest hazard that requires costly remedy.

The class of hazards in question includes a potentially serious weed problem after crop emergence, where a *herbicide-tolerance* (HT) trait would provide a cheap post-emergence solution to the realized hazard. In a 2000 study of genetic engineering in integrated pest management, Hess and Duke wrote:

> To date, herbicides that are used in HT crops are applied post-emergence, which allows herbicide application based on need. Unless the weed population is extreme, the application can be delayed until an assessment of the weed population and species present can be made to determine the optimum herbicide type and concentration to use (p. 130).

Clearly, HT crop varieties provide the flexibility to wait for and use additional relevant information on a weed infestation if and when it becomes available after crop emergence. In this study, demand for these varieties is shown to be an increasing function of the extent of post-emergence uncertainty about the post-emergence weed problem. This is

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Review coordinated by Gary D. Thompson.

because the management flexibility provided by the trait is most useful when pre-emergence decisions must be made in an uninformed environment.

The analysis also explains why the trait innovation may increase or decrease herbicide use. Use will increased if the trait allows penetration into new applications, perhaps where the targeted weeds are a relatively minor problem. Herbicide use will be decreased if the trait is mainly adopted on acres that had formerly been routinely sprayed. In addition, this investigation shows how the distribution of cropland susceptibility types also matters in determining trait royalties. The trait will be most effective in commanding royalties if acre types are concentrated around the point of indifference between a pre-emergence spray and not spraying at all.

HT crop varieties have had significant effects on U.S. agri-input markets over the period 1996 through 2002 (Fulton and Giannakas; Holmberg; Fernandez-Cornejo, Klotz-Ingram, and Jans). U.S. Department of Agriculture (USDA) survey data estimate HT seed accounted for 75% of all soybeans, 56% of all cotton acres, and 10% of all corn acres sown in the United States in 2002 (Fernandez-Cornejo and McBride). The trend is likely to continue over the early years of the 21st century. Bridges documents that the USDA had processed some 1,584 permits and notices for HT in regulated organisms in 1999, accounting for 27% of all such permits and notices.[1] While not all HT varieties have been genetically engineered, genetic engineering was involved in the development of such HT varieties as bromoxynil tolerant cotton (brought to market in 1995), glufosinate tolerant canola and corn (1997), and glyphosate (i.e., Roundup®) tolerant soybean, canola, cotton, and corn (1996–1998).[2]

Although growers may quickly see the merits of a trait, there is no reason to suggest adoption should be complete, even if trait-endowed varieties receive the same price as conventional varieties (Fulton and Keyowski). Due to location, past cropping practices, or other reasons, individual parcels of land vary in their susceptibility to any given hazard (Carlson, Marra, and Hubbell; Fernandez-Cornejo and McBride). Also, grower differences in attitudes toward risks affect the private value of a trait (Hurley, Mitchell, and Rice). Consequently, the optimal strategy for one acre may not be optimal for another.

While the advent of a genetically modified variety may simplify the managerial decision process, it does so by enriching the strategy space available to the manager. When a strategy becomes available, it may involve low managerial time requirements (e.g., the need to scout crops may no longer arise), but the manager must choose to adopt this strategy in the first place. Prior to the commercialization of an HT-endowed variety (i.e., using conventional seed), the manager may have had to decide between two strategies: incurring a prevention cost to better insure against the hazard (strategy A), or saving on the prevention cost by taking a yield risk (strategy B). When the HT variety is available, the strategy space is expanded to become either A or B, as before using conventional seed, *or* pay a premium for the trait so post-emergence remediation of the weed hazard becomes feasible (strategy C). This study inquires into the consequences of enriching the strategy space in this manner.

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[1] The number of permits and notices excludes nonregulated technologies, and so likely significantly undercounts innovation in this area.

[2] The Bridges' numbers broadly concur with field trial data presented by the National Research Council (p. 170).

The problem examined here is important for at least two reasons. First, it illustrates a mechanism through which biotechnology and information technology interact in agricultural production. The biotechnology aspect of the problem is clear, whereas the information technology component may be less readily apparent. However, when considering strategy C above, it can be seen that its contribution to value is predicated upon the revelation of additional information over the intervening time period.[3] As will be made clearer in what follows, biotechnology can be an enabling technology which places a premium on a good information structure. It will be shown that biotechnologies and information technologies can complement or substitute. If the nature of the interactions is predominantly complementary, then it would not be surprising if both of these classes of technology inputs emerged as relevant inputs in crop agriculture at approximately the same time.

The second reason the problem is important is because the addition of strategy C has nontrivial implications for the intensity of agri-chemical use and also for the intensity of soil cultivation. As agri-chemicals and intense cultivation tend to generate negative social externalities, a comprehensive study of the enriched strategy space should be illuminating for environmental policy formation. This second reason is not unrelated to the first.

One of the traditional claims for integrated pest management and organic farming practices is that a deeper understanding of one's farm permits more considered husbandry practices. An HT trait may be a technical substitute or complement for a developed database of knowledge about the land one manages. The trait is a substitute if it eliminates the need for such information. This would be true for information allowing an early (i.e., pre-emergence) judgment on the likely hazard, because the HT trait permits the postponement of the application decision. But the HT trait also complements a developed database of knowledge about the post-emergence weed status of the crop. However, because HT traits are relatively novel, growers who had previously applied only pre-emergence herbicides would have had little incentive to develop a database on assessing weed hazards after the crop has emerged. Thus, HT traits may alter the composition of data sets growers have incentives to develop. Regardless of the nature of a grower's extant data set, it does not necessarily follow that the more informed farmer would be more parsimonious with inputs. Neither does it necessarily follow that an HT trait will reduce the levels of herbicide applications. Furthermore, the impact of the HT trait may change over time as the grower develops more of the sorts of databases that are privately optimal in the new environment.

The class of problems to be addressed fits most clearly into the real options framework. A basic tenet underpinning this literature is that information has value to the extent it can change actions. In our stylized problem, biotechnology provides the grower with a costly option to defer an action until more information becomes available. An HT trait has the characteristics of a commodity call option in the sense the biotechnology provides the opportunity to place a floor on crop value in the event of a weed infestation. This option may be pursued by paying the (strike) price of a post-emergence herbicide application. There exists a large body of literature on valuing such an option and on its

[3] MacRae writes, "The basis of Precision Agriculture is applying agrochemicals only where necessary. The point of Integrated Pest Management is to apply herbicide only when it's necessary. By using these technologies in IPM (i.e., integrated pest management), we can develop 'Precision IPM,' only applying pesticides where and when it is necessary."

implications for actions on the part of the firm (Arrow and Fisher; McDonald and Siegel; Trigeorgis). In the present study, we also examine how option values affect decisions. Further, this analysis inquires into the implications of grower-level contributors to option value on patent royalties.

Related problems have been analyzed in the agricultural production economics literature. Feinerman, Choi, and Johnson studied split nitrogen strategies where early application was easy but relatively inefficient at the margin, while late application may not be feasible due to weather conditions. In this environment, there is an option to wait and apply a late dressing.[4] Ex ante, the risk of a wet weather event is traded off against the expectation over the gain if nitrogen can be used more effectively. In that framework, however, there is no innovative technology which enriches the strategy space.

Techniques in site-specific agriculture provide the flexibility necessary for real options to exist. These techniques enrich grower strategy spaces and complement information technologies in the form of global positioning satellites, mapping systems, and nutrient tests (Fee). Babcock and Pautsch, to name just one work, have investigated the application and profit implications of this technology complex. For corn in Iowa, they concluded that the option to condition application rates on geographic information increased mean yields and reduced mean application rates.[5]

Our inquiry proceeds with a formalization of a basic two-period environment for herbicide application when acres are heterogeneous and a post-emergence application of the input is precluded. The HT technology is then introduced and the determinants of equilibrium royalties and equilibrium varietal plantings are scrutinized. This is followed by a consideration of how heterogeneity in types might affect trait value to the patent holder. The study concludes with a discussion emphasizing the effects of trait innovations on the strength of local demand for farm management skills.

Basic Model for the HT Trait

Rather than develop a parameterized continuous-time model of the sort often associated with the real options literature, a discrete-time model focusing on pre- and post-emergence decision events is formulated. The model has three time points where the earliest, time 0, occurs at planting. Time 1 occurs just after crop emergence, and it may be possible to take an action at this time. Time 2 is at harvest, when crop value is realized. Crop value depends on weed damage, where weed hazards are random at time 0 but are nonrandom at time 1. Through grower inspections, the nature and extent of weed hazards become known by time 1, and thus the magnitude of the prospective loss also becomes known by time 1.[6] As always, the approach taken is to work backwards to solve the problem so that the state-contingent optimal strategies are built into the decision problem the grower tries to solve.

[4] If the weather realization is "wet," then the payoff from waiting to apply is negative, whereas the payoff is positive when the weather is "dry."

[5] Other recent work in agricultural production economics has applied the continuous-time stochastic diffusion tools perhaps most readily associated with real options theory. These include the work by Saphores on intra-season control of fruit crop pests through a sequence of sprays. However, the real option examined in the present study fits naturally into a two-period model, and there is no need to adopt the parametric constraints attending the continuous-time framework.

[6] This is a simplification. In reality, one will never know with complete certainty the consequences of not treating a weed problem.

Acreage susceptibility to weed damage is determined by a large number of factors including cropping history, past husbandry practices, weather conditions, and the use of adjacent land. This heterogeneity in cropland acres is captured through the continuously distributed infestation severity index, θ. The parameter has a continuous cumulative mass distribution $H(\theta)$: $[\theta_l, \theta_u] \to [0, 1]$, with $H(\theta_u) \equiv 1$. Here the subscripts l and u denote lower and upper bounds, respectively. Mass density is $H(\theta)$, and we hold that $H^1(\theta_u) \equiv 1$ for any mass distribution $H^1(\theta)$: $[\theta_l, \theta_u] \to [0, 1]$ which might replace $H(\theta)$ in our analysis. Therefore, cropping area is held to be fixed. A grower of acre type θ knows the type at time 0.

The weed-free crop has value V_{ni} at time 2, where the subscript ni may be taken to abbreviate "no infestation." This value is gross of the costs of buying and applying the herbicide, but the cost of standard variety seed has been removed. The seed market is assumed to be competitive. If infested, the acre has time 2 value V_i to the grower, where $V_i \le V_{ni}$. This value is random when viewed from time 0, with a type-conditioned distribution $G(V_i \mid \theta)$ having a strictly positive support on $[0, V_{ni}]$. It is assumed all growers know the distributions $G(V_i \mid \theta)$ pertinent to them at time 0. Consequently, heterogeneity does not exist in grower information sets on land husbanded.

In order to model the increasing severity of infestation, it is also assumed $G_\theta(V_i \mid \theta) \ge 0$ $\forall\, V_i \in [0, V_{ni}]$, $\forall\, \theta \in [\theta_l, \theta_u]$. Here, the subscripted θ indicates a differentiation. The derivative attribute asserts that conditional distributions are ordered by first-degree stochastic dominance. As a special example, the θ-conditioned expectation of crop value $E\{V_i \mid \theta\} = \int_0^{V_{ni}} V_i \, dG(V_i \mid \theta)$ is (weakly) decreasing in θ. This may be written as $E_\theta\{V_i \mid \theta\} \le 0\ \forall\, \theta \in [\theta_l, \theta_u]$.

The acre can be sprayed with herbicide at a cost per acre of $r = s + F$. Here, $r < V_{ni}$ is the total cost per acre of spraying the crop, $s > 0$ is the market cost per acre of the chemical, and $F \ge 0$ is the fixed per acre cost of spraying. The broad-spectrum herbicide kills all weeds, and is toxic to the crop. Thus, absent the HT trait, it cannot be applied after crop emergence. Absent an innovation, the grower has two alternatives at time 0: strategy A—to spray at time 0, or strategy B—not to spray at all. If strategy A is chosen, then the gross crop value is V_{ni} at time 2 (harvest). If strategy B is chosen, then the gross crop value is realized as V_i. By assumption, no reinfestation occurs if strategy A is chosen.

Absent the Innovation: To Spray or Not to Spray

The per acre value of strategy A to the risk-neutral producer is $U_A(\theta) = V_{ni} - r$, where the expression is invariant to θ. If the grower gambles by refraining from spraying (strategy B), then the expected value of the strategy is $U_B(\theta) = E\{V_i \mid \theta\}$. With $dU_B(\theta)/d\theta = E_\theta\{V_i \mid \theta\} \le 0 = dU_A(\theta)/d\theta$, the acre type in which both strategies deliver the same expected value is $\theta_{B,A}$, defined as the solution to

$$(1) \qquad V_{ni} - r = E\{V_i \mid \theta_{B,A}\}.$$

The solution may not be unique because $E\{V_i \mid \theta\}$ is only weakly decreasing in θ. However, the solution set is a convex set, labeled $\Theta_{B,A}$. As is standard practice, the analysis studies the impact of changes on $\hat{\theta}_{B,A} = \sup\{\theta_{B,A}: \theta_{B,A} \in \Theta_{B,A}\}$ (Milgrom and Roberts). This assumption asserts that indifferent types elect for strategy B. Acre types in $(\hat{\theta}_{B,A}, \theta_u]$ are sprayed before planting, while acre types in $[\theta_l, \hat{\theta}_{B,A}]$ are not sprayed. It merits observation that threshold type $\hat{\theta}_{B,A}$ is invariant to mass distribution $H(\theta)$. This is because each firm makes decisions based only on its own weed severity type, θ. While the weed problems of other producers may affect the grower by altering, say, the herbicide price, this is not a concern of the price-taking grower.

Now suppose the herbicide is not patented and is produced competitively. With w as the constant unit cost of producing the chemical, then $s = w$ so that $\bar{H}(\hat{\theta}_{B,A})$ acres are sprayed, where $\bar{H}(\theta) = 1 - H(\theta)$ is the types mass distribution survival function. Upon applying the implicit function theorem, $d\hat{\theta}_{B,A}/dw = -1/E_\theta\{V_i \mid \theta\} > 0$ from (1) above, the area of cropland under the "don't-spray" strategy varies directly with the price of spraying—i.e., $dH(\hat{\theta}_{B,A})/dw \geq 0$.[7] Also, if $H(\theta) \rightarrow H^1(\theta)$, where $H(\theta) \geq H^1(\theta)\ \forall\ \theta \in [\theta_l, \theta_u]$ (i.e., first-order dominance in the mass distribution of types), then $\bar{H}(\hat{\theta}_{B,A}) \leq \bar{H}^1(\hat{\theta}_{B,A})$. Specifically, acreage sprayed increases when the distribution of the infestation index becomes more densely concentrated toward the upper bound, θ_u.

Alternatively, let $G(V_i \mid \theta) \rightarrow G^1(V_i \mid \theta)$ such that $G(V_i \mid \theta) \leq G^1(V_i \mid \theta)\ \forall\ \theta \in [\theta_l, \theta_u],\ \forall\ V_i \in [0, V_{ni}]$, and the probability of a given loss in value rises for each value of θ. Then, from (1), $E\{V_i \mid \theta\}$ declines for each value of θ so that $\hat{\theta}_{B,A} \rightarrow \hat{\theta}^1_{B,A} \leq \hat{\theta}_{B,A}$ and $\bar{H}(\hat{\theta}_{B,A}) \leq \bar{H}(\hat{\theta}^1_{B,A})$. Acreage sprayed increases when the expected crop loss increases.

The Innovation and Grower Actions

Now assume a firm develops and patents the modified seed allowing the spray to be applied at time 1, i.e., when it has been established whether a weed problem exists. The grower can now pay technology fee τ in order to enrich the strategy space to include a third strategy, strategy C. This strategy entails a deferral of the herbicide application decision until after crop emergence, giving a larger information set when the decision is made. Then, in this stylized model, an application of the herbicide on the infested crop will completely restore crop value V_{ni}. We assume, after waiting, a grower can determine *without noise* what the crop value would be if the opportunity to spray is not taken. Thus, a herbicide application will occur if and only if $V_{ni} - r > V_i$. The strategy C payoff is $\max[V_{ni} - r, V_i] - \tau$, and the state-contingent payoffs for the three time 0 strategies are provided in figure 1.

For the grower, the risk-neutral value of the decision to wait for more information is specified as:

$$U_C(\theta) = E\{\max[V_{ni} - r, V_i] \mid \theta\} - \tau, \tag{2}$$

with $dU_C(\theta)/d\theta = E_\theta\{\max[V_{ni} - r, V_i] \mid \theta\}$.[8] It is readily shown that $0 = dU_A(\theta)/d\theta \geq dU_C(\theta)/d\theta \geq dU_B(\theta)/d\theta$. Thus, strategy A is least sensitive to acre type and strategy B is most

[7] The ratio $-1/E_\theta\{V_i \mid \theta\}$ is not defined when $E_\theta\{V_i \mid \theta\} = 0$, but the value of $d\hat{\theta}_{B,A}/dw$ may be defined to be $d\hat{\theta}_{B,A}/dw = +\infty$ at the limit as $E_\theta\{V_i \mid \theta\}$ increases toward 0.

[8] Equation (2) reports a convex relationship between V_i and the value of waiting. If the grower were von-Neumann and Morgenstern risk averse, then the curvature of the grower's objective function would be indeterminate because an increasing and concave function of a convex function has indeterminate curvature. Many of our results would not be robust to risk aversion.

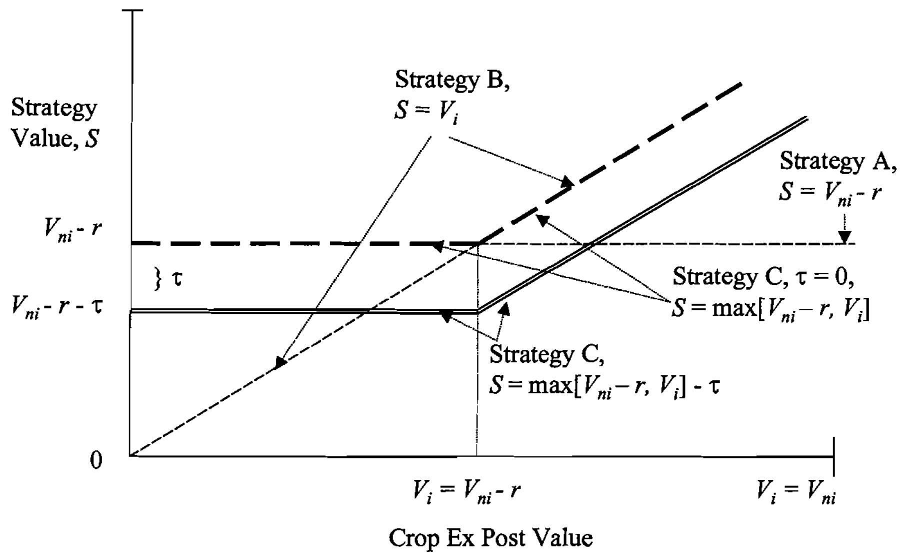

Figure 1. Comparison of ex post values of the three strategies

sensitive.[9] The intuition behind these inequalities can be found by comparing the strategy payoffs: $V_{ni} - r$ for strategy A, $\max[V_{ni} - r, V_i]$ for strategy C, and V_i for strategy B. The strategy A payoff is clearly independent of V_i, and so of θ. Strategy C has limited dependence on V_i, and so on θ, because the grower can remedy the problem ex post. The strategy B payoff is not shielded in any way from V_i, and so is the most sensitive to θ.

To clarify the effect of the seed trait premium, figure 1 shows strategy C is dominant in all states of nature when the trait price is 0 because the trait innovation has provided the grower with a real option of waiting for more information. Then it is clear that $U_C(\theta) \geq \max[U_A(\theta), U_B(\theta)]$, or $E\{\max[V_{ni} - r, V_i] \mid \theta\} \geq \max[V_{ni} - r, E\{V_i \mid \theta\}]$, because $E\{\max[V_{ni} - r, V_i] \mid \theta\} \geq V_{ni} - r = U_A(\theta)$ and $E\{\max[V_{ni} - r, V_i] \mid \theta\} \geq E\{V_i \mid \theta\} = U_B(\theta)$.[10] In other words, when $\tau = 0$, the free "option-to-spray" strategy is preferred over either of the other strategies because it combines the best outcomes of the other strategies but at no extra cost.

An interpretation of strategy C in figure 1 which focuses on the maximization statement might view the option to spray as a long call commodity option on V_i with strike price $V_{ni} - r$: $U_C(\theta) = E\{\max[V_i - (V_{ni} - r), 0] \mid \theta\} + (V_{ni} - r) - \tau$. The strike price is the realization of V_i whereby the grower is indifferent between spraying post-emergence and not spraying then.

The next task is to establish how the continuum of types may be partitioned according to strategies taken when $\tau > 0$. Note, the acre type which is indifferent between strategies A and C ($\theta_{C,A}$) solves

$$\text{(3)} \qquad \tau = r - E\{\min[r, V_{ni} - V_i] \mid \theta_{C,A}\}.$$

[9] Observe, $U_C(\theta) - U_B(\theta) = E\{\max[V_{ni} - r - V_i, 0] \mid \theta\} - \tau$ with nonnegative derivative. Furthermore, $U_A(\theta) - U_C(\theta) = E\{\min[r, V_{ni} - V_i] \mid \theta\} + \tau - r$ with nonnegative derivative.

[10] This can also be seen as an application of Jensen's inequality because the function $\max[V_{ni} - r, V_i]$ is convex in V_i.

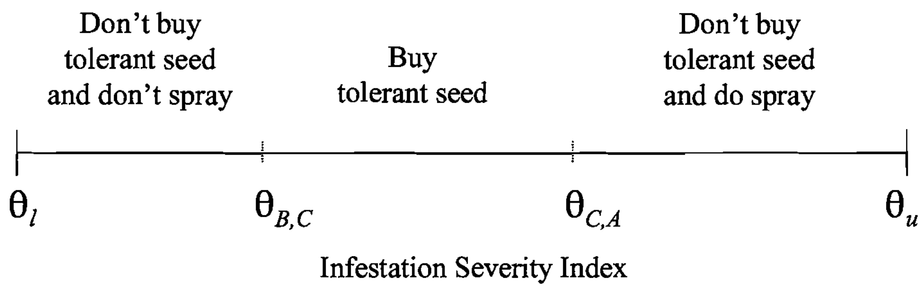

Figure 2. Partition of types by seed and spraying strategies adopted

As with $\theta_{B,A}$, there may not be a unique solution. The solution set, $\Theta_{C,A}$, is convex and the value $\hat{\theta}_{C,A} = \sup\{\theta_{C,A}: \theta_{C,A} \in \Theta_{C,A}\}$ is studied so that ties are assigned to strategy C. An implicit differentiation then establishes $d\hat{\theta}_{C,A}/d\tau = -1/E_\theta\{\min[r, V_{ni} - V_i] \mid \theta\} < 0$. Notice also, the acre type(s) that are indifferent between time 0 strategies C and B ($\theta_{B,C} \in \Theta_{B,C}$) solve

(4) $$\tau = E\{\max[V_{ni} - r - V_i, 0] \mid \theta_{B,C}\}.$$

With $\hat{\theta}_{B,C} = \sup\{\theta_{B,C}: \theta_{B,C} \in \Theta_{B,C}\}$, then $d\hat{\theta}_{B,C}/d\tau = 1/E_\theta\{\max[V_{ni} - r - V_i, 0] \mid \theta\} > 0$.

The partition of acre types on which different strategies are adopted is given in figure 2, where, as will be shown below, $\hat{\theta}_{B,C} \le \hat{\theta}_{B,A} \le \hat{\theta}_{C,A}$. Low θ types don't spray at all because the expected damage done does not warrant the cost of a for-sure spray or the cost of an option to spray. Intermediate types are willing to buy the option to spray, at premium τ. High types may spray anyway because the price τ exceeds the value these types place on flexibility. In light of figure 2, the τ-conditioned interval $(\hat{\theta}_{B,C}(\tau), \hat{\theta}_{C,A}(\tau)]$ is squeezed on both sides as τ increases.[11]

■ RESULT 1. *For exogenous trait value* $\tau \ge 0$,

(a) $\hat{\theta}_{C,A} \ge \hat{\theta}_{B,C}$, *and*

(b) $I^C(\tau_2) \subseteq I^C(\tau_1)\ \forall\ \tau_2 \ge \tau_1$, *where* $I^C(\tau) = (\hat{\theta}_{B,C}(\tau), \hat{\theta}_{C,A}(\tau)]$.

Part (b) points to an issue which would not appear to be generally recognized. Observe first that the innovation can be effectively "un-invented" by increasing price τ to an arbitrarily large value. Then, while a decline in τ would increase demand for the option to wait, part (b) does not assert from where the weight of the increase in demand would come. Viewing figure 2, suppose the distribution of types is massed largely toward the right (case I). Then the innovation will reduce demand for the chemical. If, however, the distribution is massed largely toward the left (case II), then demand for the chemical may rise on average after the innovation as growers find new uses for the (now) more versatile chemical. Existing problems with a chemical may focus industry attention on current use patterns, and so case I may appear to be more representative of reality. But Monsanto was likely motivated to introduce the Roundup Ready® technology in order

[11] $I^C(\tau, \gamma)$ is open on the left only because of the convention that distribution functions are right continuous.

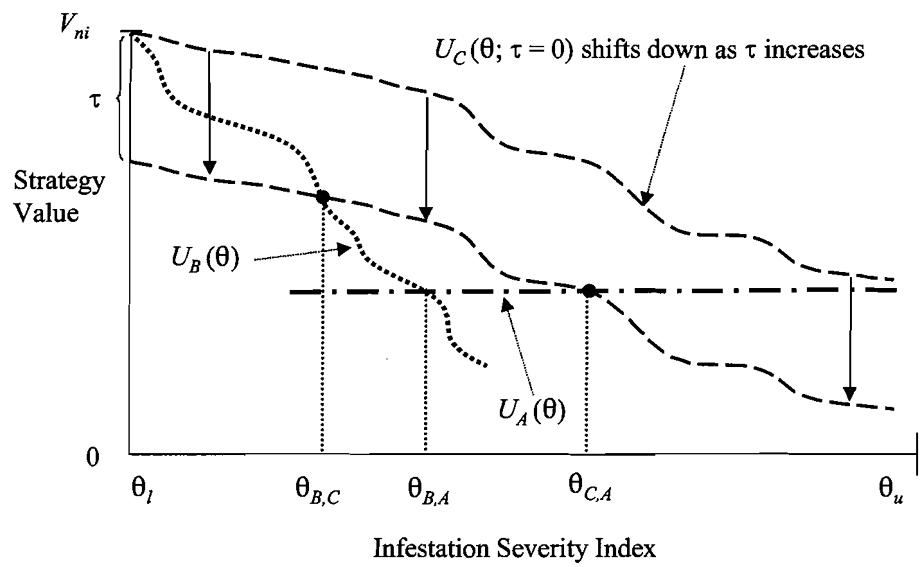

Figure 3. Effect of trait price on partition of types by strategies chosen

to capture new markets (case II), albeit largely away from other chemicals (see Carpenter and Gianessi, or Heimlich et al.).

Figure 3 depicts the impacts of an increase in τ on the partition of types according to strategies chosen. The function $U_C(\theta; \tau = 0)$ must be higher than both $U_B(\theta)$ and $U_C(\theta)$ because, as previously demonstrated, $U_C(\theta; \tau = 0) \geq \max[U_B(\theta), U_A(\theta)]$. When τ increases, $U_C(\theta)$ shifts down such that the vertical difference between curves is the constant τ. Function $U_C(\theta)$ must cut function $U_B(\theta)$ from below because $dU_C(\theta)/d\theta \geq dU_B(\theta)/d\theta$, while function $U_C(\theta)$ must cut function $U_A(\theta)$ from above because $dU_C(\theta)/d\theta \leq dU_A(\theta)/d\theta = 0$.[12] The "choke" price, above which no acre is planted under a herbicide-tolerant seed, is given by τ^+, where τ^+ is defined by $\theta^+ = \hat{\theta}_{C,A}(\tau^+) = \hat{\theta}_{B,C}(\tau^+)$. As in (1) above, it is clear $\theta^+ \equiv \hat{\theta}_{B,A}$.

Next, we engage in a farm-level (i.e., partial equilibrium) analysis of the strategies chosen. Let γ parameterize a mean-preserving spread (Rothschild and Stiglitz) in $G(V_i \mid \theta)$ for all θ. From (3) and the concavity of the function $\min[r, V_{ni} - V_i]$ in V_i, a derivation provides the response $d\theta_{C,A}(\tau)/d\gamma \geq 0$; an increase in the variability of an infestation, given it occurs, increases the prospects of getting away without spraying. Purchasing the option to spray caps the loss at r. The opportunity to limit downside risk and yet benefit from upside potential will dispose the grower toward waiting rather than spraying.

Applying (4), the convexity of the function $\max[V_{ni} - r - V_i, 0]$ in V_i assures us that $d\hat{\theta}_{B,C}/d\gamma \leq 0$. When V_i becomes more random for any θ, in the sense of a Rothschild and Stiglitz mean-preserving spread, then owning the time 0 option to spray becomes more valuable relative to not owning and not spraying before emergence either. This is because the option provided by the trait establishes a floor on the crop value net of spraying costs, $V_{ni} - r$. The increase in risk provides more in the way of upside potential from spraying

[12] See the calculations in footnote 9.

if an infestation warrants it, but has limited effect on downside consequences. In response, acres switch from strategy B to strategy C at any given trait premium value, τ. It can then be seen that the (τ, γ)-conditioned interval $(\hat{\theta}_{B,C}(\tau,\gamma), \hat{\theta}_{C,A}(\tau,\gamma)]$ of acres on which herbicide-tolerant seed is planted expands on both sides as γ increases. Summarizing, result 2 can be written as follows:

- RESULT 2. *For exogenous trait value* $\tau \geq 0$, *the set inclusion* $I^C(\tau, \gamma_2) \supseteq I^C(\tau, \gamma_1)$ $\forall\, \tau \geq 0, \forall\, \gamma_2 \geq \gamma_1$ *holds.*

This result warrants further reflection. At time 1, there is revelation of complete information about the extent of the time 1 weed problem. If the amount of initial uncertainty increases, then the demand for the trait should increase. This is because the trait's usefulness in reducing costs (when the draw of V_i is high) and increasing revenue (when the draw of V_i is low) should increase with the extent of information acquisition. The model is not sufficiently general to rigorously support the assertion that demand for the trait is strengthened by the acquisition of information over the period between a pre-emergence herbicide application and any post-emergence application. Nonetheless, this intuition seems well-founded, and the HT-trait technology likely complements information technologies or managerial capacities enabling the manager to acquire and process relevant information over the pre-emergence, post-emergence interval. However, if all relevant information were known prior to emergence, the trait would have zero value because there would be no option value to waiting.

Equilibrium Royalties to Tolerance Trait

The analysis now turns to the decision environment of the firm holding the patent on the genetic trait. The firm is assumed to license the trait to seed companies for a royalty per bag of seed sold, and the seed companies pass the fee directly on to seed consumers. Total royalties are calculated as:

$$R(\tau;\gamma) = \tau H(\hat{\theta}_{C,A}) - \tau H(\hat{\theta}_{B,C}). \tag{5}$$

Given the trait production costs are sunk, the patent holder will choose a value of τ that sets marginal revenue equal to zero. Result 2 above then readily yields:

- RESULT 3. *Receipts from trait royalties increase with a mean-preserving spread in* $G(V_i\,|\,\theta)$ *on all* $\theta \in [\theta_l, \theta_u]$.[13]

To ascertain this result, suppose $\tau = \tau_1$ is chosen to maximize the value of (5) for a given value $\gamma = \gamma_1$. Then the value of γ increases to $\gamma = \gamma_2$. From result 2, the strength

[13] Result 3 suggests it would be in the best interests of an HT trait patent holder to strengthen demand by providing information on when to use, or not use, the herbicide. In the case of Monsanto's Roundup Ready® herbicide, *both* chemical revenues and license fees from trait use propagation contribute to company profits. The company wishes to increase demand for both the trait and the chemical, a situation not covered in result 3. A review of the company's website (accessed on January 16, 2003) shows glyphosate use recommendations do advocate conditioning use on the problem's severity. However, we could find little evidence of company activities to promote grower-level information acquisition or processing technologies which would assist in informed use of post-emergence applications of glyphosate.

of demand, $H(\hat{\theta}_{C,A}) - H(\hat{\theta}_{B,C})$, increases for $\tau = \tau_1$. The reoptimized value of $R(\tau; \gamma_2)$ can be no smaller than $R(\tau_1; \gamma_2)$, so there exists a $\tau = \tau_2$ such that $R(\tau_2; \gamma_2) \geq R(\tau_1; \gamma_2) \geq R(\tau_1; \gamma_1)$.[14]

Distribution of Types

The analysis underlying figure 3 reveals it is to the benefit of the trait monopolist for types to be intermediate in value rather than massed at the extremes of the types interval. Economic intuition might suggest that what is good for the trait monopolist would be bad for the aggregate welfare of growers. This section provides precise conditions under which a reduction in heterogeneity among acres is to the benefit of the trait monopolist.

It has already been noted by equations (3) and (4) that the values of indifferent types $\theta_{C,A}$ and $\theta_{B,C}$ are not directly dependent on the mass distribution $H(\theta)$. Fixing the value of τ, suppose mass is now shifted from outside the interval $I^C(\tau) = (\hat{\theta}_{B,C}(\tau), \hat{\theta}_{C,A}(\tau)]$ to inside the interval. This will certainly be to the benefit of the trait patent holder because profit increases at any fixed trait price. However, and albeit indirectly, the sort of shift just outlined is dependent upon the initial mass distribution $H(\theta)$ because $H(\theta)$ determines the monopolist's trait pricing decision. As has been shown, $I^C(\tau) = (\hat{\theta}_{B,C}(\tau), \hat{\theta}_{C,A}(\tau)]$ contracts to the point $\hat{\theta}_{B,A}$ as $\tau \to \tau^+$. If $\tau < \tau^+$, then demand for the trait will always increase whenever the distribution of types undergoes a contraction about $\hat{\theta}_{B,A}$.

- DEFINITION 1. *Mass distribution $H(\theta)$ is said to undergo a contraction about $\hat{\theta}_{A,B}$ if $H(\theta) \to H^1(\theta)$ such that $\int_{\theta_l}^{\theta_u} dH(\theta) = \int_{\theta_l}^{\theta_u} dH^1(\theta)$ and $\int_\chi dH(\theta) \leq \int_\chi dH^1(\theta)$ for all intervals $\chi \subseteq [\theta_l, \theta_u]$ such that $\hat{\theta}_{B,A} \in \chi$.*

The form of contraction defined above need not be mean-preserving. It could be either mean-increasing or mean-decreasing. But if it does preserve the mean, then the contraction is a mean-preserving contraction in the sense of Rothschild and Stiglitz. Further, not every mean-preserving contraction is a mean-preserving contraction about $\hat{\theta}_{B,A}$. In fact, a little work would demonstrate that even if $\hat{\theta}_{B,A} = \int_{\theta_l}^{\theta_u} \theta \, dH(\theta)$, a mean-preserving contraction in the sense of Rothschild and Stiglitz would not necessarily satisfy the definition. Result 4 expresses an immediate consequence of the fact that a mass shift in types satisfying definition 1 increases trait demand for all trait prices.

- RESULT 4. *If the distribution of acre types undergoes a contraction about $\hat{\theta}_{B,A}$, then the trait patent holder's profits increase.*

Conclusion

This analysis has placed state-contingent cost-saving crop traits in a real options framework so as to better understand the implications of such traits for equilibrium production strategies when acres are heterogeneous. The analysis may warrant an

[14] The comparative statics of the patent holder's choice for τ are somewhat more involved. Assumptions, such as the hazard rate and reversed hazard rate orders applied in Chen, are then required on the distribution of types in order to guarantee a unique equilibrium. Some results are available from the authors upon request.

extension to look more closely at welfare effects. A good point of departure in this regard might be the model by Moschini and Lapan, as applied in Falck-Zepeda, Traxler, and Nelson. In this framework, an innovating input is provided by a monopolist, where the change in total social welfare due to the innovation can be represented by the sum of change in input market Marshallian surplus and change in profits to whomever the input monopolist is. The challenge in an equilibrium welfare assessment would be to accommodate the weed infestation uncertainty. At the market level, the extent of covariation between acre-level infestations would be an important issue in such an analysis.

Separately, an elaboration to capture the effect of a novel trait on incentives to accumulate information about the decisions that may have to be made might also be worthwhile. Such an extension would provide insights into the effects of trait innovations on temporal patterns in agri-input use. Policies to promote or deter the use of a trait because of alleged environmental effects may be formed after viewing the short-run effects on input use. But, because new strategic opportunities will likely be adopted in a relatively uninformed decision environment, it is not immediately clear whether the long-run effects on input use will be qualitatively the same as the shorter-run effects.

At the most general level, this study has determined that while biotechnology trait innovations, agri-chemical use, and demand for farm-level information acquisition and processing inputs are intimately related, broad statements about the nature of interactions should be treated with some suspicion. Nonetheless, we conclude with some speculations which might warrant further inquiry.

While interactions between technology choices and input choices may generally reveal themselves over a relatively short time span, this is likely to be less true for some aspects of choices in information processing capacities. Education and the acquisition of skills are key issues here. To the extent that education strengthens managerial competencies in processing information, a biotechnology trait requiring, say, extensive decision making may find more adopters in a well-educated farm sector. Then information and information management inputs will increase as factors in producing agricultural outputs, and the demand for education as an input in the sector will strengthen. But human capital formation is a long-run phenomenon, and it may take some years for enlightening empirical evidence to accumulate on how biotechnology interacts with the demand for education on the part of farm managers. Even in the more general set of agricultural technologies, Huffman has identified a dearth of research assessing how schooling, information acquisition, and technology adoption decisions interrelate.

Shifts in the structure of consumer preferences are likely to strengthen the need for research examining the effects of education on technology adoption decisions. The growing market penetration of the organic food movement (Duram; Dimitri and Greene; Greene and Kremen), with its disposition toward technology choices conditioned on the production environment, will require growers to acquire and use information in matching the environment with the suite of available production technologies.

Also, the U.S. Food Quality Protection Act of 1996 may eventually result in the removal of a large number of pesticides, including herbicides, from many of their agricultural uses. Food quality traits, including visual traits, are likely luxuries. Producers seeking to satisfy the demands of increasingly affluent consumers may need to employ a mixed bag of environment-specific technologies. The decision environment may become more complicated, and there may be premiums for managers who know their production environment well enough to judiciously exercise their technology options.

On the other hand, if HT and other genetic traits substitute for informed farm-level decision making through obviating the need to develop data sets on pre-emergence land conditions, then the agricultural crop economy may become more centralized. The information disadvantages facing cropland renters would become relatively less severe, while scale economies in asset management and reduced unit input costs may dominate in determining firm structure.

[*Received October 2002; final revision received February 2003.*]

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