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Ex post evidence on adoption of transgenic crops: US soybeans

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Abstract

Transgenic crops offer a complex new technology that is not universally dominant over alternatives. Instead, adoption decisions are conditional on incentives associated with alternative technologies and local conditions. These characteristics imply that transgenic crops can be expected to be adopted on a wide scale in existing cultural areas, if incentives are appropriate. Further, considerable potential exists for transgenic crops to be adopted in new areas where they offer advantages over alternative crops such as weed control and other management practices.
Keywords: transgenic crop; innovation adoption; diffusion; soybeans

Introduction

The potential of transgenic crops involves consideration of a technology that has several important features. First, as with many technologies that are involved with agricultural production, a shift to transgenic-crop production involves both private and public effects. Second, in each case, these effects involve both uncertain and, in some cases, irreversible costs and benefits. Third, while many technologies offer net benefits that render the innovation universally attractive to potential users, though actual diffusion is inhibited by imperfections in markets, transgenic-crop production involves a package of changes in practices, input mix, and basic opportunities for management of the crop. Because of the associated complex of private- and public-good changes, the attractiveness of these innovations may not be universal. The willingness-to-pay for transgenic crops is often conditioned by local, farm-specific conditions that result in what Weaver and Kim (2002) defined as local dominance of the technology. That is, rather than being universally adopted, an equilibrium is implied in which use of the technology is both incomplete and intertemporally unstable. Fourth, transgenic innovation has involved a change in perceived underlying attributes of food products derived from the crop. This change in attributes may or may not involve changes in the real functional value of the food product in consumption. In any case, this characteristic has proven to imply increased uncertainty with respect to the market value of the crop. Finally, the potential for public effects or changes in food attributes associated with transgenic crops has motivated national and regional regulatory responses ranging from prohibition of use to conditions for use creating a geographic fabric of varied experience.

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Within this context it is of interest to consider *ex post* evidence concerning the nature of adoption behaviour for these crops and, in particular, to provide a basis for drawing from that evidence any lessons that might be apparent concerning US experience and relevant to Europe. To proceed, the focus of this paper will be on herbicide-tolerant (ht) soybeans, leaving insecticidal-trait transgenic crops for another paper. Of particular interest in this paper is to consider United States (US) experience with adoption and to assess its implications for adoption in Europe, should current regulations be changed to allow growing of ht soybeans. Of subsidiary interest is whether adoption experience in the US appears to be consistent with well-established economic literature on the adoption of new technologies, or whether an alternative theoretical framework is needed to understand and predict adoption behaviour with respect to transgenic crops. Given that the assessment of environmental effects is considered elsewhere in the workshop, this paper will focus more sharply on adoption-behavioural implications of known or possible environmental effects.

To proceed, the outline of the paper will be to consider briefly the salient features of transgenic crops, though to defer consideration of regulation to another context. Next, implications of these features for adoption decisions will be considered. Third, evidence across US experience will be considered for the case of ht soybeans. In closing, conclusions will be drawn with a brief consideration of the relevance of US experience to Europe.

Salient features

Current status

Before proceeding, a brief consideration of the current status of genetically modified (GM) crops is in order. James (2002) estimates that globally 58.7 million hectares were planted to transgenic or GM crops in 2002, across 16 countries. He estimated that 27% of this area was planted in developing countries with Argentina and China accounting for the majority of this area. However, India, Columbia, and Honduras will rapidly claim a place on these charts as they shift to *Bt* cotton. Herbicide tolerance has dominated as a transgenic trait available in soybeans, corn and cotton, accounting for 75% of global transgenic area planted. Insecticidal traits of *Bt* claimed 17% of area with the remainder claimed by stacked genes delivering herbicide tolerance and insecticidal traits. Transgenic soybeans claimed 62% of global area accounting for 51% of soybean area while *Bt* corn claimed 13% of global transgenic area. These trends suggest that as a technology, transgenic crops might be distinguished as a universally dominant technology. That is, one that generates a benefit–cost stream that makes the technology dominant across a wide spectrum of heterogeneous producers.

The United States produces more soybeans than any other country involving approximately 380,000 farms in 29 states. A decade ago, in 1994, the US crop yielded 2.558 billion bushels of soybeans with an estimated farm-gate value of $13.813 billion and an average price of $5.40 per bushel; soybean production has expanded to cover 74.1 million acres (30.0 million hectares) in 2001, producing a record 2.891 billion bushels (78.68 million metric tons) of soybeans at an average farm price paid of $4.25 per bushel ($156 per metric ton) generating a crop value of $12.28 billion. Interestingly, soybean production in the US does not only take place in the wide, flat fields of the Midwest. Increasingly, soybeans are grown further north and in states such as Pennsylvania, where traditional crop rotations range across small grains, hay and forage, and corn. In these states, transgenic soybeans are being adopted by producers with no past experience with soybeans.

In fact, US experience indicates that two cases can be defined with respect to adoption experience. First, a substantial proportion of the US growing region can be viewed as having homogeneous growing conditions, farm scale and farm diversification. This would include what many would view as the traditional or primary areas where soybeans have been grown and accounted for a large percentage of principal crop area, e.g. Illinois, Iowa, Indiana, Missouri and Ohio. For these states, soybean area accounted for over 20% of principal-crop area before transgenic soybeans were available and adoption has continued to increase, though at a reduced rate (see Table 1). In addition to these areas, a secondary area is apparent. In the US, this area comprises states where soybeans accounted for less than 20% of area, however, more recently soybeans have expanded dramatically with the introduction of transgenic varieties. Nebraska, North Dakota, South Dakota, Wisconsin and Pennsylvania would be included in this category (see Table 1). In these secondary states, it is clear that soybean production is expanding through entry by farmers who previously did not produce soybeans, though with the availability of transgenic soybeans find the technology and crop attractive.

Private and public effects

The nature of innovation offered by transgenic crops is inherently complex. While most would agree that the innovation they offer is fundamentally different from a new variety or hybrid, the exact nature of the facets of the innovation are subject to substantial debate, uncertainty and variation across growing conditions and crops. One aspect of particular importance for consideration is the private and public effects of the innovation. With respect to private aspects, the yield effect is of particular interest. Yield impact of transgenic soy depends on weed control as well as the extent of adaptation of conventional varieties. Past studies have not found a striking difference in yields that cannot be unequivocally assigned to weed-control differences, or plant-growth or damage effects from application methods. Going a step further, transgenics provide opportunity for substantial changes in management practices, timing, flexibility and intensity of input use. Ervin et al. (2000) provide a thorough review of both the private and public effects.

Fernandez-Cornejo and McBride (2002) studied the private farm-level impacts of transgenic crops for the period 1996-98 focusing on yields, pest management and net returns. They found that use of ht cotton led to significant yield and net return increases, though no significant herbicide-use changes. Alternatively, for ht soy they found small increases in yield, no change in net returns, and significant decreases in herbicide use. However, their results varied substantially across farms and regions. In addition to changes in input mix or management practice, the incomplete knowledge of private and public effects of transgenics results in uncertainty concerning efficient input combinations, performance of the crop, costs and revenues. Although evidence from analysis of farm-level experience is not available, the flexibility in timing of use of herbicides and of field practices for ht soy would suggest that efficiency gains could be realized compared to conventional practices for soy.

Public benefits in the form of both short- and long-term environmental benefits are a potentially important dimension of the adoption of transgenics. Ervin et al. (2000) note that substantial environmental benefits may be associated with transgenic crops,

Table 1. Evolution of soybean area: US percentage of total crop acres planted to soybeans

Region	State	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
South central	AR	41.27	40.90	40.90	43.74	41.72	40.20	39.46	34.54	35.67	36.27
	KS	9.52	9.36	8.48	10.21	11.06	12.44	12.88	11.89	11.86	11.62
	LA	29.53	27.74	27.26	34.65	29.59	26.91	24.64	17.19	21.08	26.05
	MS	39.67	38.14	36.89	44.03	42.62	39.76	35.64	25.47	32.04	31.55
	OK	2.79	2.73	2.65	3.11	4.43	4.36	4.20	4.16	2.59	1.76
	TX	1.01	1.11	1.19	1.80	1.85	1.60	1.24	1.08	0.93	0.95
North central	IL	40.09	41.99	41.38	42.12	44.82	45.07	44.36	45.67	45.15	45.41
	IN	37.90	41.87	42.69	41.27	43.31	44.02	43.32	45.01	47.63	44.29
	IA	36.35	39.57	39.26	42.49	41.95	43.39	42.82	44.69	42.38	41.87
	MI	22.12	22.09	23.49	26.59	28.04	28.34	30.29	32.18	30.94	31.77
	MN	28.43	30.81	30.00	32.18	33.63	34.70	35.97	37.67	35.49	37.94
	MO	36.17	38.16	30.89	36.50	37.42	39.67	37.64	36.68	36.48	35.51
	NE	15.18	16.96	16.21	18.83	20.05	22.25	24.22	25.62	24.55	24.54
	ND	2.95	3.19	3.75	5.16	6.96	6.73	8.75	10.51	11.92	14.11
	OH	38.44	40.40	44.23	40.56	41.31	43.52	41.76	43.45	45.73	43.53
	SD	14.84	17.79	15.97	18.82	20.92	24.81	25.45	25.47	24.70	23.45
	WI	10.20	10.13	11.27	12.98	14.23	16.13	19.85	20.84	19.03	19.09
Northeast	DE	44.12	46.35	44.00	45.19	42.39	41.16	43.00	42.09	39.92	42.79
	MD	35.69	35.53	31.11	34.06	31.97	32.91	33.96	34.76	33.29	36.04
	NJ	32.75	30.97	28.10	30.57	25.56	25.24	27.17	30.12	28.57	30.49
	PA	7.71	7.72	7.00	8.69	9.20	8.61	9.20	9.91	9.74	9.30
	VA	18.58	16.84	17.03	17.43	17.06	16.14	17.24	18.03	16.80	19.63
Southeast	AL	13.73	10.89	14.19	14.75	15.09	10.77	9.11	6.26	8.05	9.27
	FL	4.13	2.80	3.16	4.32	3.11	1.82	1.81	0.93	0.91	1.03
	GA	12.18	7.55	9.23	9.05	7.42	5.70	4.35	4.27	4.11	4.73
	KY	20.69	20.49	20.53	21.19	20.80	20.65	20.32	22.64	23.44	20.35
	SC	29.44	27.83	28.41	28.57	28.39	26.86	26.87	26.33	25.33	30.85
	TN	22.56	21.46	23.00	25.18	25.86	25.44	23.31	21.08	23.27	23.80
	NC	29.60	24.79	26.28	28.48	29.41	28.31	28.52	27.90	27.41	30.10
US		19.02	19.64	19.20	20.95	21.83	22.37	22.61	22.80	22.53	22.64

Data source: USDA-National Agricultural Statistics Service: Crop-Production-Acreage Supplement; Crop Production–Annual Summary though they also note that ecological negative effects have been suggested by some research. Other chapters in this volume address this issue in detail, though for this paper it is sufficient to note that a review of US experience would reveal, for most readers, an absence of accepted scientific conclusions concerning the private and public effects of transgenics. The knowledge base is small and does not support consensus interpretation. As might be expected for any innovation, some uncertainty remains concerning the extent and nature of these effects. Recent USDA data shows that herbicide-tolerant seed slightly reduced the average number of active ingredients applied per acre, while slightly increasing the average amount applied per acre (Benbrook 2001).

In the long term, it was expected that transgenic crops would facilitate the introduction of pesticides that imply reduced environmental risk. While rapid adoption of such crops suggests that strong incentives may be in place to motivate these decisions, the interplay of private vs. public effects in these decisions is not clear. Based on ERS/USDA estimates, the expansion of ht soy in the US followed rapidly after 1997 and was accompanied by increased use of glyphosate (Economic Research Service USDA 1999b) and decreased use of other herbicides leading to a net reduction in total weight applied. ERS (1999a) indicated that ht soy allowed reduced active-ingredient application. Numerous other studies find that change in herbicide use overall has not been significant, e.g. Benbrook (2001), although the extent of impact varies by crop. Most recently, Conner, Glare and Nap (2003) noted that the variety of concerns raised relative to the impacts of GM crops on the environment remain open to debate. These include putative invasiveness, gene flows and ecological effects, and drift of GM material into other products (e.g. feeds to animals).

A more specific look at farm-level survey data suggests that changes in production practices for ht soy include a shift toward conservation tillage, a notable reduction in the number of active-ingredient herbicides used with a sharp focusing on glyphosate; and finally, that the planting window has become much wider offering substantial flexibility for timing of planting, weed control and movement toward no-till planting that eliminates tillage and other field preparation activities. From 1989 to 1998 the acreage of soybeans planted with conservation-tillage methods increased from 30% to 54%; see Carpenter and Gianessi (1999). These changes appear to offer reduction in fuel use.

Nonetheless, some evidence exists that supports the claim that changes in practice include shifts to no-till planting, pre-emergence herbicide use, change in the type of active ingredients used, and perhaps substantial changes in environmental impacts of crop practices. Benbrook (2001) provides evidence that herbicide-tolerant varieties have slightly reduced the average number of active ingredients used per acre while increasing the average pounds applied per acre. Carpenter and Gianessi reviewed shifts in practices citing in particular the role of transgenic soybeans as a natural extension of an evolution toward increased use of post-emergence herbicides, simplification of weed-control programmes, and improved effectiveness of active-ingredient applications; see e.g. Pike, McGlamery and Knake (1991). Importantly, this shift in practice had substantial implications for tillage practices that had focused on field preparation and post-emergence tillage. Given post-emergence herbicides, adoption of conservation tillage was facilitated, leading to over 50% adoption by 1998; see Kapusta and Krausz (1993) and Conservation Tillage Information Center (1999). This shift was further extended by introduction of herbicide-tolerant soybeans that allow post-emergence, broad-spectrum herbicide application at nearly any stage of plant growth. Second, improved post-emergence herbicides have allowed for a reduction in row spacing, significantly reducing cultivation, improved weed control due to canopy closure and increased land-area yield. The key innovation offered by transgenic soybeans is the reduction of crop damage (e.g. stunting, delayed canopy closure) from herbicide application (see Padgette et al. (1996)) and increased effectiveness of weed kill (see Rawlinson and Martin (1998)). This latter effect follows directly from tolerance that allows effective dosage to be determined with consideration of crop-damage relaxing constraints in conventional systems with respect to timing (early in weed emergence).

Some negative environmental effects that have been considered include impacts on soil structure (no till results in macropore development and exposure of groundwater to surface effluents) and reduced incorporation of plant residue or animal waste to amend the soil. In addition to these, concern regarding cross-pollination between GM (genetically modified) and non-GM soybean strains as well as the potential for evolution of herbicide-resistant weed varieties has been noted. That there are possible (unverified) negative effects of biotechnology products has been a social concern. In the United States, substantial concern with respect to BST use was initially raised among dairy producers, though after a period during which scientific evidence was interpreted and debated, these concerns subsided. A similar pattern of learning has been associated with transgenic soybeans. Importantly, the shift to reduced tillage has been credited with increased crop residue, reduced fuel, labour and machine time, reduced wind and water erosion; see American Soybean Association (2001).

Uncertainty and irreversibility

The productivity and market value of new products and production practices or technologies that result from innovation are inherently uncertain. In the case of transgenic crops, the extent of this uncertainty is extensive. This scope of uncertainty follows from uncertainty in applied science, the complexity of the production-process changes involved with transgenic crops, and the scope of private and public effects that may exist or are perceived along the supply chains through which value is created from these crops. In addition to this uncertainty, both private and public costs and benefits associated with transgenic-crop adoption may be or are perceived to be irreversible. On the uncertainty front, adoption of transgenics allows for or requires substantial change in production practices as reviewed above. This by definition introduces uncertainty that characterizes the adoption of most innovations. However, to the extent that the performance of transgenic crops is conditioned by local climate, soils and pest exposure, the extent and speed of resolution of this uncertainty through learning will be reduced. The suggestion of physical science is that site- and environmental-condition-specific characteristics can significantly affect the performance of ht soy. Nonetheless, the rapid and widespread adoption across the primary states in the US is consistent with experience with other technological change in agriculture and suggests that much of the technological uncertainty has been quickly resolved in these states.

Irreversibility is a key feature of many innovations. Typically, investment costs must be incurred for learning, change in management practices or acquisition of machinery or other services for assets. Where these are irreversible, adoption of the innovation is affected. In the case of transgenic crops, both irreversible costs and benefits have been cited including both private and public effects.

Transgenics: universal or locally dominant?

The characteristics of the technology and its impacts on production practices and input mixes suggest that transgenic seed constitutes a complex set of changes in the overall production technology, rather than a single augmentation of a particular input. Within this context, the role of heterogeneity across agents would be expected to be accentuated. Bullock and Nitsi (2001) found that the potential of transgenics varied with extent of pest exposure and the type of pest-control practices used. This confirms the physical science evidence concerning the complexity of the changes induced by the transgenic technology. In the presence of a substantial potential role of heterogeneity that might result in heterogeneity in adoption, adoption of transgenic soybeans has been rapid within what has been labelled the primary-states region of the US. However, a different story is apparent in the secondary-states region. In this section, we briefly note the distinction between these two cases.

To begin, past literature has considered technology adoption both at an individual-agent level and at the level of various aggregations. While the individual agent's decision to adopt is most often a binary one, its timing is conditioned by a variety of individual determinants that imply that adoption will not be instantaneous by all producers. Instead, over time the proportion of adoption in an aggregation of agents has been described as 'diffusion' process (see e.g. Karshenas and Stoneman 1995). The role of agent-specific factors implies that as these conditions evolve, the technology choice of particular agents will change. Recognition of the role of heterogeneity across agents in adoption decisions and timing has been expanded to include agent managerial characteristics, risk preferences, labour-market participation, exposure to uncertainty with respect to technological performance, and information access. Fernandez-Cornejo and McBride (2002) presented estimates of adoption of GM crops in the US that indicated that scale of operation (farm size) was not a significant determinant for ht soybeans, while indicators of operator characteristics (experience, operator risk aversion, use of marketing contracts) and general indicators of farm characteristics (limited resource, location in marginal crop region) were found statistically significant.

Feder and Umali (1993) note that factors affecting adoption may vary over the life span of the innovation (early vs. late phase).

Heterogeneity is also recognized in theargument that rationalizes why a technology does not immediately 'diffuse' as would be expected within competitive market settings with instantaneous information and costless adjustment; see most recently Fernandez-Cornejo and McBride's (2002) diffusion model for GM crops in the US. Importantly, this theory of adoption suggests implicitly that after some finite time period, for a particular population of producers, adoption will be complete or, in other words, the market for the new technology will be saturated. This interpretation translates into the postulation of ceiling or upper limit for adoption that may be conditioned by factors that characterize the population of producers. Fernandez-Cornejo, Klotz-Ingram and Jans (1999) and Fernandez-Cornejo and McBride (2002) use estimates of pest pressure. Below, we continue in this tradition and consider the case where producers are not homogeneous, implying that for particular incentive vectors and quasi-fixed factor positions, adoption may not be chosen by some producers. Note that this perspective differs from that of Moschini and Lapan (1997), who consider input-price adjustment as a reason for incomplete adoption.

Marketing and consumer preferences

The feasibility of marketing transgenic crops poses an important basis for distinguishing them from other crop innovations. Two issues deserve note. First, the geographic scope of transgenic crops appears to be changing. In this regard, the availability of marketing channels and opportunities are essential determinants of the feasibility of expansion of the crop into new locations. A second concern is consumer reaction to transgenic crops that might be used for or affect foods used for human consumption or for animal feed. In the soybean complex, three forms of products must be considered: beans, oil and meal. Traditionally, soybeans have been marketed either through local grain elevators or feed mills for animal feed, or to crushing plants that produce soybean meal and oil. While direct, local feed use of soybeans has evolved in secondary states such as Pennsylvania, sale to crushing plants remains constrained in these locations due to absence of nearby plants. The processing market as well as the large-scale feed-user procurement in the US operates through use of forward contracting and brokerage. This approach minimizes search costs and stabilizes procurement price risk. The question of consumer response to transgenic crops has been considered in depth elsewhere, though it is important to note that transgenic crops constitute an innovation for which the level and uncertainty of private and public effects results in consumer response. To the extent that consumers adjust preferences based on news or scientific announcements, consumer behaviour may be unstable until uncertainty is resolved and a consensus is formed concerning the nature of private and public effects.

Implications for adoption decisions

Static perspective

Based on the salient features of the transgenic crop innovation, the economics of adoption of the innovation deserve attention. To summarize, these salient features include private and public effects, uncertainty, irreversibility and regulation.

Clark (1999), Fernandez-Cornejo, Klotz-Ingram and Jans (1999) and Weaver and Kim (2002) note that transgenic-adoption decisions are complicated by factors that go beyond the private economics. Weaver and Kim (2002) note the complexity of effects on production practices that suggest the innovation goes beyond a single input augmentation. In contrast, transgenic technology has often been specified as a single factor augmenting technological change, see e.g. Moschini and Lapan (1997). Fernandez-Cornejo, Klotz-Ingram and Jans (1999), Nadolnyak and Sheldon (2001) and Neill and Lee (1999) discuss adoption of transgenic soybeans though they do not pursue actual empirical modelling. Fernandez-Cornejo and McBride (2002) present empirical results for models of adoption of GM crops as noted above. Further, they consider the possibility that adoption of GM technology and no-till technology is simultaneous. Based on estimates of structural equations for such simultaneous choice they find evidence that is consistent with the conclusion that simultaneity does not exist, however, adoption of GM seed is conditioned by use of no-till practices. Weaver and Kim (2002) present a table summarizing available literature. To consider the adoption decision as well as the nature of dominance of transgenic-crop technologies, the notation of Weaver and Kim (2002) is useful.

Define the production function for cth crop output y^{i}_{jc} (quantity per land area, e.g. hectare) from the jth farm operating the ith technology. Suppose that while a common technology is available across farms, the technology is conditioned by farm-specific

quasi-fixed and fixed input flows represented by a vector, θ_j. Suppose crop output is also conditioned by a stochastic shock, ε_j, generated by a density function $g(\varepsilon_j|0,1)$, and a vector of inputs, $x^i{}_c$. Note, this input vector includes inputs relevant for the *i*th technology, though some elements may also be relevant for other technologies. The technology-specific production function reflects unique technological attributes such as planting flexibility, management intensity, etc. Define the crop output per land-area production function as: $y^i{}_{jc} = y^i{}_{cj}\,(x^i{}_{cj},\ \theta_j,\ \varepsilon_j)$ and producer profit per land area for crop *c* produced with technology *i* as:
$\pi^i_{jc} \equiv p_{jc}{}^i y^i_{jc} - r^i_{jc}x^i_{jc} - w^i_c\delta^i_{jc}$ where p^i_{jc} is the output price that is allowed to be technology- and farm-differentiated, $r^i{}_{jc}$ is the input-price vector, $\delta^i{}_{jc}$ is the seeding rate per land area, and w^i_c is the price paid for *i*th seed type for crop *c*. The seed price w^i_c is uniform. The differences in seed prices at the farm gate are captured by the input price and input vector.

Based on this notation, sequential planting decisions will first select the optimal technology to operate for each crop that might be grown, and second select the area allocation and production plan across crops conditional on the optimal technology selected for each crop. The choice of optimal technologies follows from a consideration of optimal-value functions indicating the value per land-area unit for each crop *c* and technology *i*:

$$(1)\, V^i_{jc}(\rho^i_{jc}) = V^i_{jc}(p_{jc}{}^i, r^i_{jc}, w^i_c, \delta^i_{jc}, \theta_j) \equiv \max EU(\pi^i_{jc}) \ \ where\, \pi^i_{jc} \equiv p^i{}_{jc}y^i_{jc} - r^i_{jc}x^i_{jc} - w^i_c\delta^i_{jc}$$

s.t. $y^i{}_{jc} = y^i{}_{jc}(x^i{}_{jc},\ \theta_j, \varepsilon_j)$.

Define the farm-specific vector of determinants of value as an 'incentives' vector $\rho^i_{jc} \equiv [p_{jc}{}^i, r^i_{jc}, w^i_c, \delta^i_{jc}, \theta_j]$ and the set *I* as the set of all economically feasible alternative technologies for crop *c* defined as those technologies *i'* for which $V^{i'}_{jc} > 0$ at the prevailing $\rho^{i'}_{jc}$. Based on this notation, the producer's relative net benefit for technology *i* versus technology *i'* for the same crop is: $\omega^i{}_{jc} = V^i{}_{jc} - V^{i'}{}_{jc}$.

The implications of heterogeneity across farms is clear by defining a technology *i* for crop *c* as *locally dominant* on farm *j* relative to other technologies $i' \in I$ if $\omega^{ii'}{}_{jc} > 0 \quad \forall \quad i' \neq i, i' \in I$, and is *universally dominant* relative to other technologies *i'* and for a set of *J* farms if $\omega^{ii'}{}_{jc} > 0 \quad \forall \quad i' \neq i, i' \in I, j \in J$. Thus, the dominance of a technology involves comparative evaluation of value across alternatives at the farm level. This implies that a wider scope of incentives become involved in the adoption decision than simply those that determine the value of the dominant technology. That is, it is clear that the choice of technology involves a comparative, though discontinuous, role for the incentive vectors $\rho^i_{jc}, \rho^{i'}_{jc}$ across the set of possible technologies, *I*. Further, the composition of the set *J* of farms for which technology is universally dominant is similarly conditional on and discontinuously related to the vectors $\rho^i_{jc}, \rho^{i'}_{jc} \quad \forall \quad j \in J$; especially noteworthy are the farm-specific characteristics embedded in these vectors. To continue the story, given the sequential nature of cropping decisions, dominance of technology *i* for crop *c* does not imply that the associated crop will be dominant. Thus, adoption or use of the dominant technology follows from dominance of the crop conditional on the dominance of the technology. In each case, the dominance condition involves discontinuous roles for incentives.

To consider choice of crops conditional on the set of dominant technologies, define local crop dominance of crop c for farm j as occurring for the locally dominant technology i $\quad if\ \omega^{i}_{jcc'} \equiv V^{i}_{jc} - V^{i}_{jc'} > 0 \forall c' \neq c \in C$ where C is the set of all economically feasible alternative crops defined as those crops c' for which $V^{i}_{jc'} \geq 0$ at the prevailing $\rho^{i'}_{jc}$. It follows for area a and input vector x demands can be immediately derived and used to analyse or model these choices; see Weaver and Kim (2002). However, more relevant to this paper is that *relative willingness-to-pay* for technology i for crop c versus the second best alternative can now be defined as $\omega^{ii'}_{jcc'} \equiv V^{i}_{jc} - V^{i'}_{jc'} > 0 \quad \forall \quad [i,c] \neq [i',c'], c \in C, i \in I$.

Several propositions follow. First, the choice of the locally dominant technology is conditional on, though not continuous in, the vectors of determinants of value across all technologies, i.e. $\rho^{i}_{jc} = (p^{i}{}_{jc}, r^{i}_{jc}, w^{i}_{c}, \delta^{i}_{jc}, \theta_{\mathrm{j}})$ as well as $\rho^{i'}_{jc} = (p_{jc}{}^{i'}, r^{i'}_{jc}, w^{i'}_{c}, \delta^{i'}_{jc}, \theta_{\mathrm{j}}) \forall i'$. Further, the choice of crop is conditional on the vectors of determinants of value for dominant technologies across all crops, i.e. ρ^{i}_{jc} and $\rho^{i}_{jc'}\ \forall\ c'$. Despite this conditionality, the final choice of area allocated to and, therefore, demand for seed for crop c produced by technology i, is not a continuous function of these determinants of value for alternative technologies and crops. Instead, demand for seed is functionally continuous only in the vector of determinants of value of the dominant crop using the dominant technology, i.e. ρ^{i}_{jc}. That is, we define the demand for seed: $s^{i}_{jc} = s^{i}_{jc}(\rho^{i}{}_{jc}) \equiv a^{i}_{jc}(p^{i}{}_{jc}, r^{i}_{jc}, w^{i}_{c}, \delta^{i}_{jc}, \theta_{\mathrm{j}})\delta^{i}_{jc}$. This last result has often led to confusion concerning the implications of a patent grant as noted by Weaver and Kim (2002) and Weaver and Wesseler (2003). Viewed alone, the demand function for seed seems to imply that a patent grant transfers monopoly power to the innovator to price the seed for technology i for crop c. However, it is clear from the above notation that this pricing power would only exist in the case where no other technologies or crops were economically feasible alternatives for the farmer.

The implications of this theory for empirical study of adoption are clear. The relative willingness-to-pay rule provides the basis for definition of a binary indicator of local crop dominance conditional on a particular technology:

(2) $\quad \lambda^{i}_{jcc'} = 1 \quad if\ V^{i}_{jc} - V^{i}_{jc'} \geq 0\ otherwise\ \lambda^{i}_{jc} = 0$.

Providing further definition to the underlying functions motivates an empirical approach to estimating the probability of particular types of dominance by a given technology or innovation. For example, adding a stochastic error to the value function,

$$V^{i}_{jc}(\rho^{i}_{jc}) = v^{i}_{jc}(\rho^{i}_{jc}) + \omega^{i}_{jc}\ define \quad \lambda^{ii'}_{jc} = 1\ if \quad \omega^{i}_{jc} - \omega^{i'}_{jc} \geq -v^{i}_{jc}(\rho^{i}_{jc}) + v^{i'}_{jc}(\rho^{i'}_{jc})$$

This motivates the probability of *local dominance* of technology i over alternatives i' on farm j *(*by generalization, a group of farms)

$$pr(\lambda^{ii'}_{jc} = 1\ \forall i') = \prod_{i' \neq i} pr(\omega^{i}_{jc} - \omega^{i'}_{jc} \geq -v^{i}_{jc}(\rho^{i}_{jc}) + v^{i'}_{jc}(\rho^{i'}_{jc}))$$

and the probability of *global dominance* of technology i on a group of farms J:

(3) $\quad pr(\lambda^{i}_{c} = 1\ \forall i', j) = \prod_{j=1}^{J} \prod_{i' \neq i} pr(\omega^{i}_{jc} - \omega^{i'}_{jc} \geq -v^{i}_{jc}(\rho^{i}_{jc}) + v^{i'}_{jc}(\rho^{i'}_{jc}))$.

By extension, crop choice can be similarly motivated, and by addition of parameterization to the underlying functions, we have the basis for a parametric approach to estimation of the dominance probabilities, or equivalently, the adoption probabilities for a particular technology or crop for a particular farm type or group of farms.

Dynamics perspective

The presence of uncertainty and irreversibility is an important feature of the setting in which transgenics are considered. These characteristics suggest that the static nature of the above framework could be fruitfully extended to consider the timing of adoption, or equivalently, the dynamics of dominance of a technology or crop. The theory for this problem has been developed by Weaver and Wesseler (2003) and illustrated with simulation. In essence, the framework above defines a relative willingness-to-pay that can be viewed as a return in the current period if the innovation were adopted. Adoption involves investment, a cost that can be viewed as irreversible if rental and resale markets are incomplete or sticky. The nature of this investment will vary across transgenic crops, though as an example, adoption of transgenic soybeans may involve a change in equipment used for tillage, planting, herbicide treatment, and herbicide handling and storage. From the perspective of learning, investment will be necessary to facilitate adjustment of management practices. Further, as claimed by some, and based on a certain amount of evidence, it is possible that adoption of transgenics results in private or public irreversible benefits. These may involve benefits such as improved long-term weed control, reduced soil erosion, or reduced surface water pollution. In each case, these benefits may be private and local, or public and go beyond the boundaries of the farm.

Weaver and Wesseler (2003) consider the adoption decision within the context of uncertainty and irreversibility from a real options perspective. They find that under uncertainty, irreversibility, and flexibility the relative willingness-to-pay for the new technology will be smaller than in the deterministic setting considered above. Further, the decision to adopt is shown to be delayed as uncertainty increases, and as either irreversible costs increase, or irreversible benefits decrease. Importantly, they show that as irreversible benefits are emphasized relative to irreversible costs, adoption is accelerated. This clarifies the importance of balanced research that is unbiased in its consideration of irreversible benefits as well as costs.

Evidence from US Perspective

Past studies of adoption of GM crops have taken a static approach and have not considered the role of the incentive vector for competing technologies. More generally, these studies have been motivated most frequently by a theory of diffusion that presumes the innovation is universally dominant for a subset of producers. On this basis a ceiling or maximum adoption proportion is defined. As noted above, this is not likely to be the case for transgenic crops. Past work has identified six types of factors affecting adoption: farm characteristics (farm size, field characteristics), experience and knowledge of the technology, market conditions (price risk, profitability, cost and yield effects) and environmental implications (e.g. decreased use of pesticides). Farm characteristics such as farm size (measured by acres planted or total gross farm income) and farm-operator demographics (farmer’s age, experience, education), and tenure (share land owned) have been found to be statistically significant determinants; see Alexander, Fernandez-Cornejo and Goodhue

(2002). Their survey results show that farms with high total gross farm income and high education are more likely to adopt GM crops. Cameron (1999) found evidence of a role of accumulated knowledge of the performance of the GM crop that is consistent with learning theory. Market conditions such as the perceived ability to market GM crops, existence of premiums for non-transgenics, and consumer acceptance have been considered in surveys though not related to adoption. Perceived profitability has been decomposed into existence of unrealized cost savings (due to unsatisfied expectations), realized cost savings, premiums received, reduced pesticide cost, improved pest control and increased yield. Environmental factors such as perceived benefits from decreased use of pesticides to environment have also been considered; see Darr and Chern (2002). Results from past studies are summarized in Table 2 of Weaver and Kim (2002).

To close, results are presented for adoption of transgenic soybeans based on a static adoption model for a secondary state, Pennsylvania. Equation 3) motivates a probit model for this decision and results for a model of the adoption of transgenic soybean seed are presented in Table 2. Data are from a 1999 sample of Pennsylvania producers of soybeans based on the Agricultural Resource Management Survey (ARMS) implemented by the Pennsylvania Agricultural Statistics Service with funding from the National Agricultural Statistics Service, USDA. The survey includes information on the adoption of herbicide-tolerant soybean seeds, as well as an extensive set of data recording possible exogenous determinants of the adoption decision. Previous related studies include the Alexander, Fernandez-Cornejo and Goodhue (2002) consideration of Iowa GM corn, Darr and Chern's (2002) consideration of Ohio's soybean and corn experience from 1996 to 1999, and Fernandez-Conejo and McBride (2002).

Results reported in Table 2 are based on a data set of 158 observations. Descriptive statistics are reported in the right-hand side of this table. Given the observations are drawn from a common geographic region, the market environment across farm respondents can be assumed homogeneous and is not empirically described. About 46.6% of respondents cited increased yield as a reason for adoption of GM soybeans, 12.5% cited reduction in pesticide-input cost, 8.1% cited increased planting flexibility, and less than 1% cited perceived improvement in environmental effects of field practices as a reason, respectively. Eighty-two percent of respondents indicated farming as their major occupation. About 50.3% of respondents indicated farm gross value of sales between $50,000 and $250,000. Eighty percent of respondents had high school or less education. Respondents averaged 17.3 years of experience operating the farm. Over 76.6% of the respondents used post-emergence herbicides only, while 28.6% used pre-emergence herbicides. With respect to past experience with ht soy, only 5.6% of respondents planted ht soy the previous year (1998). Eighty-five percent of respondents indicated growing corn as the preceding crop to soybeans. While it would be of interest to explore the conditionality of adoption on use of no-till technology, data for this characteristic are not available for the sample and based on Fernandez-Conejo and McBride's results, its exclusion will result in inefficiency, though not bias estimates. However, data were available indicating whether tillage or cultivation was conducted in the soybean field for weed control during the growing season. Five point six percent of respondents indicated such a practice.

Results in Table 2 indicate that based on summary statistics, the model's fit can be interpreted as acceptable. Education level of the operator was found to have a

Table 2. Probit results
Adoption of transgenic soybeans Pennsylvania 1999 (=1)

Variable	**Definition & Type**	**(Mean, SD) Freq. %**	**Coefficient**	**t-stat**
Intercept			-1.51896	-4.65389**
Education	polychotomous =1 if < high school =2 if high school grad =3 if some college =4 if college grad =5 if grad school	 31.1% 50.3 9.3 7.5 1.9	-.07037	-1.48634
Gross value of sales	Polychotomous 1 if \$1k<x<\$2.5k 2 if 2.5<x<4.999 3 4 by \$5k intervals 5 6 7 if 25k<x<39.999 8 if 40k<x<49.999 9 if 50k<x<99.999 10 if100k<x<249.999 11 if 250k<x<499.999 12 if > \$500.000	 .6% .6 2.5 2.5 5.6 1.9 3.7 5.6 20.5 29.8 18.6 6.9	-.07104	-.14812*
Experience	Years as operator	(17.32 13.45)	.00296	.96726
GM used 1998	=1 if yes, =0 if no	5.6%	.01294	.31286
To increase yield	=1 if yes, =0 if no	46.6%	.51979	3.63506**
To decrease pesticide cost	=1 if yes, =0 if no	12.5%	.73090	4.30910**
To increase planting flexibility	=1 if yes, =0 if no	8.1%	.62445	3.51113**
Previous crop corn	=1 if yes, =0 if no	85.1%	-.31661	-2.48402**
Used pre-emerg herbicide	=1 if yes, =0 if no	28.6%	-.21260	-1.98350**
Used post-emerg herbicide	=1 if yes, =0 if no	77.6%	-.06791	-.45372
Major occup. 1= farm	1= farm, 2=hired manager, 3=other, 4=retired	82.0% 0 17.4 .6	-.01887	-.28994
Till/Cultivate	=1 if yes, =0 if no	5.6%	-.20075	-.95449

* Significant at 5% level; ** Significant at 10%.
Pearson goodness-of-fit chi square = 224.012 DF = 145 P = .000

negative, though statistically insignificant effect on adoption. Using a polychotomous indicator of gross value of crop sales as a measure of scale, the results indicate a negative relationship that is significant. Experience and occupation were both found insignificant. Past use of GM herbicide-tolerant seeds was found to be a positive factor though it is statistically insignificant. Use of tillage or cultivation during the growing season for weed control was found statistically insignificant. Estimates corroborate the low frequency of respondents reporting concern for environmental impacts as a motivation for adoption. Results indicate that hedonic factors played a key role. Specifically, an expectation of increased yield, decreased pesticide costs and increased planting flexibility were found to be positive and highly significant factors in predicting adoption. Use of pre-emergent herbicides was found to be a negative factor, as was previous planting of corn.

Overall the results confirm the importance of private economic performance as a determinant of GM soybean adoption. This is reflected in the significant role found for hedonistic rationale for adoption. Evidence was found that the technology is not scale-neutral, and a bias against large scale was found. Adoption was found to be strongly conditional on and negatively related to the previous crop being corn, perhaps reflecting continuous cropping of corn. Results emphasized the importance of perceived increase in yield as a factor that is interpretable as a hedonistic rationale, however, the interpretation of this result cannot go beyond yield increase given that no further explanation concerning the origin of such expected increases in yield was available. In general, increased yield could result from varietal performance, improved weed control, reduced plant suppression or damage due to herbicide intolerance, or increased seed density. The finding that planting flexibility and reduced pesticide costs also have a positive relationship with adoption is consistent with this interpretation.

While past work has focused on wide geographic areas, the results reported here are for a more geographically restricted area. It is also important to note that these results characterize a region in which soybeans are grown within a context of an agricultural system that is dominated by dairy farming with some limited animal feeding (beef and pork). Given that the predictions of physical science suggest that the appeal of GM soybeans will be field- and site-dependent, our results suggest that the economic appeal of this technology is dominant over substantial heterogeneity in field and site characteristics

Conclusions

At first consideration, US experience with respect to transgenic-crop adoption appears to suggest that this innovation involves a universally dominant technology motivating rapid adoption by all producers. However, at a deeper level it is clear that this type of innovation involves a multiple faceted technology, a complex set of changes in input mix, production practices and outputs. Further, the performance of the innovation is, in many settings, conditioned by local characteristics. This implies that the innovation is not universally dominant across the landscape of the US. This result is likely to hold for the E.U. as well. While the technology may be associated with public effects, either in the short term or irreversibly, results in hand do not suggest that these effects have been a driving force behind producer decisions to adopt. In this brief paper, an overview of representative results was presented, along with more recent results from the state of Pennsylvania where soybean cultivation has expanded. In this type of setting, transgenic crops may offer important flexibility in crop management as well as in efficiency of weed management. Empirical results reported here suggest that in this type of setting, producers remain focused on private net benefits associated with the technology as a determinant of their adoption decision.

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