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The Adoption and Diffusion of GM Crops in United States: A Real Option Approach

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The article aims at modelling adoption and diffusion decisions of farmers towards genetically modified crops under a real option framework. Modern GM crops help farmers to resolve two main sources of uncertainty: output uncertainty and input uncertainty. Those crops represent a revolutionary form of farming compared to the technology adoption studied in the literature in the late '70s and early '80s. The article develops a theoretical model of adoption and diffusion of new GM crops under uncertainty and irreversibility. We test our theoretical predictions using data from 2000 to 2008 of a panel dataset constructed for 13 US states involved in the production of four different GM crops. These conclusions may appear to contradict the general perception of a delayed penetration for the GM crops, whose success seems to be retarded by lack of information, mistrust, and an exaggerated perception of risks. GM crops tend to be invasive, in that their short-term profitability is so high as compared with the investment needed, that once the hump of uncertainty is overcome, they operate a veritable takeover of agriculture.

Key words: adoption, diffusion, uncertainty, irreversibility, real option.

Introduction

Genetically modified (GM) crop adoption has experienced an unprecedented rate of growth over the past 10 years. Worldwide, in 2008 there were 125 million hectares of land under GM crops, with nearly 25 countries adopting this new technology (James, 2008). The early adopters, namely the top eight countries, growing more than 1million hectares of land are the United States, Argentina, Brazil, India, Canada, China, Paraguay, and South Africa. Together they represent 98% of the 125 million hectares of land under GMOs, out of which 57% is located in North America, 32% in Latin America, 6% in India, 3% and 1.5% in China and South Africa, respectively. GM maize has been the major crop adopted by most of the countries. Since their introduction in 1996, GM crops exhibit a peculiar form of new technology, which could run counter the cases examined in earlier literature that has analyzed the adoption problem. The distinction between adoption and diffusion has emerged as a consequence of the problem of the sequential nature of farmers' decisions. In the traditional approach, because the innovative technology was divisible (improved seed, fertilizer, and herbicides), a farmer had to decide first how much land to cultivate under the new technology and then decide the amount of fertilizers and pesticides to use. Farm-level adoption was expressed as the degree of utilization of a new crop such as hybrid maize, and diffusion (or aggregate adoption) referred to extent of utilization of a technology (Feder, Just, & Zilberman, 1985; Just & Zilberman, 1983; Marra & Carlson, 1990; Rogers, 1962, 1983).

The dichotomy between adoption and diffusion can be explained by two main reasons. Whether the farmers' decisions are sequential or simultaneous, the empirical evidence has indicated that a time gap existed between adoption and diffusion. If, at the early stage of their introduction, social, cultural, economic, technical, and environmental factors (Jamison & Lau, 1982) explain low levels of adoption, it has also been observed that differences in access to and diffusion of information may be important determinants of adoption decisions (Aklilu, 1974; Ayana, 1985; Feder et al., 1982; Longo, 1990). Social networks are also of fundamental importance in order to understand different degrees of adoption. In rural economies, farmers within a group tend to share information and learn new agricultural practices from each other (Conley & Udry, 2000; Foster & Rosenzweig, 1995). The degree of adoption depends on the presence of "opinion leaders" in a community; these are people who appear to be more exposed to sources of information—such as mass media or change agents (e.g., extension workers)—have higher degrees of education, and have more income and wealth (Chatman, 1987; Rogers, 1995; Valente, 1996; Weimann, 1994). Diffusion depends on whether and how communication among farmers within the community occurs, and, in particular, whether individuals communicate more easily with people who are homophilic (similar from them) or heterophilic (different from them). The empirical evidence is ambiguous, with some pointing towards a major flow of information from higher-status rural groups to lower strata (Röling, Ascroft, & Wa Chege, 1976; Van de Fliert, 1993), while for others, the results are not straightforward (Feder & Savastano, 2006).

The duality adoption/diffusion that characterized the literature on new technology adoption during the 1980s and 1990s seems to be confounded when dealing with GM adoption. When farmers or countries have decided to adopt, they adopt and diffuse at an exponential rate. In this respect, the measure of diffusion in terms of the S-shape function is invalid. The statement that if *large* farmers adopt first, diffusion over a resource will occur more *quickly*, and that if *small* farmers adopt first, diffusion over a resource will occur more *slowly* fails to be endorsed by observations.

In this article, we look at the process of diffusion of GM crops by focusing on two unconventional characteristics of the new varieties—their extremely high short-run comparative advantage and the irreversibility of their adoption in the face of dynamic uncertainty—on the market for agricultural commodities on their long-term sustainability. By looking both at theoretical arguments and empirical evidence, we claim that, because of these two characteristics, GM crop diffusion can be best explained in a real option framework, as a succession of reluctances and eager waves of adoption.

The article is organized as follows. Next, we summarize the literature on adoption diffusion duality, then depicts the theoretical model of adoption and diffusion decisions under uncertainty and irreversibility. We then present the derivation of the conceptual framework underpinning the empirical work in the article, followed by the description of the data source and the empirical results. The last section provides conclusions and policy implications.

Adoption and Diffusion

The decision to adopt a new technology has been widely documented throughout the literature. From a general point of view, a decision maker will invest in a new technology if this helps reduce the causes of uncertainty he has to face and when the expected marginal benefits are larger than the costs he has to sustain. In this respect, modern GM crops help farmers resolve two main sources of uncertainty: output uncertainty and input uncertainty. By delivering the promise to increase the yield and reduce the amount of pesticides used, those crops represent a revolutionary form of farming compared to the technology adoption studied in the literature in the late 1970s/early 1980s. In those years, most studies focused on the benefits of introducing new technology such as hybrid maize into farming, where the main question was whether the higher fertilizer and pesticide requirement of the new crop was sufficiently offset by higher yields.

Since the pioneering works of Dillon (1971), and Anderson, Dillon, and Hardaker (1977), a substantial body of the literature has tried to formalize and rationalize the decision-making process of farmers who face imperfect knowledge (when there is uncertainty) and when the outcomes of those decisions are uncertain (that is, the farmers face risk). Despite the large number of studies on risk, uncertainty, and learning in the adoption of new technologies, there are two commonly observed theoretical and empirical regularities or "stylized facts" of new technology adoption: risk preferences would lead risk-averse farmers to postpone the adoption decision, and the succession of early and late adopters would result in the S-shaped adoption/diffusion curve.

On the one hand, the adoption of a new technology can be conceived as resulting from a fine balancing act between its profitability and the farmer's attitude towards the risk associated with it. An impressive set of empirical evidence among the early literature of new technology adoption, has shown that farmers in developing countries are risk averse and tend therefore to delay the decision to adopt a new technology (Antle, 1987; Binswanger, 1980; Dillon & Scandizzo, 1978; Moscardi & de Janvry, 1977). According to these studies, even a small uncertainty related to the increase in pesticide costs, as well as the higher prices of the seeds, could make small and risk-averse farmers delay the decision to adopt a new crop variety.

Farm size and land endowment are two other important diversifying factors affecting the decision to adopt a new technology. In the empirical studies, a positive relation between adoption and farm size is often found when food security is not a binding constraint, or when there are fixed transaction and information acquisition costs associated with the new technologies, therefore preventing smaller farms to engage in innovation (Feder et al., 1985; Feder & Just, 1980; Feder & O'Mara, 1981). Earlier studies (Cochrane, 1958; Reimund, Martin, & Moore, 1981; Schumpeter, 1942) and later ones (Cohen & Klepper, 1996) have embraced the S-shape theory of the adoption/diffusion curve. Other studies, however, have pointed out a negative relationship between farm size and technology adoption, mostly due to farmers' risk aversion and their tendency to follow a technological ladder in adoption. Studies have also focused on the relationship between farm size and adoption for size invariant traditional and size dependent technology (Fernandez-Cornejo, Klotz-Ingram, & Jans, 2000; Fernandez-Cornejo, Daberkow, & McBride, 2001). Some studies claim that farmers follow a stepwise approach (first improved seed, and then fertilizers; Byerlee & Hesse de Polanco, 1986; Kaliba, Featherstone, & Norman, 1997; Kaliba, Verkuijl, & Mangi, 2000; Norman, Worman, Siebert, & Modiakgotla, 1995), and that such an approach tends to delay technology adoption.

More than 50 years have elapsed since the first experiments and field trials of the hybrid maize (Shull, 1909—"inbred-hybrid maize"; Jones, 1916—"double-cross hybrid") replaced the overall area planted under "Open-pollinated variety" (OPV) maize in the late 1960s. In particular, 30 years had elapsed from the emergence of the first hybrid seed companies (late 1920s) to the development of the real hybrid seed industry. By 1960, hybrid maize completely replaced the area under OPV maize production in the United States.

Although maize did not experience the so-called green-revolution of rice and wheat, dating from 1960 onward improved crop varieties (such as hybrid maize, rice, and wheat) started to be introduced in developing countries. The degree of adoption and dissemination of these modern technologies varied across and within countries, with differences due to size of the farm, risk attitudes, cash liquidity in order to buy fertilizers, geographical locations, and so on.

In the United States, less than 15 years have elapsed since the first development of genetically modified Roundup Ready soybeans became commercially available, followed by Roundup Ready corn in 1998. By 2008, GM corn accounted for 85% of the 35.3 million hectares in the United States (James, 2008; Fernandez-Cornejo & Jiayi, 2005), with roughly 78% constituted by hybrids with either double- or triple-stacked traits, and only 22% by hybrids with a single trait.

The speed of the adoption rate, as well as dissemination, has been multiplied by 3. It took only a few years to bring GM crops to their complete maturity stage (that is, to the stage where GM crops are completely commercial) and are the predominant technology available to farmers.

Three main types of GM crops are today available: first, second, and third generations. The major commercial GM crops are first generation. These crops possess enhanced input traits modified for herbicide tolerance and insect resistance (James, 2003). Since their commercial introduction in 1996, they delivered the double promise of increasing agriculture yields and reducing farmers' operating costs, thereby fighting against the two main sources of uncertainty of agricultural operation. They thus appear to benefit farmers by lowering production costs, improving crop yields, and reducing the level of pesticides required for the control of insects, diseases, and weeds. Although their buoyancy in the first years of cultivation seems to be followed by a less spectacular performance in the later years, once adoption starts, the process of diffusion seems to proceed with an impetus unmatched by any previous experience with improved crop varieties. In particular, after an initial period of resistance (which seems to be based on uncertainty and risk aversion), their diffusion is not limited to replacement of previous crops of the same type, but it has the characteristic of a true takeover, using all potential land—including pastures and forests—that can be converted to their cultivation.

Diffusion and Adoption

The twin concepts of diffusion and adoption characterize the debate on the spread of technology and the role of innovation in the evolution of economic systems. One of the most clarifying models is due to Rogers (1962, pp. 79), who defines diffusion as "the process by which an innovation is communicated through certain channels over time among the members of a social system." According to Rogers (1962), diffusion is characterized by five stages: awareness, interest, evaluation, trial, and adoption. Thus, according to this interpretation, adoption is the final step of the diffusion process and is part of decision making, "i.e., not only is it merely a component of diffusion, but it also characterizes the moment at which the decision maker acts to make the spread of technology happen."

While this interpretation of diffusion and adoption appears to be generally shared by the subsequent literature, its operational validity hinges on its capacity to support a system of measurements. On one hand, in fact, diffusion seems to call for a measure directly related to the pervasiveness reached by technology over a given territory or population. On the other hand, adoption itself appears to be related to such a spread, even though its implicit reference to actions taken by individual agents calls for going beyond the mere coverage of the territory, to take into account some subjective element linked to the act of choice.

In this article, we propose a definition of diffusion and adoption that incorporates the idea—already present in Rogers (1962) and in most of the subsequent literature—that adoption and diffusion are two related processes referring respectively to collective spread and individual choice. More specifically, we propose to consider **adoption** as the decision on the part of the individual farmer to adopt innovation under the influence of acquired information on the new technology and a host of exogenously determined variables such as farm size, land tenure, and education as well as idiosyncratic differences across farmers. We thus consider adoption, in line with the standard microeconomic model, as determined at the farm level by decisions conditioned by exogenous variables (relative profitability of the technology). We instead propose to define **diffusion** as the endogenous process by which individual adoption decisions influence each other and coalesce, thus causing the endogenous determination of the spread of the new technology. This spread is a process that, while initially relying on motivated adoption decisions, at some point claims its own momentum, based on interdependent activities, such as imitation, collective (herd) behavior, and external effects, such as marketing and transportation economies. In the case of GM crops, other, possibly irreversible phenomena (like contamination, gene flows, and the demise of suitable traditional varieties) may also be at play. The causal structure of diffusion thus may go far beyond the individual factors motivating adoption, and its spread may extend to areas previously used by other cultures, forestry, or pasture, thus becoming a process of agricultural frontier advance or colonization.

These definitions, in addition to being intuitively appealing, are useful for measurement purposes because they correspond respectively to a measure of the intensity and the determining factors of the taking up of the technology by each individual (adoption) and to the extension of the new technology over a given territory or population over a given interval of time. This means that, as in Dawkins' famous account (1976) on genes and memes, adoption and diffusion can be conceived as the two processes whereby farmers are used by a technology as vehicles for taking over specific farm activities first, then whole farms, and finally entire territories.

Irreversibility of GM Crops

GM crop adopters may be concerned with irreversible effects both from adoption and from diffusion. Irreversibility from adoption is associated to both costs and benefits. It may originate in the sunk costs sustained to switch from the traditional to the new technology by individual farmers. These costs include information, experimentation, land preparation, various types of investment, and transaction costs. Even though it may appear that farmers may switch back and forth from traditional to GM varieties without significant costs, at least five factors tend to render the costs involved in these types of action difficult to recover. First, for most crops, farmers must decide to use GM varieties corn before they know what the pest pressure (from insects or weeds) will be that year, with damage varying stochastically from year to year. When farmers incorrectly forecast infestation levels, prices, and/or yield losses due to pest infestations, this results in non-recoverable "overadoption" or "underadoption" costs. Second, significant sunk costs are associated with learning and experimenting with the new technology. In most cases, the GM seed requires special care, a different input mix from the traditional seed, and new patterns of supervision and control. Third, in many cases, to the extent that they allow the introduction of new crops or the extension of farming to unused land or pasture, GM crops require some investment in the farm; this may include land preparation, irrigation, terracing, the acquisition of machinery, etc. Fourth, effects from adoption and diffusion may cause losses in biodiversity; development of resistance to insects, viruses, and weeds; and, through gene flow to non target wild species, irreversible effects on the biological equilibrium. Irreversible benefits may also occur (i.e., reduced negative effects in comparison to the counterfactual), such as gains in human health due to reduced poisonings from pesticide use and gains in biodiversity from reduced pesticide use (Wesseler, Scatasta, & Nillesen, 2007).[1] Finally, irreversible effects may be present or feared on the consumption side

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[1] *For example, GM opponents(see http://www.bangmfood.org) claimed that the following irreversible effects could be feared from GM introduction.*

GM could create foods that are toxic, allergenic, and less nutritious than their non-GM counterparts.

GM crops could damage vulnerable wild plant and animal populations and harm biodiversity.

GM plants cannot be recalled, but as living organisms will multiply, passing any damaging traits from generation to generation.

GM crops could cause irreversible changes to our food supply, with serious effects on the environment and human and animal health.

(Kikulwe, Wesseler, & Falck-Zepeda, 2008) and reverberate on producers, who may be concerned that the new products would not be accepted.

The fact that GM crops are associated with dynamic uncertainty depends both on these possible irreversible effects and on the informational nature of uncertainty. Because external effects that might occur through cross pollination and pest resistance are largely educated guesses based on preliminary evidence, whether these worries are justified can only be established through further experience and, paradoxically, by experimenting a degree of diffusion. Thus, while the waiting option has a clear value, some of the information needed can only be obtained by exercising the option itself. The existence of irreversible benefits (Demont, Tollens, & Wesseler, 2004; Wesseler, 2009) gives further strength to the idea that the key uncertainties are involved and can only be resolved by carefully comparing the net benefits from "learning and then act" with those of "act, learn, and act."[2] The input-intensive nature of the new technologies have also ingenerated the doubt that GM diffusion may constitute yet another step in the commoditization of agriculture, progressively and irreversibly deprived of its sacral and cultural traditions of environmental care and primary food provider (Scandizzo, 2009).

Income generation through the new biotechnology is thus characterized by a stochastic trend and by increasing variance, since diffusion tends to increase unevenly over time. This occurs because as diffusion goes on, a larger and larger number of micro-processes coalesce in determining the degree of acceptance of producers and consumers and the behavior of market operators, seed-producing firms, and other actors in the field. As a consequence, Brownian motion appears to be the best way to represent the GM diffusion process and, because of the irreversibility involved, real option theory suggests itself as a useful way to model the intricacies and discontinuities of adoption decisions. In this respect, it is interesting to consider the case of GM crops as a situation where, being confronted with fixed entry costs under uncertainty, adopters would adjust discontinuously to the availability of the new technology and the flow of new information, by acting on adoption only when appropriate levels of understanding and entry costs appear to be reached. Thus, GM adoption is a typical case of the "economics of inaction" illustrated in a recent volume by Stokey (2009), whereby phenomena of decision making under uncertainty and fixed costs can be considered as intrinsically characterized by areas of hysteresis and thresholds of action.

A Theoretical Model for Diffusion and the Rate of Adoption

Assume that the GM technology, as a new source of wealth for farmers, is exogenous and stochastic. Specifically, both the average income Q earned from biotechnology innovation (BTI) and its variance tend to increase over time, as the result of the many concurring factors resulting from demand volatility, the experimental nature of the crops, the diversity of the terrain, the population where the diffusion occurs, etc. In particular, income from BTI is assumed to be a random variable following a diffusive stochastic process of the Brownian motion variety

$$dQ = \alpha Q dt + \sigma Q dz, \tag{1}$$

with dz being a random variable with mean 0 and variance equal to dt. The units of measure of Q are in terms of yield equivalents (e.g., tons of produce per ha of land), and the parameters α and σ^2 represent the drift or trend in income and the variance, respectively. Individuals (depicted by the subscript i) obtain income y_i, assumed for simplicity to be proportional to price P multiplied by yield Q and the area under GM crops, N_i.

$$y_i = PN_i\, Q \tag{2}$$

The individual obtains a share w_i of GM area (i.e., $N_i = w_i\, N$) and therefore can obtain w_iQ of innovative activity, where Q is the yield earned per unit of activity of the i^{th} farm. Because of the fact that traditional technology may entail different levels of inputs depending on technological know how and risk aversion, individuals are heterogeneous in their ability to obtain an income x_i from the traditional crops, but not for the GM crop.

$$x_i = Pv_iG_i\,;\, y_i = PQN_i\,, \tag{3}$$

where v_i is the yield of the traditional crop, $G_i = \omega_i G$ is the area of traditional crop, and N_i is the area of GM crop from the i^{th} farm. Both yields are assumed to be independent of the farm size of operation. In each period, the farmer can sell or buy land services S_i at the price p, and this may include purchasing or selling land

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[2] *With regard to the scepticism that some scholars still demonstrate on irreversible effects of the GM technology and the "complications" and the variety of assumptions involved in the use of real options, see Wesseler (2009).*

to other farmers as well as developing new farm land from alternative previous uses, such as forests and pastures. The price of land p thus summarizes average costs to bring additional land into farm production, including investment and opportunity costs from alternative uses according with a land supply function of a given elasticity. The land farmed by each farmer respects the constraint $S_i = \omega_i G + w_i N$, where $\omega_i = G_i / G$ and $w_i = N_i / N$.

The i^{th} farmer faces the dual problem to determine the size of his farm and to distribute his farm land between the two technologies by trying to maximize his extended net present value (ENPV) according with the expression

$$\max_{w_i} ENPV_i = \frac{1}{\delta}[(P-c)v_i(S_i - w_i N) + (P-k)w_i NQ - pS_i] + w_i NI - B_i Q^{\beta_1}. \tag{4}$$

In Equation 4, $\delta = \rho - \alpha$, while I represents the investment that is necessary to undertake in order to adopt the new technology. $B_i Q^{\beta_1}$ is the waiting option[3] corresponding to the investment in the new technology according to the following value matching condition.

$$B_i Q^{\beta_1} = \frac{1}{\delta}[(P-c)v_i(S_i - w_i N) + (P-k)w_i NQ - pS_i] - w_i NI \tag{5}$$

Maximizing with respect to farm size brings the farmer to seek the equality between the net marginal product of land and land price. Thus, in the initial situation, with no GM adoption, the expected net present value (NPV) of the traditional technology can be expected to be greater than the opportunity cost of land, the difference reflecting rents from the fixity of land and other transaction costs.

From the point of view of the GM crop, however, we face a completely different situation for two major reasons. First, adoption requires an irreversible investment,[4] both because of irrecoverable costs and because the new varieties tend to spread outward in ways that cannot be reversed (Beckmann, Soregaroli, & Wesseler, 2006). Even though some of these costs have a social rather than private nature, it is reasonable to assume that they will be internalized, to a degree, by each farmer through social pressure, information, Coasian bargaining with other farmers, and the belief that any irreversible damage to the environment may itself jeopardize future profits. Second, crop profitability is uncertain because of lack of sufficient information on performance and risks (yields follow a stochastic process). Maximizing Equation 4 with respect to the farmer's share of the GM crop, therefore, under the stochastic constraint in Equation 5, we find that the choice of the area under the GM crop that would maximize the ENPV is

$$w_i^* = \frac{\beta_1[(P-c)v_i - p]S_i}{N\beta_1[(P-c)v_i + I\delta] - N[(\beta_1 - 1)(P-k)Q]} \tag{6}$$

This choice corresponds to what can be defined as "adoption," i.e., the level of technological development at which the i^{th} farmer will decide to enter the new technology. Such a level will depend on his exposure and information to it, and can be quantified by his share (w_i) of the total GM area. As already noted, before the process of adoption starts, net margins per ha of the traditional technology can be expected to exceed the opportunity cost of land (i.e., either the cost of developing new land or renting it). This means that the numerator in Equation 6 will be positive. At the same time, the NPV of the cash flow per ha expected from the traditional crops may be expected to exceed the NPV per ha of GM crops since this includes investment costs, and expected yield from the stochastic process is still low and more uncertain. Here, the drift of the stochastic process ruling the GM yield incorporates both the tendency of yield to grow with more experience in cultivation (at

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[3] *The term* $B_i Q^{\beta_1}$ *measures the value of the option to wait, or to undertake the investment in the future and* β_1 *is the positive root of the characteristic equation* $\rho - \beta\alpha - \frac{1}{2}\beta(\beta - 1)\sigma^2 = 0$, *which ensures that the level of Q is chosen according to the dynamic optimization criterion.*

[4] *We refer here to net irreversible costs, i.e., irreversible costs minus irreversible benefits. Under the assumption that the social incremental reversible benefits follow a continuous time continuous state process, it can be demonstrated (Wesseler et al., 2007) that GM crops should be released at the point in time where the current social incremental reversible benefits are greater than the difference between the net social incremental irreversible costs, weighted by the size of the uncertainty and flexibility associated with the adoption of a new technology (or hurdle rate). The hurdle rate is commonly expressed in the form β/(β-1), where β>1 captures the combined flexibility, irreversibility, and uncertainty effect (Demont, Wesseler, & Tollens, 2004).*

least from the first, buoyant years that characterize most GM crops) and consolidation of (not necessarily founded) farmers' expectations of higher and growing yields for the future. After a period of cautious experimentation, however, once the level of Q is reached for which adoption becomes convenient (i.e., expected NPV from the new technology exceeds the NPV for the old one even after adjusting for uncertainty and investment costs), the price of land p will be driven above marginal productivity per ha of the traditional crops. Both the numerator and the denominator of Equation 6 will thus see their signs reversed and the substitution of the new for the old technology will become total when the following equality is reached.

$$\frac{\beta_1}{\beta_1 - 1}(p + \delta I) = (P - k)Q \tag{6a}$$

At this point, all farms will also have totally adopted the new technology. Because GM yield continues to grow, however, Equation 6a denotes a movable bound, as the price of land will continue to increase under the push of the new technology. Thus, the process of diffusion will not be complete until all available land has been drawn into the new technology and the price of land has risen to the point where no increase in expected GM yields will be capable to bring new land into culture.

To summarize, with zero adoption rate, the numerator of Equation 6 will be greater or equal to 0 (the net margins per ha of the traditional technology are greater than the cost of land services). When the threshold of profitability of the new technology is reached, however, the price of land will start being driven up by growing GM expected yields, and soon the price of land will exceed the marginal product of the traditional crops. Land will be progressively shifted toward GM crops, but it will soon generate a race between the accelerating price of land services and the increase in GM yields. The adoption process will be slowed down by uncertainty and accelerated by GM yield increases. While land prices are sufficiently low, however, the two technologies may coexist; in this case, the GM share will be higher given that GM yield Q is higher, related net margins $P - k$ are higher, the cost of land services (and other land-augmenting inputs) is lower, and the profitability of the traditional technology is lower. In this intermediate stage, as can be seen by differentiating *w.r.t.* to β_1, the optimal share w_i increases with the value of this parameter[5] and thus decreases with uncertainty and irreversibility (since $\beta_1$is negatively related to the variance of the stochastic process and positively related to the discount rate as the opportunity cost of any effect that cannot be time-reversed).

To find the total number of ha N under the GM crop, we recall the condition $\sum w_i = 1$, where the sum is over all farms involved in the adoption process. Performing this sum in Equation 6 and solving for N, we obtain

$$\frac{N}{S} = \frac{(P - c)\bar{v}_s - p}{(P - c)\bar{v}_n - [\frac{(\beta_1 - 1)}{\beta_1}\bar{(}P - k)Q - I\delta]}, \tag{7}$$

where $\bar{v}_s = \sum \frac{S_i}{S} v_i$ and $\bar{v}_n = \sum w_i v_i$ denote the average yields of traditional crops on total land and on the land devoted to the new technology, respectively.

Equation 7 shows how the diffusion and adoption mechanisms differ. While the individual shares (i.e., the level of adoption) depend only on exogenous variables, some of which vary idiosyncratically across farmers (e.g., the distribution of farm size and the yield of the traditional crops), the total area under GM crops depends on adoption from a plurality of farmers and thus, endogenously, on the distribution of the individual farm areas between the new and the old technology. Note that $\frac{N}{S}$ is equal to 1 only when all farmers have adopted, but for less than full adoption, diffusion will be larger (i.e., $\frac{N}{S}$ will be closer to 1), and the closer the NPV of the new technology will be to the aggregate opportunity cost for switching from the old to the new technology.

$$(P - k)Q = \frac{\beta_1}{\beta_1 - 1}[(P - c)(\bar{v}_n - \bar{v}_s) + p + I\delta] \tag{7a}$$

The first term in square brackets in Equation 7a is negative if the farmers that adopt the new technology are, on average, less productive with the old technology. This seems reasonable, under most circumstances, since the first adopters would be those that gain most, *ceteris paribus*. Thus, diffusion will be faster, the more diversified the farmers are in their ability to increase incomes by using the old technology.

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[5] *The derivative equals* $\frac{dw_i}{d\beta_1} = [(P - c)\, v_i - p]\, S_i$ *and is greater than zero if the traditional crop is grown on the* i^{th} *farm.*

From Equation 6 we can also derive the value for the equilibrium price p of land services by applying the constraint of the total land available $S = \sum S_i$. Assuming a constant elasticity supply function for land $S = S_0 p^{\eta}$, we find that at full adoption land will be drawn into cultivation at the average rate

$$\frac{dS}{dt} = \eta\alpha\,(\beta_1 - 1)(P - k)Q, \tag{8}$$

where we have applied $EdQ = \alpha dt$ from the definition of the stochastic process in Equation 1.

To summarize, our analysis shows that for a given price of land, the adoption rate of the individual farmer will depend in principle on how profitable the GM crop is as compared to the traditional crops. For a sufficiently higher differential profitability, all farmland will be devoted to GM crops. The process of diffusion, however, will cause land prices to rise, and new land will be drawn into cultivation. A race between the yield increases spurned by new technology and land prices will ensue with uncertain results, since the apparent ever-increasing character of GM economic profitability will result in a progressive takeover of a whole variety of other land uses, including pastures and forests.

Some Empirical Evidence

From Equation 6, we obtain the following estimable equation for the rate of adoption.

$$w_i = f(\underset{+}{N}, \underset{+}{S}, \underset{+}{P}, \underset{-}{p}, \underset{+}{c}, \underset{-}{k}, \underset{-}{\sigma^2}, R) + u_i, \tag{9}$$

where we have introduced the variable R to indicate (in addition to variance) the perceived level of risks that may affect the farmers' decisions. In Equation 9, u_i is a well-behaved random disturbance and the symbols under the variables indicate the expected pattern of signs. While we do not have farm-level data to estimate Equation 9, we have data of adoption at the level of each US state for 5 years. We can thus rewrite Equation 9, denoting time with the subscript t, as

$$\psi_{jt} = \sum_{i=1}^{n_j} w_{it} = g(\underset{+}{N}, \underset{+}{S}, \underset{+}{P}, \underset{-}{p}, \underset{+}{c}, \underset{-}{k}, \underset{-}{\sigma^2}, R) + \sum_{1=1}^{n_j} u_{it}. \tag{10}$$

Because total land at the state level can be considered also a measure of diffusion of the new technology, by a simple transformation of Equation 10, we can also specify a "diffusion" equation of the following form.

$$\begin{aligned} N_{jt} &= \psi_{jt} N_t = N_t \sum_{i=1}^{n_j} w_{it} \\ &= h(\underset{+}{S}, \underset{+}{P}, \underset{-}{p}, \underset{+}{c}, \underset{-}{k}, \underset{-}{\sigma^2}, R) + V_{jt}\ , \end{aligned} \tag{11}$$

where N_{jt} denotes the area under the GM crop considered in the j^{th} state in the t^{th} year, and V_{jt} is again a well-behaved random disturbance.

Data Sources

We make use of a panel dataset built upon a set of different sources. Data for GM crop adoption are drawn from the US Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) survey from 2000 to 2008 for 13 states of the United States involved in the production of four different GM crops: Bt and herbicide tolerant (HT) corn, all genetically engineered (GE) corn, and HT soybean. Additional state-level and aggregate data for the same period are drawn from the Economic Research Service (ERS) of the USDA. In particular, for each traditional crop we have state-level information on total area harvested, price per unit of crop, whereas, at the US level, our analysis includes time series on index of fuel, herbicides, insecticides, and fertilizers. We complement our analysis with geographical dummies, and variables on yearly news about GMOs constructed from "Google News." Finally, we have computed a time-series variable on the number of GM permits approved by USDA's Animal and Plant Health Inspection Service (APHIS).

To analyze the effect of uncertainty on GM crop adoption and diffusion, we ran two types of regressions. The first regression was the log difference of the area allocated to each GM crop and the total area in the United States. This will test the adoption rate by each state. The second regression was on the adoption, namely the amount of area allocated to each GM crop by state in every year.

We have two measures of uncertainty. The first is the variance of the area under each GM crop in the United States over the period 1996 to 2008. Data at the state level are only available between 2000 and 2008, and computing state-level variance would have reduced the length of the panel. For each year, beginning with 2000, uncertainty proxy is computed as the variance of the residual of an OLS on time between t and $t - t_0$. The second proxy of uncertainty is represented by the parameter $\frac{\beta_1}{\beta_1 - 1}$, applying specific values to $\rho - \delta$ (the percentage

Table 1. Bt corn adoption and diffusion.

	(1)	(2)	(3)	(4)
	OLS on log area Bt corn state *i* = Diffusion	**OLS on log area Bt corn state *i* = Diffusion**	**OLS on log area Bt corn state *i* - log total area Bt corn in United States = Adoption**	**OLS on log area Bt corn state *i* - log total area Bt corn in United States = Adoption**
Var log area US Bt corn (detrended)	-0.046		-0.481***	
	(0.83)		(8.68)	
($\beta/(\beta$ - 1)) of Bt corn		4.640		48.638***
		(0.83)		(8.68)
Log share of farm in the state relative to United States	-0.128*	-0.128*	-0.128*	-0.128*
	(1.65)	(1.65)	(1.65)	(1.65)
Log total area of corn harvested	0.025***	0.025***	0.025***	0.025***
	(6.22)	(6.22)	(6.22)	(6.22)
Log price per unit	-0.016	-0.016	-0.016	-0.016
	(0.54)	(0.54)	(0.54)	(0.54)
Log # permit approved	-0.037	-0.062	-0.025	-0.285***
	(0.64)	(0.75)	(0.43)	(3.45)
Log index of fertilizer prices paid	0.046	-0.016	-1.228***	-1.879***
	(0.34)	(0.10)	(9.14)	(12.25)
Log index of fuel prices paid	-0.017	-0.042	0.443***	0.177**
	(0.23)	(0.50)	(5.92)	(2.07)
Log index of herbicide prices paid	0.022	0.000	-0.170*	-0.405***
	(0.23)	(0.00)	(1.72)	(3.62)
Log index of insecticide prices paid	0.002	0.160	1.752***	3.399***
	(0.02)	(0.52)	(11.11)	(11.07)
Log # of pages on Google news GM crops adoption	-0.005	-0.005	0.034***	0.034***
	(0.65)	(0.65)	(4.50)	(4.44)
Log # of pages on Google news GM corn adoption health risk	0.002	0.000	-0.031***	-0.046***
	(0.43)	(0.03)	(8.06)	(11.23)
Dummy Northern Crescent Region	1.063	1.063	1.063	1.063
	(1.51)	(1.51)	(1.51)	(1.51)
Dummy Northern Great Plains region	-0.606	-0.606	-0.606	-0.606
	(0.59)	(0.59)	(0.59)	(0.59)
Dummy Prairie Gateway region	0.597	0.597	0.597	0.597
	(0.84)	(0.84)	(0.84)	(0.84)
Observations	117	117	117	117
Number of states	13	13	13	13
R-square within	0.32	0.32	0.99	0.99
R-square between	0.87	0.87	0.87	0.87
R-square overall	0.32	0.32	0.99	0.99

Source: Authors' computation on NASS, ERS, and APHIS data
Absolute value of z statistics in parentheses
** significant at 10%; ** significant at 5%; *** significant at 1%*

growth of farm revenue that the holder of the option is foregoing) in order to keep alive the option to invest in GM crops. As shown in the previous section, this measure becomes larger when the variance is smaller and the discount rate adjusted for the stochastic trend is higher. It can thus be considered a combined measure of the degree of uncertainty (the variance component) and the economic damage caused by irreversibility (the relative weight of the present with respect to the future expressed by the discount rate).

Empirical Results

Tables 1-4 present our results from the application of Equations 10 and 11 to the database mentioned. While

Table 2. HT corn adoption and diffusion.

	(1)	(2)	(3)	(4)
	OLS on log area HT corn state *i* = Diffusion	**OLS on log area HT corn state *i* = Diffusion**	**OLS on log area HT corn state *i* - log total area HT corn in United States = Adoption**	**OLS on log area HT corn state *i* - log total area HT corn in United States = Adoption**
Var log area US HT corn (detrend)	-1.610		-7.479***	
	(1.22)		(5.66)	
($\beta/(\beta$ - 1)) of HT corn		2.342		10.877***
		(1.22)		(5.66)
Log share of farm in the state relative to United States	-0.086	-0.086	-0.086	-0.086
	(1.09)	(1.09)	(1.09)	(1.09)
Harvested	0.021***	0.021***	0.021***	0.021***
	(5.28)	(5.28)	(5.28)	(5.28)
Log price per unit	-0.020	-0.020	-0.020	-0.020
	(0.71)	(0.71)	(0.71)	(0.71)
Log # permit approved	0.084	0.105	0.881***	0.979***
	(1.05)	(1.09)	(11.00)	(10.21)
Log index of fertilizer prices paid	0.140	0.074	-1.392***	-1.698***
	(1.02)	(0.59)	(10.16)	(13.47)
Log index of fuel prices paid	-0.080	-0.059	0.407***	0.504***
	(0.91)	(0.75)	(4.62)	(6.40)
Log index of herbicide prices paid	-0.073	-0.071	-0.539***	-0.532***
	(0.52)	(0.51)	(3.86)	(3.84)
Log index of insecticide prices paid	0.105	0.167	2.401***	2.692***
	(0.49)	(0.65)	(11.25)	(10.47)
Log # of pages on Google news GM crops adoption	-0.001	0.004	0.101***	0.123***
	(0.09)	(0.46)	(14.87)	(13.81)
Log # of pages on Google news GM corn adoption health risk	0.004	0.001	-0.037***	-0.047***
	(0.95)	(0.38)	(9.90)	(12.98)
Dummy Northern Crescent Region	1.202*	1.202*	1.202*	1.202*
	(1.68)	(1.68)	(1.68)	(1.68)
Dummy Northern Great Plains region	0.063	0.063	0.063	0.063
	(0.06)	(0.06)	(0.06)	(0.06)
Dummy Prairie Gateway region	0.724	0.724	0.724	0.724
	(1.00)	(1.00)	(1.00)	(1.00)
Observations	117	117	117	117
Number of states	13	13	13	13
R-square within	0.52	0.52	0.99	0.99
R-square between	0.79	0.79	0.79	0.79
R-square overall	0.52	0.52	0.99	0.99

Source: Authors' computation on NASS, ERS, and APHIS data
Absolute value of z statistics in parentheses
** significant at 10%; ** significant at 5%; *** significant at 1%*

the results on the diffusion variable appear weak, those on the adoption variable (the share of land) are mostly significant and show all the expected signs.

Uncertainty over GM crops is more a matter of adoption rather than diffusion. As the figure of the pattern of Bt corn development shows, once farmers adopt this new type of crop, the rate of diffusion may be fast and follow the traditional S-shape curve of technology diffusion (Figures 1 & 2).

The coefficient of the uncertainty proxies (variance and beta parameters) reflects the negative relationship between adoption and objective risk. In addition to that, to take into account the uncertainty associated with health risk of GMO, we have included a variable that

Table 3. All GE corn.

	(1) OLS on log area all GE corn state *i* = Diffusion	(2) OLS on log area all GE corn state *i* = Diffusion	(3) OLS on log area all GE corn state *i* - log total area all GE corn in United States = Adoption
Var log area US Bt and HT corn (detrend)	-0.114 (0.89)		-401.264*** (3.60)
($\beta/(\beta$ - 1)) of all GE corn		2.360 (0.89)	
Log share of farm in the state relative to United States	-0.015 (0.14)	-0.015 (0.14)	141.611*** (4.11)
Log area harvested	0.026*** (5.28)	0.026*** (5.28)	-6.023*** (3.41)
Log price per unit	-0.029 (0.91)	-0.029 (0.91)	-250.558*** (38.46)
Log # permit approved	-0.051 (0.90)	-0.064 (0.95)	-330.352*** (9.01)
Log index of fertilizer prices paid	0.129 (0.88)	0.078 (0.51)	
Log index of fuel prices paid	-0.050 (0.61)	-0.066 (0.78)	-459.855*** (27.53)
Log index of herbicide prices paid	0.036 (0.33)	0.020 (0.17)	1,348.944*** (15.91)
Log index of insecticide prices paid	-0.057 (0.34)	0.063 (0.24)	-204.158* (1.87)
Log # of pages on Google news GM crops adoption	-0.009 (1.08)	-0.008 (1.04)	-5.498** (2.08)
Log # of pages on Google news GM corn adoption health risk	0.004 (0.92)	0.003 (0.61)	-3.099*** (7.74)
Dummy Northern Crescent Region	1.145 (1.28)	1.145 (1.28)	-958.918*** (3.33)
Dummy Northern Great Plains region	0.365 (0.24)	0.365 (0.24)	-1,378.572*** (2.78)
Dummy Prairie Gateway region	0.377 (0.44)	0.377 (0.44)	811.690*** (2.95)
Observations	117	117	117
Number of states	13	13	13
R-square within	0.47	0.47	0.75
R-square between	0.76	0.76	0.52
R-square overall	0.47	0.47	0.75

Source: Authors' computation on NASS, ERS, and APHIS data
Absolute value of z statistics in parentheses
** significant at 10%; ** significant at 5%; *** significant at 1%*

summarizes the Google page encompassing the words "adoption + GM crop + health risk." As expected, there is a negative relationship between adoption and the news, pointing towards an increasing reluctance to adopting before uncertainty is resolved. The coefficient of the remaining variables confirms the theoretical expectations of a supply function estimation. In particular, supply of GM crops increases land area under crop cultivation with the price of the input trait of the GM crop, while it decreases with the price of any other input used.

With reference to the $\beta/(\beta - 1)$parameter, significant effects are measured for Bt corn and HT corn adoption but not for HT soybeans, and for HT soybean diffusion but not for Bt corn and HT corn. Since this parameter depends negatively on the volatility of the underlying

Table 4. HT soybean adoption and diffusion.

	(1) OLS on log area HT soybean state *i* = Diffusion	(2) OLS on log area HT soybean state *i* = Diffusion	(3) OLS on log area HT soybean state *i* - log total area HT soybean in United States = Adoption	(4) OLS on log area HT soybean state *i* - log total area HT soybean in United States = Adoption
Var log area US HT soybean (detrend)	-0.026**		-208.307	
	(2.39)		(1.33)	
(β/(β - 1)) of HT soybean		0.653**		
		(2.39)		
Log share of farm in the state relative to United States	-0.001	-0.001	0.455	-0.145
	(0.44)	(0.44)	(0.03)	(0.02)
Log area harvested	0.012***	0.012***	-0.543	0.121
	(19.15)	(19.15)	(0.14)	(0.05)
Log price per unit	0.000	0.000	0.912	4.479
	(0.11)	(0.11)	(0.15)	(1.18)
Log # permit approved	-0.001	0.001	-185.511***	-12.080
	(0.18)	(0.30)	(3.26)	(0.69)
Log index of fertilizer prices paid	0.001	-0.007	195.955***	312.617***
	(0.25)	(1.55)	(4.05)	(10.17)
Log index of fuel prices paid	-0.004	-0.006**	-186.266***	-39.953**
	(1.60)	(2.00)	(4.89)	(1.99)
Log index of herbicide prices paid	-0.004	-0.008		-935.842***
	(0.51)	(0.87)		(12.41)
Log index of insecticide prices paid	0.011	0.030	-390.843***	328.499***
	(0.88)	(1.56)	(3.97)	(4.60)
Log # of pages on Google news GM crops adoption	-0.000	0.000**	-28.675***	-34.260***
	(0.26)	(2.32)	(8.23)	(19.48)
Log # of pages on Google news GM corn adoption health risk	-0.000	-0.000*	10.072***	16.957***
	(0.19)	(1.84)	(6.85)	(17.01)
Dummy Northern Crescent Region	0.030	0.030	-24.502	11.439
	(0.32)	(0.32)	(0.04)	(0.03)
Dummy Northern Great Plains region	0.078	0.078	-26.467	33.233
	(0.81)	(0.81)	(0.05)	(0.09)
Dummy Prairie Gateway region	0.198**	0.198**	-44.646	25.330
	(2.16)	(2.16)	(0.08)	(0.07)
Observations	117	117	117	117
Number of states	13	13	13	13
R-square within	0.85	0.85	0.73	0.89
R-square between	0.98	0.98	0.53	0.49
R-square overall	0.85	0.85	0.73	0.89

Source: Authors' computation on NASS, ERS, and APHIS data
Absolute value of z statistics in parentheses
** significant at 10%; ** significant at 5%; *** significant at 1%*

process and positively on the discount rate,[6] it can be considered a measure of the degree of dynamic uncertainty, i.e., of the uncertainty arising from the fact that the volatility of the stochastic process increases with time and that the penalty for a premature decision increases as the discount rate becomes larger. Since Bt corn and HT corn adoption rates appear to offer the highest private risks from mis-predicting the pest pressure (Fernandez-Cornejo et al., 2001), the significance of the beta parameter suggests that their effects have been considered with more caution by individual adopters, because the perceived degree of uncertainty and

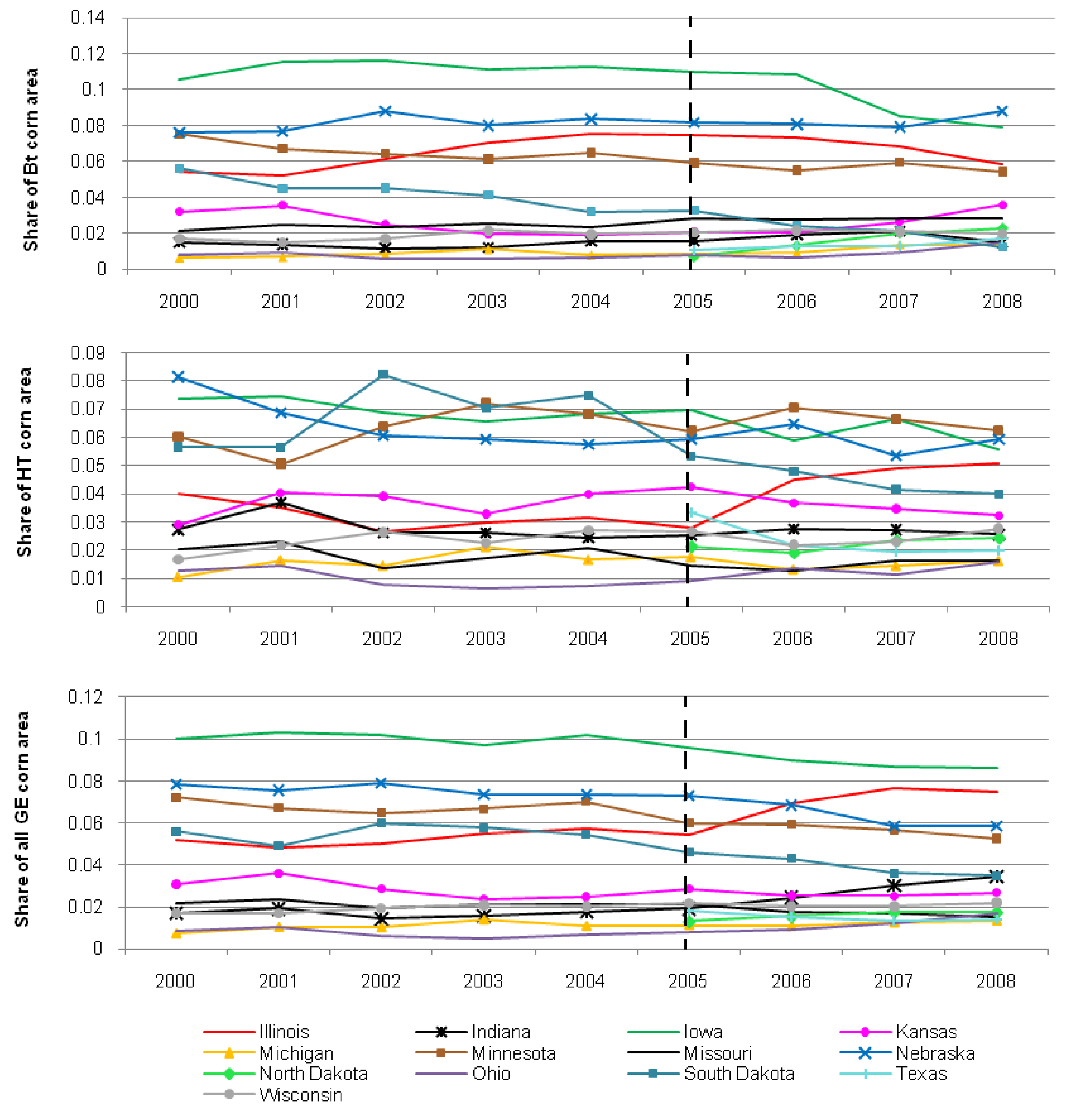

Figure 1. Adoption of Bt corn (top), HT corn (middle) and all GE corn (bottom) in 13 US states.
Source: Authors' computation on NASS, ERS data

irreversibility was higher. HT soybeans, on their part, may have been associated with higher environmental risks, so that their diffusion rates (i.e., their progressive spread over a larger and larger territory) may have been delayed by higher volatility.

With respect to the questions concerning the factors that may have favored and retarded the adoption/diffu-

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6. *The positive dependence of the beta parameter on the rate of discount implies that a larger volatility (i.e., more uncertainty about the future) is reinforced by a higher premium attached to future consumption (i.e., a greater penalty for any irreversible losses). In a broad sense, in the real option model, time becomes irrelevant (and so does dynamic uncertainty) if there is either full information or no concern about the future (or both).*

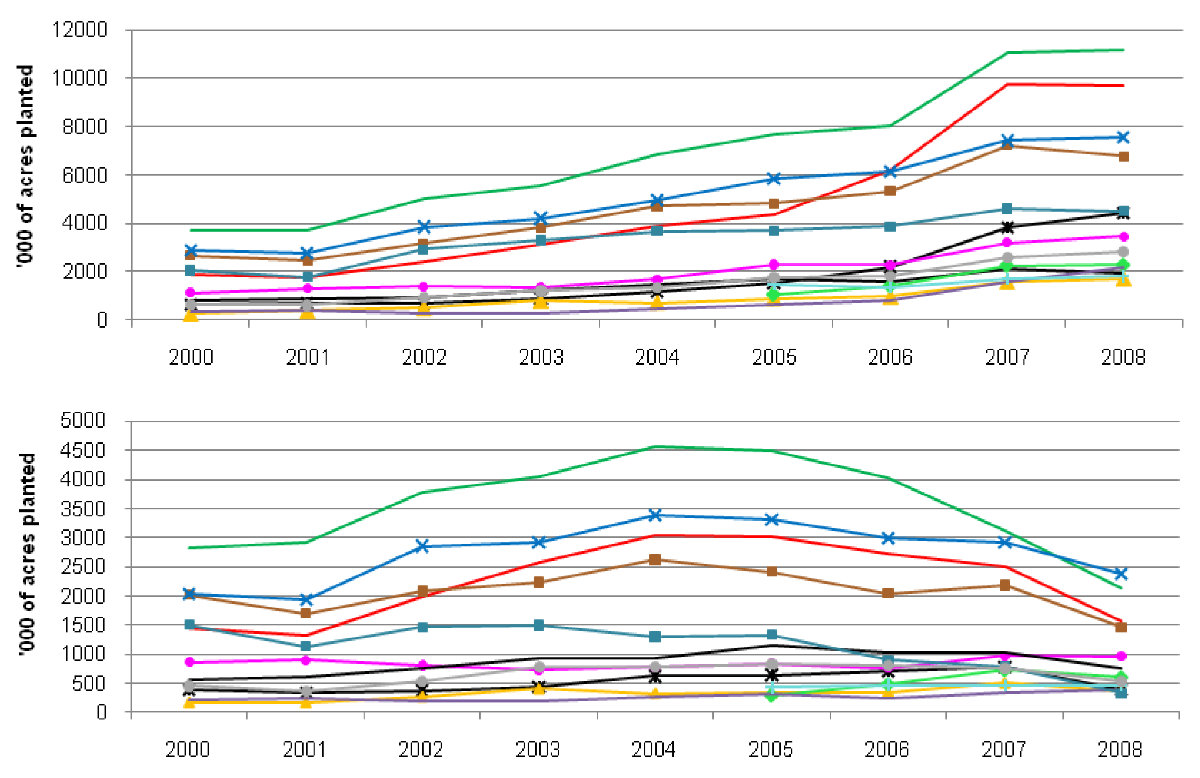

Figure 2. Diffusion of Bt corn (top) and HT corn (bottom) in 13 US states.
Source: Authors' computation on NASS, ERS data

sion process, it is interesting to compare our results to two recent studies. First, Banerjee and Martin (2009) used Agricultural Resource Management Survey (ARMS) data from 2003 to estimate two binary logit models for two definitions of GM cottonseed adoption. Even though the interpretation of their cause/effect relationships is open to debate, their results seem to suggest the lack of impact of conservation tillage (CT) practices and "refuge" non-GM cottonseed planting on adoption rates. While we did not test for the influence of CT practices, we did find significant effects on adoption and diffusion of GM varieties of non-GM corn. In the case of soybeans, however, we found that a significant influence could be measured only on our diffusion variable.

A second study (Piggott & Marra, 2008) tested for non-pecuniary factors explaining adoption and found significant benefits from progressive adjustment to the new technology. These benefits include simpler systems to operate, more powerful mechanical implements, and large savings of time for farm operators. Since our model is a reduced form of a broader choice model, however, the omission of these factors should not bias our estimates of the parameters of the pecuniary variables, such as the prices and the other measurable variables such as the total acreage, the US crop share, etc. Moreover, to the extent that these non-pecuniary benefits (and possibly costs) may increase the irreversibility of the adoption/diffusion events, they should be captured by the coefficient of the beta parameters.

Conclusions

Unlike other cultures and technologies, GM crops present distinctive characteristics in the adoption-diffusion stages. While adoption goes on by convincing farmers to experiment and substitute the new crops for the old ones, diffusion may proceed much more dramatically by endogenously generating scale economies and other external effects. Its spread may thus go much beyond full adoption on the part of all farmers on the existing cropland. With the spread of the new crops to areas previously destined to other types of culture—and even to pasture and forests—diffusion tends to become a process of colonization, where potential land is progressively taken over by GM technology.

Both adoption and diffusion depend, for their deployment, on thresholds of perceived profitability and risks being crossed. These thresholds, in turn, depend on internal and external factors, such as experiments on and off farmers' own estates, information, and prices. Diffusion, however, depends both on the crossing of the critical thresholds on the part of existing farmers for the same crops, and on its own thresholds to spread to other potential farming land. In the end, therefore, the two processes together are likely to show a much greater momentum of traditional innovative agricultural technologies.

These conclusions may appear to contradict the general perception of a delayed penetration for the GM crops, whose success seems to be retarded by lack of information, mistrust, and an exaggerated perception of risks. As the experience in the United States and in several other countries (e.g., Argentina and China) shows, GM crops tend to be invasive, in that their short-term profitability is so high compared to the investment needed, that once the hump of uncertainty is overcome, they operate a veritable takeover of agriculture. While adoption may still proceed slowly in several cases, and diffusion may thus be blocked by lack of information, administrative decisions, or government interventions, the drive to extreme diffusion of GMOs seems inevitable, given sufficient time. In fact, the only remedy for the loss of biodiversity implied by such a drive may be the diversification potential of the same GM crops.

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